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MODELING FORWARD BASE CAMPS AS COMPLEX ADAPTIVE
SOCIOTECHNICAL SYSTEMS

by

LORI ANN MILLER

A THESIS

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Approved by

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ABSTRACT

Work for this thesis focuses on managing complexity within complex adaptive sociotechnical systems by using model based systems engineering and virtual engineering tools. The hypothesis of the work is that integrated virtual models can be used to increase the understanding of these complex adaptive sociotechnical systems, resulting in a reduction in the perceived complexity. This was tested by the use of a two factor survey given to experts of a system (the customer and members of the model design team) and to a target user-group. This group received a demonstration and had hands on experience with a preliminary model of the same system. Results of the survey show that new system designers using an integrated virtual modeling tool view the system as less complex than experts involved with designing the same system without using a tool. Further data is required to support this conclusion, and a plan for gathering more data is described. The application of this method to an emergency response system is then discussed to show how it can be applied to other complex sociotechnical systems and guidelines for applying this methodology are proposed.

ACKNOWLEDGMENTS

Martha Jones: I battle with textbooks.
The Tenth Doctor: I battle with monsters.
Martha Jones: I've tried to save money.
The Tenth Doctor: I've tried to save the universe.
Martha Jones: I'm going to be a doctor.
The Tenth Doctor: I *am* the Doctor.
Martha Jones: Well, let's hope this box is big enough for the both of us.
- ***Doctor Who, BBC America***

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1   INTRODUCTION

There is a global trend evolving that involves looking at any situation from a perspective of a system. A system is said to be a collection of parts that are interrelated and join to serve some purpose. Some systems are defined as closed, which means they have clear boundaries and operate in isolation from their environment. Most systems, however, are open and have regular interaction with the world around them.

In what could be seen as a method of simplification, engineering has traditionally focused on the behavior of the mechanical or technical components of a system with very little regard for the human component. From an engineering perspective, human behavior is difficult, if not impossible, to predict with the same degree of accuracy that result from modeling technical systems. Humans do not often operate by the linear logic we can attribute to technical and mechanical systems. Although the degree of accuracy may be reduced, the same processes used to model traditional systems can be applied to modeling organizations as sociotechnical systems, systems that combine humans and technology. As George Box (1987) is known for saying, "All models are wrong, but some are useful." A model is not required to be perfect for it to improve our understanding of the system.

The field of systems engineering strives to gain understanding of systems and their interactions. Once a system is understood, it can be manipulated to make it more efficient and effective. When a systems gets too large and interrelated to be easily understood, the concept of complexity comes into play. Complexity refers to the nature of an alteration to one component to trigger other unintended changes in a system. In order to manage the system and understand all of the effects a single alteration might have, the detailed relationships and points of integration need to be captured. While

systems engineering offers multiple solutions to understanding complex systems, the technique covered in this research is using model based systems engineering to create virtual models.

Model based systems engineering (MBSE) is the use of models to capture the components and flows within systems and systems of systems in order to increase understanding of the function and integration of system attributes. These models can be scaled down physical versions of systems or virtual models. Virtual models are computer-based representations of the systems. This allows models to be used to run scenarios of systems operations in a safe and secure manner without incurring the time, resources, and expenses of running tests on the full-scale system.

While MBSE is most often used to study purely technical systems, the theory explored here is that the same concepts and procedures can be used to reduce the perception of complexity and improve the understanding of sociotechnical systems. Tsutomu Shimomura (1996) is quoted as saying "We call things we don't understand 'complex', but that means we haven't found a good way of thinking about them." The efforts of this project are working towards finding a new "good" way of thinking of sociotechnical complex adaptive systems.

Included herein is a thorough literature review of sociotechnical systems, complexity and complex adaptive systems. Those are found in chapter two. Chapter three is a summarization of the technique used to build a virtual model, including a discussion of the two-factor survey technique for analyzing the level of complexity within a system. The two-factor survey technique is proposed for use in the discovery phase of a project to determine whether the level of complexity in the system justifies the outlay of resources

required to build a virtual model. The first application, focused on the development of the Virtual Forward Operating Base project for the United States Department of Defense, comprises chapter four. This is where the hypothesis was tested and the results of the test can be found. In a discussion about possible expansion of the work to another sociotechnical complex adaptive system, an emergency response organization, is proposed in the fourth section. Also discussed is the future work needed to validate assumptions made for the purposes of the simplified two-factor model. Lessons learned relevant to the two factor survey and general project management from the Virtual Forward Operating Base project are then summarized for expansion of the methodology to other sociotechnical complex adaptive systems, such as the emergency response organization proposal.

2 LITERATURE REVIEW OF SOCIOTECHNICAL SYSTEMS THEORY, COMPLEXITY, AND COMPLEX ADAPTIVE SYSTEMS

The term sociotechnical systems originated in the 1960s. Walker, Stanton, Salmon, & Jenkins (2008) established sociotechnical systems theory as being composed of two principles of managing systems that involved both sociological (human) and technical components. The first principle proposed that sociological and technical elements combine to form attributes and relationships that either make or break the system in terms of performance. These interactions include linear, predictable, planned relationships, as well as relationships of a non-linear, complex, emergent nature. The second principle is that both the sociological and technical systems need to be managed simultaneously (Walker et al, 2008). If either component is optimized without respect to the alternate subsystem, the system as a whole will not be optimized, and could in fact be reduced in efficiency due to unintended effects to the alternate subsystem. For example, a vehicle can be designed to mechanically transfer cargo from point A to point B, and the efficiency of the vehicle can be optimized and the materials in the vehicle minimized to reduce cost. However, if the design does not consider the human component, the driver, the vehicle will never make it to market. Similarly, an organization can be optimized through training and team building exercises, through practice in the area of communications and task skills, but if the equipment needed to perform the task is ill-designed and malfunctions, the task will not be efficiently completed. Sociotechnical theory provides a holistic approach to system management.

One of the more traditional applications of sociotechnical systems is in the arena of work design. When attempting to manage a new technology as part of a task sequence,

Cooper & Foster (1971) viewed the technological component of the sociotechnical theory as part of the environment. As a result, Cooper & Foster proposed a standard notation and framework for looking at processes within sociotechnical organizations and the environment as a holistic system. Their framework consisted of a simplified flow chart, with columns representing work accomplished by humans, work completed by machine, and work performed upon different materials combined with arrows to provide a sequence of actions. Cooper & Foster laid the foundation for traditional work design applications of sociotechnical systems theory.

Building on the foundational work of Cooper & Foster (1971), Adler & Docherty (1998) demonstrated an approach of sociotechnical systems (or sociotechnical business systems as they termed it) to be an advantage for improving teamwork on product development teams. The anonymous organization they studied used sociotechnical business systems to organize and manage a multi-generational technical product design. Not only did the anonymous organization focus on improving the technical product, but by incorporating a mix of new designers and designers from the first generation design into the second phase of design they were able to maintain the project and product knowledge while adding new perspectives and talent of the new designers. This application of sociotechnical systems theory improved not only the design of the product, but the productivity and culture of the organization as a whole (Adler & Docherty, 1998).

Appelbaum (1997) reviewed sociotechnical theory as applied to work design through the 25 years between his work and that of Cooper & Foster, but applied sociotechnical theory more broadly as a change agent or intervention strategy in evolving organizations. He proposed a series of approximately 30 questions that should be

considered when developing a sociotechnical organization. The questions were intended to eliminate mistakes in applying too strong of an influence from the organizational design professional instead of focusing on the needs and problems that belong to the organization itself (Appelbaum, 1997).

As Appelbaum broadened the application to work design, sociotechnical theory is being applied, or being suggested for implementation, to solve a variety of problems in business and organizational systems around the world; it is not just work design anymore. As the industrial world becomes more and more machine-based, from the factory floor to the board room, the requirement for humans to interface with technology becomes an essential attribute of any organization, and the interfaces become more complex. Three modern case studies demonstrated this shift in perspective and application involving sociotechnical systems theory.

The first of the case studies evaluated discussed the application of sociotechnical systems to addressing issues of human factors and ergonomics within virtual Intensive Care Units (Carayon, 2006). The virtual aspect of this system increased the complexity by integrating two geographically separated organizations through application of modern technical systems to address the needs of individual patients. Through the application of sociotechnical systems, specialists at one location were able to monitor the progress and care of patients at the second location with the assistance of the less experienced local staff (Carayon, 2006).

As a second example of the broadening of sociotechnical theory application, Greenwood (2002) approached work redesign from the point of view of an outside contractor providing "sociotechnical intervention." The organization Greenwood was

working with wishes to remain anonymous, but her walk through a Human Resource Information System upgrade to multiple sub-organizations was a great example of how the culture of an organization can impact the way a technology is implemented. The difficulties an outside consultant has in understanding the existing relationships and how they affect expectations and interactions within one organization, from one sub-organization to the next were stressed (Greenwood, 2002).

With a different spin on sociotechnical systems, Haavik (2011) discussed using sociotechnical theory as accident analysis for two case studies from the offshore drilling industry in Norway. Safety analysis traditionally looks at the failed physical, mechanical, and technical pieces as separate from the human reactions. Haavik's work demonstrated an area for expansion of lessons learned and organizational improvements through applying sociotechnical theory to safety analysis after any accident or incident involving both human and technical failure. This would account for the interaction and influence that the technical failure plays on the human response, and vice versa (Haavik, 2011).

While the case studies mentioned above have valid applicability of the conceptual theory and needs of a modern sociotechnical organization, none of the literature addressed how this theory was to be applied. One is left questioning how the intricacies and complexity of a sociotechnical organization can be captured in order to properly manage both the human and technology needs in coordination.

In 1948, Warren Weaver introduced the concept of organized and disorganized complexity within a system. Weaver used the phrase disorganized complexity to describe interactions within a system that are not well understood. In contrast, studying the complexity of a system can be seen as moving disorganized complexity into organized

complexity (Weaver, 1948). A truly complex system will never reach the full transition into organized complexity. If it is possible to fully understand the interactions of the system, it is not truly complex. However, every move we make towards organizing the complexity is a move in the direction of improved knowledge. When we improve our understanding of the interactions of a system, we can more easily manipulate and manage the interactions and make the system more efficient. This is the ultimate goal of systems engineering.

One indicator of complexity would be system responses that cannot be predicted by the given knowledge of the system. These responses can be tied to various attributes of the system leading to these emergent behaviors. Included in these attributes are interactions across scales (both spatial and temporal), self-directed components (such as human operators), and distributed systems.

Complex Adaptive Systems (CAS) are a sub-class of complex systems that include adaptability as one of the defining characteristics of the system. The difficulty caused by these interactions results in a need to develop meta-heuristic algorithms and techniques to represent and model this complexity with any accuracy (Cilliers, 1998).

Cilliers identified eight qualities of a CAS. They are:

- SIZE: too large for management by traditional techniques
- INTERACTIONS: multiple points of integration
- CASCADING: changes to one subsystem cause second, third, and higher changes to other subsystems.
- REBOUND: changes can cascade back onto the original subsystem
- OPEN: open systems, constantly interacting with their environment.

- ENDOTHERMIC: requiring intake of resources to maintain stability

- EVOLVING: changing, learning, and growing

- ISOLATION: subsystems or components can function in isolation

Several techniques exist to manage and represent complexity within a system. In general, these techniques all exist at a high level of abstraction; they must be tailored to the system/sub-system/component being analyzed. There are several methods for modeling, investigating, and evaluating these complex adaptive systems. These methods include computational intelligence, agent-based techniques, and model based systems engineering.

Computational intelligence (CI) covers a broad area of algorithm development to allow for computers code to mimic natural processes, with the three major focus areas being evolutionary computation, neural networks, and fuzzy systems. Each of these focus areas uses different techniques, but they share a common characteristic in that they allow for the manipulation and assessment of non-continuous, imprecise, mixed format, or incomplete data so that it can be used to evaluate a solution to a given problem. These problems range from numerical optimization to control theory and group membership. Because of their ability to handle non-standard data, computational intelligence methods have proven an invaluable tool for working with complex adaptive systems.

One of the ways in which computational intelligence techniques can be used to assist in complexity management is in the area of modeling autonomous responses. One of the most common methods used to model these types of behaviors are agent based models. Most agents have four important features:

- Perception: the ability to detect changes in an environment, possibly including other agents.

- Performance: programmed to perform a set of behaviors including motion, communication, and action.

- Memory: the ability to record their perceptions of the environment.

- Policy: performs to a set of heuristics that determine what behavior should be performed based on the perception of the current environment.

These features allow for the agents to mimic any number of seemingly self-directed actions, such as the behavior of soldiers occupying and interacting with the base camp as well as potential invaders for security scenarios. Because each can be applied in a specialized manner there are many situations that can be modeled if the proper algorithms are applied.

Systems engineers use model based systems engineering (MBSE) to create models of systems to study and troubleshoot the design and operation of systems, whether they are simple, complicated, or complex. MBSE provides many benefits to the system design process, such as reusability, traceability, and methods for consistency checking of the model, and therefore the system representation.

Models can also be used to explore the responses of a system being assessed and to determine the impact proposed changes may have on that system. This provides users the ability to make several modifications quickly and determine the resulting system performance. When an impact can be identified within seconds of a change in the virtual model, with little associated cost, more changes can be explored for a more thorough exploration of the search space. Designers traditionally look only at a single scale. MBSE

allows multiple scales to be rolled together to look at impacts that would not be seen from

a traditional design perspective. This can be used to identify a variety of weaknesses that

would otherwise be overlooked.

3   VIRTUAL ENGINEERING APPROACH

The approach presented here to manage complexity within a system is to develop a virtual model of the system using model based systems engineering paradigms. As discussed in 2.2.3, a virtual model will allow designers to capture and understand the relationships between components of a system. Users can then test various solutions to situations in a commitment free environment. Manipulation of the virtual model does not require the time and resources that construction of even a prototype would require. In addition, working with the virtual model removes the physical risks associated with building and qualifying a full system. Once the model is completed, scenarios can be built and tested to analyze the adequacy of the design.

Virtual models are a vast improvement over a typical multi-user approach to base camp design. In a traditional design effort, elements are added with limited consideration as to how they impact other components in large part because this information is not apparent or available. This continuous improvement process is also limited by the inherent involvement of the human element. As Hazelrigg (2007) pointed out, "…you want to keep your processes as simple as possible, with as few steps as possible, and with as few people involved as possible." Using a virtual model allows the system to be designed by one person, with assistance of the computational engines and optimization calculations. This gives virtual modeling an advantage over traditional modeling in that every alternative can be tried in a quick and efficient manner with little cost to determine which alteration provides the most efficient system without inducing human bias and group dynamics as distracting factors.

3.1   BASICS OF THE VIRTUAL MODEL

One method for capturing and recording the information about the system, subsystem, components, and their relationships is by using the Systems Modeling Language (SysML) (Friedenthal, 2008). SysML is a standard graphical modeling language defined by the Object Management Group (OMG). This results in a graphical record of the system information.

While SysML is not an executable format, the information contained in a SysML model can be read and edited by other methods, such as VE-Suite. VE-Suite is a software package developed at Iowa State University that is being used to access, pull information from, and feed information back into the SysML model (Bryden & McCorkle, 2005). VE-Suite feeds the information to computational models that do the engineering calculations and can provide accurately altered information back to the SysML model. As the information is updated back to the model, any changes trigger VE-Suite to provide updated information to the various appropriate computational engines and the cycle repeats. Figure 3.1 represents this interaction.
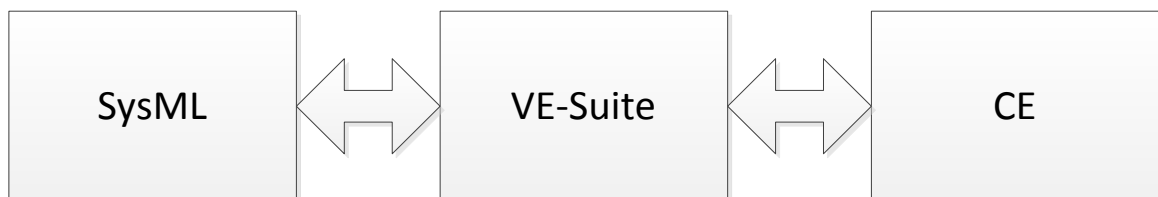
Figure 3.1. Information Flow within a Virtual Model

3.2   STEPS TO BUILDING A VIRTUAL MODEL

3.2.1   Establish as a Sociotechnical System. While this approach could work for other types of systems, we want to ensure the system as sociotechnical and that it initially appears to meet Ciller's (1998) eight qualities of a complex system. This sets up a solid foundation for determining the level of complexity within the system. The type of model discussed herein should not be applied to anything that is either too simple or highly complex. The level of complexity is further determined in the next step.

3.2.2   Identify System/Subsystem Design. The next step to building a comprehensive virtual model is to break the system into subsystems. A top down approach is used to ensure the ability of the subsystems to represent the entire system, much like the typical functional decomposition used in systems engineering. This also allows the interfaces between subsystems to be captured from a high-level view. It cannot be stressed highly enough that the intricate flows of information between systems need to be identified. This information can be in the form of data, energy, physical resources, manpower, etc. A preliminary capturing of what is known of the subsystems, and flows within the systems, assists in determining the needs of the computational models. Figure 3.2 shows one example of how this method of diagraming flow at a high level can be executed early in a project to capture what is known and what is recognized as existing gaps before a decision to proceed is made.
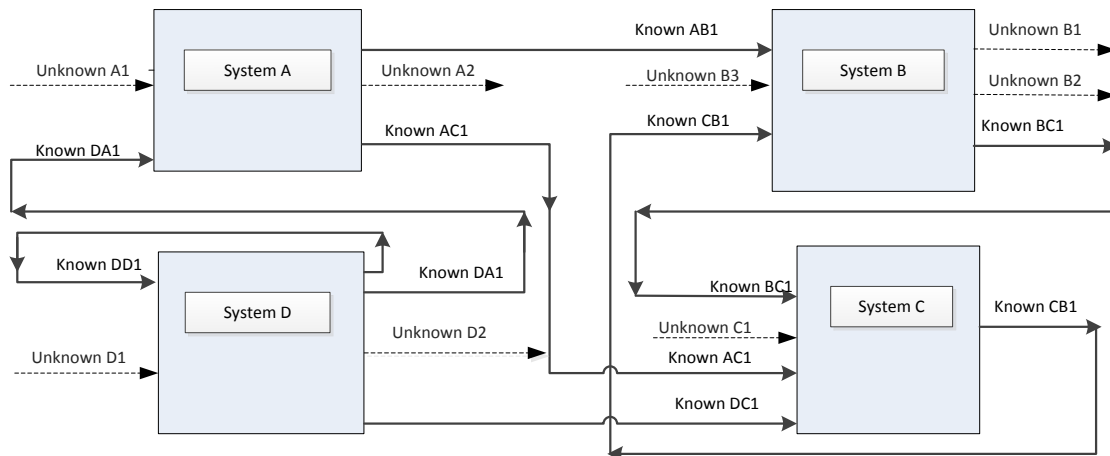
Figure 3.2. Example of Capturing Flow to Determine Complexity

As one might notice, there are two levels of information represented on the above diagram: the known-knowns and the known-unknowns, with the unknowns visually distinguishable. In the example above, they are shown by dotted lines. Also, be aware there are also unknown-knowns (using Subject Matter Experts helps to reduce the number of these) and unknown-unknowns. The unknown-unknowns are the factors that can be observed when behavior escalates above and beyond what the model predicts. The breakdown between knowns and unknowns is one factor that gives us an idea of the level of complexity of the system. If there are no unknowns, the system likely is not complex. The more unknowns there are (whether known-unknown, unknown-knowns, or unknown-unknowns), the more complex the system is likely to be, and the more disparate from reality the model can be expected to behave. The number of interactions can also indicate the possibility of cascading and rebounding effects within the system, although these effects are less obvious at this point in the analysis. These two factors, unknowns

and integrations are the factors used in the two-factor scale proposed as an early

prediction tool for determining the complexity of a system.

   3.2.3   **Determine the Level of Complexity**. In order to determine if the system

is complex, a two-factor scale is proposed. Table 3.1 and 3.2 are an example of a two

dimensional rubric used to assess a system and place it appropriately on the two-factor

graph (Figure 3.3).

Table 3.1 Rubric for Complexity Determination: Integration

INTEGRATION				
LOW				HIGH
1-2	3-4	5-6	7-8	9-10
EFFORT: Easily diagrammed by hand, easily understood	EFFORT: Moderate difficulty to diagram manually but can be completed	EFFORT: Diagram executed with difficult manual work, or assisted by computer graphics	EFFORT: Diagram requires software assistance to be completed, resulting product is easily understood	EFFORT: Diagram requires computer assistance to model, resulting product is not easily comprehended
SYSTEM: Majority of interconnections are to only one other subsystem, all flows move in one direction.	SYSTEM: Moderate recursive feedback within the system or interconnections linking several sub-systems at different points	SYSTEM: Moderate recursive feedback with interconnections between three to five major sub-systems	SYSTEM: Many sub-systems are connected at one or two different interfaces, several feedback and control loops with occasional nonlinear behavior	SYSTEM: Interconnections exist between most major sub-systems, recursive feedbacks and control loops common practice, many causing non-linear behavior

Table 3.2 Rubric for Complexity Determination: Unknowns

UNKNOWNS				
LOW				HIGH
1-2	3-4	5-6	7-8	9-10
<10% Unknown Minor modification to existing technology, incremental implementation.	10-20% Unknown Moderate modification or expansion of existing technology	20-35% Unknown Major redesign of existing technology or new system using tested legacy components	35-50% Unknown New and/or experimental system with new untested components	>50% Unknown New and/or experimental system with several untested components with multiple functions.

Figure 3.3 Two-factor Graph of System Complexity

The two factors used for this scale are the number of interactions and the number of unknowns, each rated on a scale of 1 to 10. The numerical values for the unknowns and interactions can be weighted to account for differences in the impact upon the system and other factors such as size and separability of system elements, with the numerical values tied to a numerical and/or Likert scale evaluation of subject matter expert input. The lower corner, with low interactions that are highly known, indicates a simple system. If a system is either highly interactive, but well known (upper left corner) or lowly interactive and highly unknown (lower right corner) are probably complicated, but do not require the same degree of modeling a complex system does. The target zone for this technique is a system that, before modeling, rates in the complex zone, is in the moderately integrated and moderately unknown. The remaining zone of the scale, at the upper right corner, represents a system that is highly integrated and highly unknown. This combination would suggest a system that may be too complex to be modeled with any degree of accuracy. In this situation, there are two alternatives: either limit the scope of the model to represent a smaller system, i.e. to include a fewer subsystems (and therefore fewer interactions), or keep asking questions of subject matter experts until more of the unknowns become known.

While this scale provides the basics of whether a virtual modeling approach should continue to be pursued for a system, other factors need to be considered. This scale covers only two factors that make a system complex. However, they are the two factors that are most easily observable early in the modeling process. This tool makes a few assumptions, mapping the two early observable factors to the eight qualities published by Cillers (1998). As mentioned previously, the cascading and rebounding

effects can be suggested by a high degree of interaction. If some of the interactions involve the environment, reach outside the defined bounds of the system, the system is open. The sociotechnical nature of the system is tied to the endothermic quality, as humans will always require outside energy, either in food and water or in replacement manpower. Whether the system is able to learn, change, and evolve is a quality that cannot be observed at this point in the modeling process. Another quality that has not been addressed by Ciller's qualities, but is essential to understanding complexity, is the existence and implications of non-linear interactions. This is tied to both unknowns and integrations. The higher the interaction rate, the more non-linearities are expected. Also, some of the unknowns will likely be due to poorly understood non-linearities.

If the system in question meets the criteria of a) being sociotechnical and b) falls into the appropriate zone on our numerical scale, we can conclude that it is an appropriately complex sociotechnical system and proceed with building a virtual model.

This two-factor complexity evaluation tool has also been tested for one application as a post-design evaluation tool. The purpose of the post-design test is to measure the difference in appearance of complexity from the initial stages of the project (pre-evaluation by experts) to the post-evaluation by end-users. The results of that test supported our hypothesis that virtual modeling can increase the understanding of a system and therefore decrease the appearance of complexity, making the system easier to manage. Details of this test are found in section four, as they are explained with the Virtual Forward Operating Base (VFOB) system they were tested upon.

3.2.4   Identifying Computational Engines. Once the initial graphical flow model represents all knowns (known-knowns and known-unknowns) the computational engines can be selected. Two options for this include choosing from commercial off-the-shelf (COTS) packages, or developing a piece custom designed for the model. Factors in this decision include the integration capabilities of the available COTS packages and the level of specialization needed for a particular system. These computational engines need to meet all of the requirements for integration into the larger model as well as accurately modeling the specific behaviors they are chosen to represent. This is key to keeping a model accurate; the model will only be as good as the computational components.

3.2.5   Integration of Computational Engines. The third major step of this process is to program the agent (in our case, within the VE-Suite framework) to identify changes to the SysML model and feed those changes to the computation engines possibly effected by the altered information. This is where the detailed information about the integration of subsystems is essential. If a change is made to a component in SysML, by the user or by the computational engines, that information needs to be fed to the computation components of all systems effected by that component. This allows the second, third, and higher level effects of a single change to be represented in the system.

3.2.6   Account for the Known-Unknowns. The computational engines work well for purely technical engineered systems where actions and reactions follow understood logical rules of behavior to a high degree of accuracy. However, such engines do not accurately account for the human involvement in a system. To account for the known-unknowns, such as effects of humans on the system, one method is to establish a baseline of component behaviors and realistic resource usage. This can be developed by

obtaining expert data from real scenarios. This data becomes the default settings for the

model, but can be adapted by the user based on environmental factors of the instance

being modeled. This process of base-lining can also help the model to account for non-

linear reactions due to unknown interactions, or poorly understood reactions. Analysis of

these reactions within a model using base line data can improve knowledge of the

previously unknown interactions.

 3.2.7 **Make the Model Usable**. From here, a user interface will need to be

designed. The state of the system needs to be in a format that is easily understood and

altered by the user. The final step is the validation of the final virtual model. This

involves an expert or a group of experts, preferably independent of the design process,

manipulating the model and validating the changes to the system.

4   APPLICATION TO BASE CAMP WORK

4.1   DEFINITION OF PROBLEM

The Department of Defense has steadily been moving towards virtual models for Command, Control, Communication, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR), battle space simulations (Virtual Battlespace 2), and advanced weapons systems, but to date these simulation techniques have been applied only to combat operations and weapon systems. To achieve the full benefit of these computer simulations, it is necessary to develop a tool that allows designers across the armed forces access to these new virtual engineering methods. Providing these tools to military professionals will speed the system design process, lower development costs, and provide a final system that has been verified to meet the end user's needs.

The ultimate goal of this research is to develop a versatile modeling approach that enables army engineers to layout a base camp design in a virtual environment where asset attributes are considered as well as the spatial location. Using virtual engineering tools allows for the configuration, evaluation, and modification of components in a virtual environment where changes can be made and the results observed quickly with no material costs. In the case of base camp design, this provides a holistic method of evaluation to promote mission success by providing service members with appropriate support and resources. A variety of systems can take advantage of the software, ranging from a laptop computer to an immersive virtual reality system. This versatility results in a tool capable of being used by designers to layout the base camp using an immersive virtual reality system at a research lab or by a deployed engineer in the field making changes to the facility layout. In addition, this virtual environment allows collaboration

over distance, so that the layout changes made by the deployed army engineer would be synchronized with a collaborator in the virtual reality system, and vice versa. The end result is a toolkit that uses a virtual engineering framework to enable the modeling and simulation of the dynamic interactions between base camp components, allowing personnel to modify and evaluate a variety of configurations to determine base camp capabilities and limitations

4.2   BASE CAMP LITERATURE REVIEWS

To learn more about the current structure and requirements for building a military base camp, the Construction and Base Camp Development in the USCENTCOM Area of Responsibility: "The Sand Book" (Headquarters, 2009) and Base Camp Facility Standards for Contingency Operations: "The Red Book" (United States Army, 2004) were used to derive our utility components as well as the performance requirements of each component. This resulted in the areas of power, water, wastewater, and security being chosen as our primary emphasis areas for our survey of off-the-shelf software.

A preliminary survey of scholarly research was conducted to see what other work had been performed in this field. A selection of works performed by Argonne National Lab in conjunction with the Construction Engineering Research Lab (CERL) was found to be relevant (Sydelko, et al, 1999; Sydelko, et al, 2000; Sydelko, et al, 2001). This work focused on modeling the environmental impacts of base camps on the surrounding ecosystems. The process of moving to an object-oriented model was noted, along with a few items from the toolkit that enabled real-time editing from the field. These are topics that may be touched on in the future development of our product.

The implementation of these tools involves the physical layout of a forward operating base camp and supply chain plus operational requirement models. The current method for laying out a base camp is through manual integration of tools such as the Theater Construction Management System (TCMS) for placement of computer aided drafting (CAD) models. These tools allow for the integration of computer drawings and the Army Facilities Component System (AFCS) design information to a computer representation of the base camp layout. While helpful, this method has a very limited ability to interact with the components being placed in the design space, showing only information relating to the spatial placement of components on a single desktop or laptop computer. These short-comings prevent it from being fully utilized as a design tool for creating models and simulation scenarios to fully investigate the resources necessary to meet the lifecycle needs of an operating base camp.

4.3   BASE CAMPS AS SOCIOTECHNCIAL SYSTEMS

Human Factors, the study of designing technology to complement the human body, has been applied to the design of military technical systems for years. Military Standard 1472 (1989) established a basis of design standards for any equipment designed for human use within the U.S. Military. This is also being implemented by other nations. Walker, et al (2008) proposed the application of sociotechnical contexts to the United Kingdom's military command and control. Jenkins, et al, (2011) used the U.K. military land headquarters as a case study in application of domain analysis in improving performance of complex socio-technical systems. Additionally, the field of systems engineering has improved the efficiency and understanding of many military grade weapons systems and how their users interact and use these systems. However, the

application of systems engineering for non-weapon complex sociotechnical systems has not previously been attempted.

For a complex system such as the military base camp, humans are behaving in ways that impact every utility and subsystem of the model. The inherent involvement of humans within a base camp system requires acknowledgement of their impact on the systems at hand. Historically, engineers have skirted around the concept of modeling human behavior. While Pentland & Liu (1999) claimed to be able to model human behavior to a 95% accuracy using dynamic models and Markov chains, they focused on only modeling a single individual performing a single behavior. Modeling one person's performance of a single focused task, or even a series of focused tasks to a significant degree of accuracy is reasonable. In fact, there has been a great deal of research focused on modeling military task-behavior; The National Research Council (1998and 2008) and others have written books on the subject. However, modeling individual and organizational behavior throughout days, weeks, months, and years is a challenge to engineers who are used to working with logical systems. This is one of the challenges faced when developing an accurate model of a base camp.

Not only is the base camp system inherently sociotechnical, it is also a complex adaptive system (CAS). A CAS is defined by a number of things, and a military base comp meets all of the requirements identified by Cilliers (1998):

- SIZE - In a CAS, the size of the system surpasses traditional methods of understanding the interactions between components. In a base camp, interactions

are not understood by conventional designs due to the number of varying components: number of personnel, different mission types, etc.

- INTERACTIONS - Components in CAS involve multiple points of integration, so that each component affects and is affected by multiple components. For example, a single generator driving a motor on a pump providing water pressure for a dining facility will be integrated with the power system, the water system, the fueling system, and the manpower component.

- CASCADING - Small changes to components can have large impacts on the system. One generator going out on a base camp could cause a cascading blackout affecting the rest of the camp.

- REBOUND: When a change is made to one system, effects are triggered through surrounding systems that can cause the single change to reflect back on to the same subsystem, thus triggering another round of downstream effects. The inclusion of a Reverse Osmosis Water Purification Unit (ROWPU) at a base camp will obviously have an effect on the water system. However, it will also require an increase in power usage, and an increase in manpower, which will in turn cause an increase in housing and dining facilities, which will affect the amount of water needed to be produced by the ROWPU.

- OPEN: CAS are open systems, continually interacting with their surroundings. In the example of base camp utilities, the surrounding environment influences the sourcing, usage, and disposal activities.

- ENDOTHERMIC: A CAS maintains operations outside of equilibrium, and constantly requires input of energy or resources to remain stable. Base camps are constantly being supplied with resources from food to fuel from outside sources.

- EVOLVING: Base camps have varying missions and designs, with the past having substantial impacts on current and future designs. This is typical of a CAS.

- ISOLATION: Subsystems of a CAS tend to respond to behavior within close proximity, without consideration for the larger system as a whole.

The base camp consists of an integration of subsystems. Each subsystem is, of itself, complex as well as interdependent upon other subsystems. The identification of these interdependencies is key to understanding, and subsequently managing, the complexity of the overall system. The next step is to look at the input and output of each utility to begin to determine the integration points.

4.4   IDENTIFY SYSTEM/SUBSYSTEM DESIGN

The integration of water in utility planning affects the following other systems: power, fuel, wastewater, and solid waste. The amount of water required to sustain the base camp can possibly lead to an increase in personnel to manage the water supply. The increase in manpower then increases the power, fuel, waste, and water requirements in a trickle-down effect. The planning factors for water volumes need to take into account the number of personnel, various operations of the personnel, as well as the climate in which the base is located.

The process above is repeated to determine integration points for all other subsystems: power, wastewater, solid waste, force protection, manpower, and mission activities. From there, we need to determine what type of load is expected for any variety

of base camp that could be modeled. For this project, models need to be designed for base camps ranging from 50 to 20,000 person camps. To determine our baselines of load information, we relied again on TCMS, the Construction and Base Camp Development in the USCENTCOM Area of Responsibility (The Sand Book) and Base Camp Facility Standards for Contingency Operations (The Red Book), and on expert input from the field. In June of 2011, a Base Camp Workshop was held at Missouri S&T. This provided access to a group of subject matter experts who were able to provide a minimal set of data on usage, prioritization, and a collection of anecdotes that helped the developers identify non-conventional impacts to the system. Once load levels are determined, either through expert input or data analysis, the parameters are used to develop equations based on the expected usage of each utility, broken down by facility. The product of this effort is a lengthy series of both linear and non-linear equations describing the usage of each utility. This allows for a model of facility demand based on expert provided information that is a function of population size of the camp. These equations are then set into a mathematical solver for simultaneous processing. This allows the system of equations to rebalance itself each time a modification is made to the demand, giving an initial baseline of utility usage for the base camp as laid out on the map.

The resulting basic schematic can be seen in Figure 4.1 on the next page. The "knowns," as previously discussed in Section 3.2.2, are shown in black and the "unknowns" are shown in grey. Five major subsystems, each utlities, were initially identified as requiring their own computational engines. As one may notice, the sociotechnical aspects of this design are initially identified as unknowns. Further research on the human element of base camp design is required for the model to be accurate.
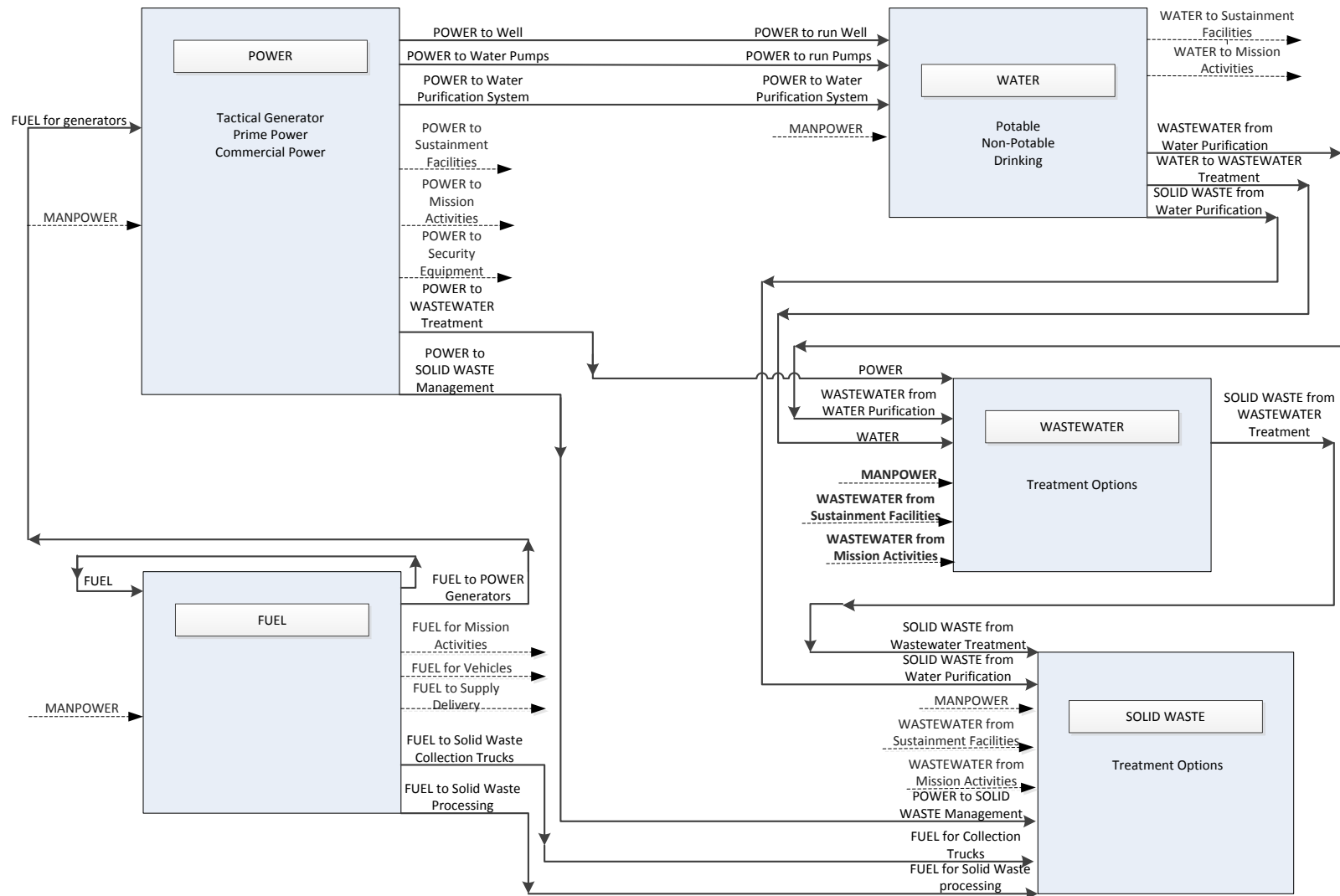
Figure 4.1 Initial Base Camp System Flow Diagram

4.5   DETERMINE THE LEVEL OF COMPLEXITY

A tool using two early-observable factors has been developed to determine the complexity of a proposed model from the planning stages of a modeling project. As a test of this tool's ability to accurately capture the complexity of a proposed system, test of the system was composed. The primary hypothesis stated that the tool could reliably be used to determine the complexity of a system. As a secondary test of the tool, another hypothesis was proposed that users of a tool would rate the system as less complex than the expert group. Both of these hypotheses were tested using one survey.

4.5.1   A Test of the Two-Factor Complexity Rating Tool. In order to test the reliability of the two-factor rating tool and the perceived complexity between user and expert groups, a four question survey with supporting background information was given to two different audiences. The first group was a set that will be referred to as the experts. This group contained seven individuals with high familiarity with the project due to involvement in the development. Four individuals were from the design team on at Missouri S&T and three were from the customer organization.

The second set of individuals, referred to here-in as the users, were members of the Captain's Career Course on Fort Leonard Wood. These individuals were assigned the task of designing a base camp during their coursework. A demonstration version of the VFOB product was briefed to the 80 individuals, along with the opportunity to design a base camp using the demonstration version. The theory being tested is that the second group, the users, would view the system as lower in complexity than the expert group. This would support the hypothesis that a perceived reduction of complexity is accomplished by using a virtual engineering modeling tool.

The survey led the respondents through the first steps of determining the complexity of the system. The first question asked whether a base camp fit the definitions of a sociotechnical system. The expert group unanimously responded with a yes. The user group had a 73.8% yes vote. Both of these sets of data individually passed a chi squared test rejecting the null hypothesis (Experts = 0.0081, Users=.000021). When compared against each other, a chi squared test for independence between the two groups resulted in an 88.1% independence rate. This is considered a failure against the standard 95% threshold. However, this is a promising result. The conclusion is that both groups agree that base camps qualify as sociotechnical systems.

The second question asked whether a base camp fit the eight qualities of a complex adaptive system (Cillers, 1998).Again, the expert group unanimously responded that a base camp is a complex adaptive system. The user group, however, only had a 56.3% yes rate. This question failed to reject the null-hypothesis. Possible conclusions include that the user group had a poor understanding of what a complex adaptive system is, or under-estimated the complexity of the system after using the design tool. When this survey is conducted again, a follow-up question will be included to ask, "If no, please specify which of the eight qualities of a complex system does a base camp not meet, and why?" This will assist in understanding the low consensus of responses among the user group.

The third question asked the respondents to use a rubric to rate a base camp on the interactions of the system. The rubric is provided in Table 4.1.

Table 4.1 Interaction Rubric

	1-2	3-4	5-6	7-8	9-10
Interactions	EFFORT: Easily diagrammed by hand, easily understood	EFFORT: Moderate difficulty to diagram manually but can be completed	EFFORT: Diagram executed with difficult manual work, or assisted by computer graphics	EFFORT: Diagram requires software assistance to be completed, resulting product is easily understood	EFFORT: Diagram requires computer assistance to model, resulting product is not easily comprehended
	SYSTEM: Majority of interconnections are to only one other subsystem, all flows move in one direction	SYSTEM: Moderate recursive feedback within the system **or** interconnections linking several sub-systems at different points	SYSTEM: Moderate recursive feedback with interconnections between three to five major sub-systems	SYSTEM: Many sub-systems are connected at one or two different interfaces, several feedback and control loops with occasional nonlinear behavior	SYSTEM: Interconnections exist between most major sub-systems, recursive feedbacks and control loops common practice, many causing non-linear behavior

The resulting data on this question had a mean of 7.0 on the Likert scale, with a standard deviation of 1.4, by the expert group. The user group responded with a mean of 5.8 with a standard deviation of 1. 7. Both sets passed the chi squared test, rejecting a null hypothesis. When compared against each other, however, the results failed the chi squared test for independence at a standard 95% threshold. As a result, further data is planned to verify the difference in mean and gather more information to either support or reject the idea that users find the system less complex after using a modeling tool. One possible explanation for this failure is due to familiarity with base camps due to previous deployments. The subjects could be biased due prior exposure and not relying purely on

the modeling tool to base their answers. The data from this question is plotted in a bar

graph shown in Figure 4.2.
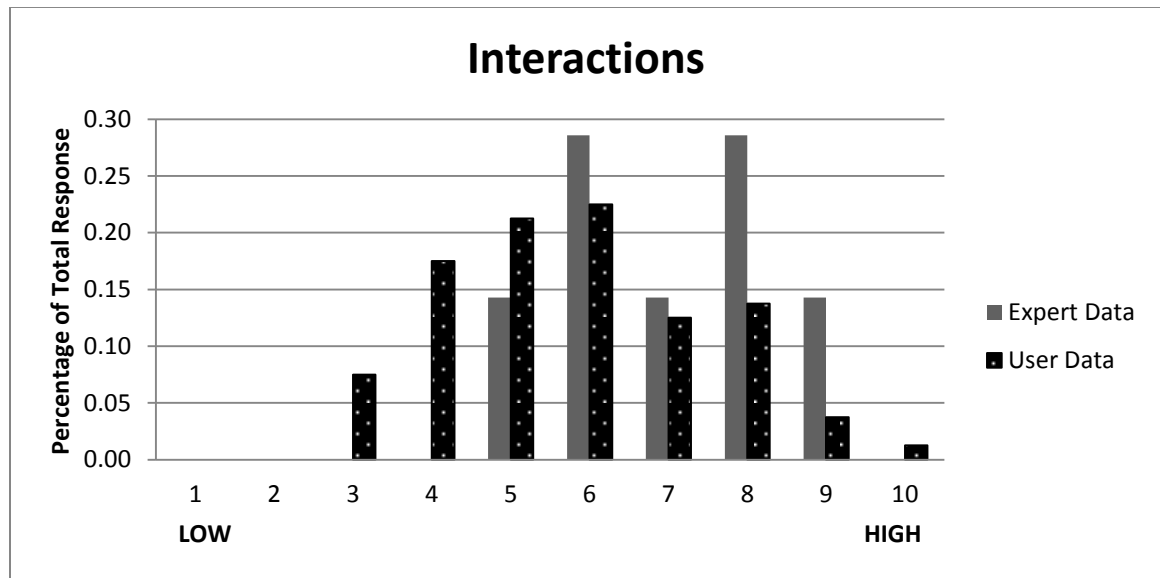
Figure 4.2 – Graph of Interactions Ratings

The fourth question on the survey asked the respondents to use a rubric to

evaluate a base camp on the basis of unknowns. The rubric in Table 4.2 was to be used to

help determine placement on the Likert scale. Experts rated the system as a 7.29, with a

standard deviation of 1.25. The user group rated the base camp system as a 4.65, with a

standard deviation of 1.81. The chi-squared test rejected the null hypothesis. A chi-test

for independence passed for this question, with a 99.8% independence rate. This suggests

a significant difference between the evaluation of unknowns between the experts

contributing to the development of the modeling tool, and the users of the demonstration

modeling tool. This response supports our hypothesis that users of a modeling tool view

the system as less complex. The significant dip in the expert results graph, Figure 4.3, is due to only having 7 responses from that group. Figures 4.4 and 4.5 are individual graphs of results from each of the two subject groups.

Table 4.2 – Unknowns Rubric

	1-2	3-4	5-6	7-8	9-10
Unknowns	<10% Unknown	10-20% Unknown	20-35% Unknown	35-50% Unknown	>50% Unknown
	Minor modification to existing technology, incremental implementation	Moderate modification or expansion of existing technology	Major redesign of existing technology or new system using tested legacy components	New and/or experimental system with new untested components	New and/or experimental system with several untested components with multiple functions
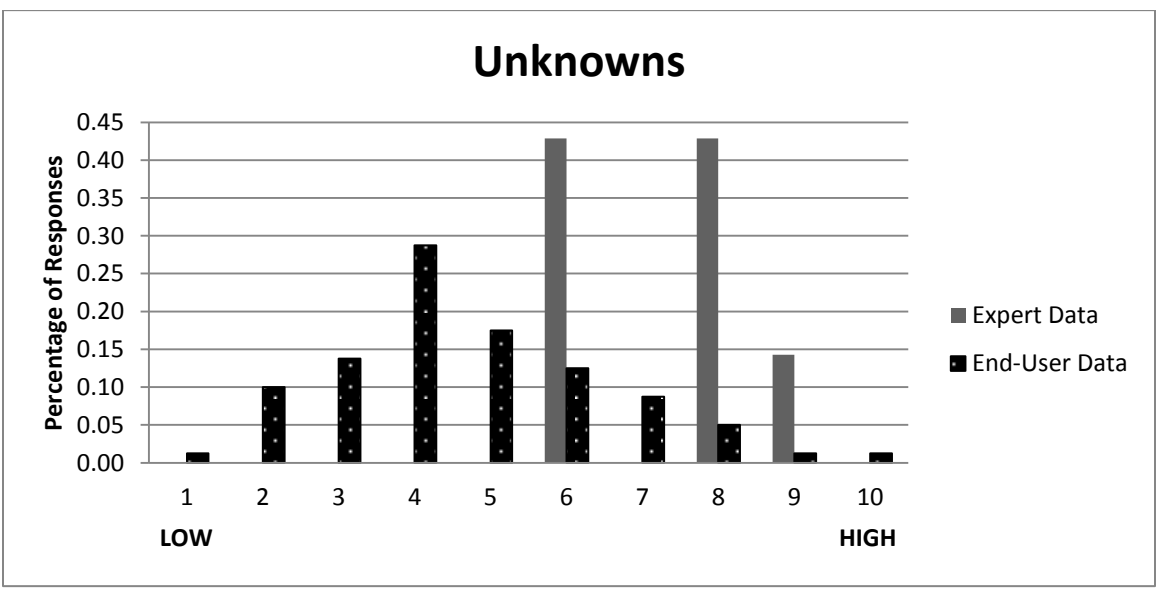
Figure 4.3 – Graph of Unknowns Ratings
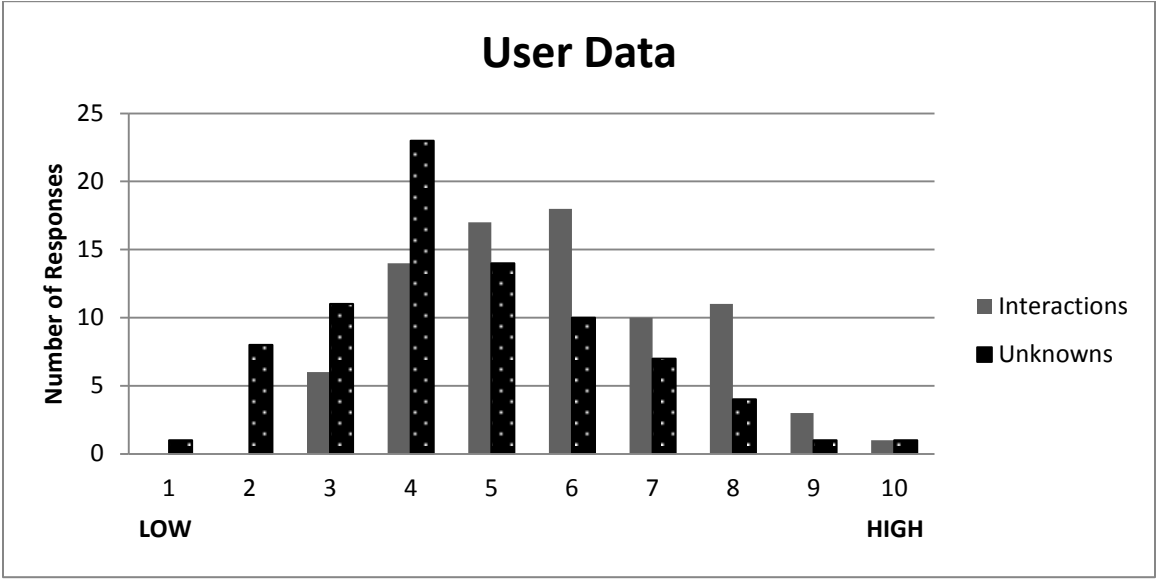
Figure 4.4 – Graph of User Data
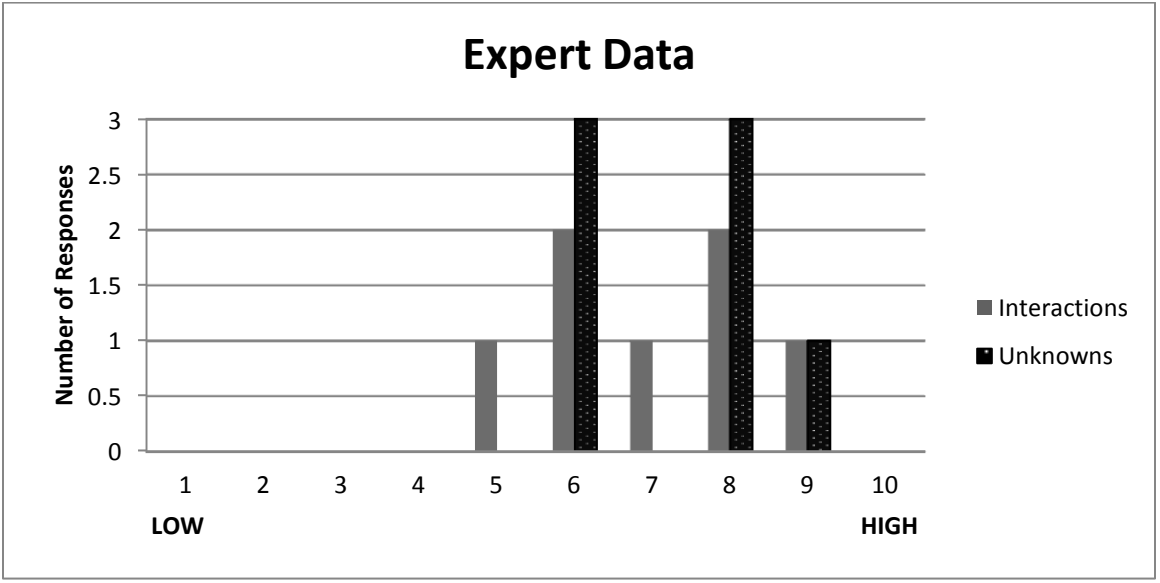
Figure 4.5 – Graph of Expert Data

When all of the results are plotted to the two-factor evaluation tool, the results

appear to support our hypothesis. The expert group rated the system as complex

(moderately high in complexity) using our two factor rubric. The user group rated the system as complicated (moderately lower in complexity). On Figure 4.6, the two Xs represent the mean from each the two data sets. The vertical and horizontal bars are representative of one standard deviation from each mean. The upper right set corresponds to the expert data, and the lower left set is the user data.
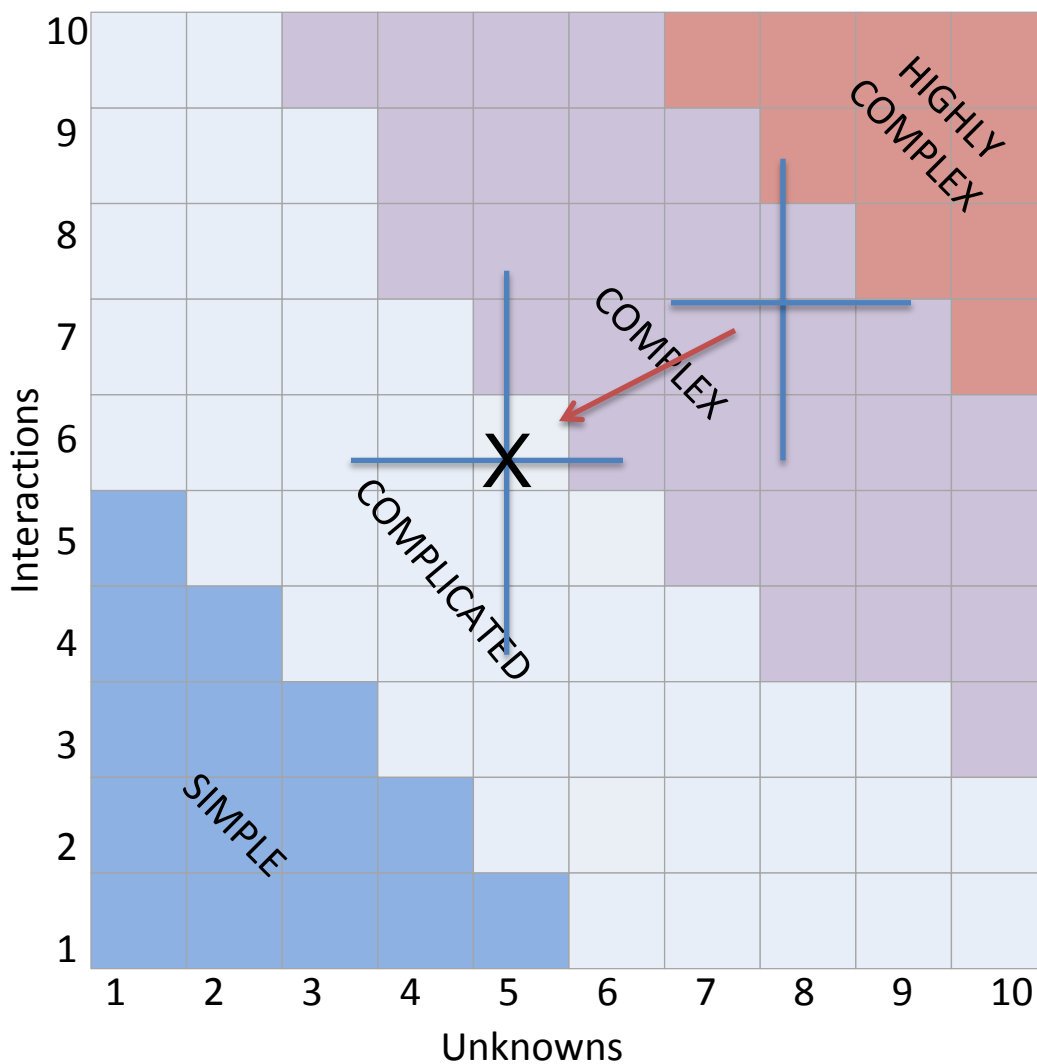
Figure 4.6 – Results of the Survey Shown on the Matrix

Overall, the comparison of the two data collections did result in a 98.8% independence evaluation. This supports the hypothesis that the expert group and the user group view the complexity of the system differently, based on using the two factor approach.

4.5.2 Future Work on the Two-Factor Complexity Rating Tool. Further data using this tool will be collected by submitting a slightly revised survey to the next group of the Captain's Career Course students taking base-camp design training at Ft. Leonard Wood. The intention is to evaluate their perspective of base camp complexity prior to being introduced to the VFOB modeling tool. This should be followed up with a survey that collects their perception of complexity in a base camp after being briefed on and using the demonstration version of the VFOB design tool.

Additionally, some validation of assumptions is necessary to further support this complexity estimation tool. The two-factors used in this approach need to be concretely tied to the eight factors they are intended to represent. Also, this tool should be tested against other socio-technical complex adaptive systems.

4.6 IDENTIFYING COMPUTATIONAL ENGINES

The base camp system has been identified as sociotechnical and meeting the preliminary expectations for a complex system. A basic system flow depicting subsystems and integrated flows has been developed. The two-factor complexity evaluation tool has been used to verify that a model could be useful to increase the understanding and reduce the perception of complexity in the system. The next step in the process is to identify computational engines to model each of those subsystems. Upon request of the customer, a search for appropriate COTS modeling software was

performed. Packages covering electrical power production and distribution were the first to be evaluated.

4.6.1   Power. The search for COTS software began with a survey of the military standards applicable to power generation and distribution. This was to ensure that the commercial modeling software were compatible with the standards of military application.

4.6.1.1   Determining the power performance measures. There are two divisions of generator based power used in base camp operations. The smaller output capacity, and therefore highly targeted output, is referred to as tactical power. Tactical power incorporates both precise and utility generation. Tactical generators (TACGENS) are limited to a range of 0.5 to 200 KW output. This makes it the most common type of power provided to small forward operations. Power for use on larger bases is supplied by generators is referred to as prime power. Prime power plants consist of non-tactical generators larger than 200 KW. Modeling prime power would be similar to modeling usage from commercial power. This type of generation is commonly used for communications centers or intermediate/semi-permanent staging bases. Commercial power is a possible alternative for larger operations, but rare for smaller base camps (Headquarters, Department of the Army, April 2007). A COTS modeling package would need to address both on-site generation as well as commercial supply.

Distribution systems for TACGENs are not highly complex. However, that does not mean an elimination of planning and forethought in designing the layout. In order to make a generator-based system more efficient, placement of generators is a prime concern. The placement should be near enough to a facility to reduce surface-laid

transmission cables, but centrally located as to provide access by a centralized fueling system and streamline preventative maintenance activities.

A secondary point of consideration when designing for the use of TACGEN is the required redundancy for continued operations. TACGEN requires a number of generators be on stand-by for emergency and maintenance situations. An increased number of generators and an increase in required periodic maintenance also lead to an increase in manpower. An increase in manpower increases the load on the sustainment facilities, which in turn requires more power and more manpower. This is one example of the rebounding quality of a CAS.

If one recalls the base camp flow diagram, Figure 4.1 the inputs required to produce power for a base camp are few in number, but substantial in impact. However, power capacity is a far reaching concern. The demands indicated by the dotted lines in Figure 4.1 are often beyond the knowledge of base camp designers. Designers may know the needs of the first wave of occupants, but planning for future occupation of the base is sketchy at best. Be that as it may, the demands are significant enough to justify recognition of their substantial impact on the system. A change in mission will severely impact the volume of utilities needed for any given base.

All of this gives one a basic understanding of what an appropriate software package needs to be able to model. This information was used to assemble a list of technical performance measures to assess the fit of the COTS modeling packages. A second set of performance measures specifically addressed the need of the software package to be easily integrated into the bigger full-system model. The performance measures were then assembled into a weighted decision analysis matrix. This technique

allows for a series of alternatives to be measured and compared based on compatibility to the performance measures. The addition of a weighted rank, assigned to each performance measure, allowed for some measures to more heavily influence the results, as deemed appropriate. For this project, the weights were proposed to the customer based on background research, allowing the customer to make any adjustments necessary.

4.6.1.2   Identifying potential COTS packages. The search for COTS packages began with once the appropriate performance measures had been identified. It was noted that hundreds of building energy modeling packages had been developed, enhanced and used throughout the building energy community. The Department of Energy had published a survey of various packages (U.S. Department of Energy, Energy Efficiency and Renewable Energy). That survey provided an up-to-date comparison of features and capabilities of various building energy software packages, based on the information provided by the vendor. It explained the basic concept of energy simulation in building design and the properties of simulation design tools. The range of applications and the limitations of existing simulation tools were also described.

The number of power modeling packages in commercial space was significant, so the list was narrowed down to those packages surveyed and approved by the Department of Energy. (U.S. Department of Energy, Energy Efficiency and Renewable Energy) The choices were further refined by including packages with the highest match of capabilities required from an electrical power model, based upon the requirements from review of United States military standards.

4.6.1.3   Evaluating COTS packages. Each software package was evaluated at a high level to determine the degree to which it met the requirement for modeling power usage of an army base camp. A rank was assigned by an electrical engineering subject matter expert by using the criteria in Table 4.3. That ranking was then multiplied by the weight, as found in the second column of Table 4.4, for each performance requirement. These weighted rankings were entered into the corresponding cell, then each column was summed to provide an overall score for each software package. The higher the overall score, the better match the software package was expected to be in meeting the needs of the end product.

Along the top of Table 4.4 each software package was assigned a column. For each performance measure, an individual package was assigned a weighted rank, based on how well it meets the performance measure in that row. The possible ranks were limited to 0, 4, or 9. For example, if we consider the price of the software, a rank of 9 was given if the software license if free, a rank of 4 if the cost of the single license of the software was less than $5000, and a rank of 0 is used if the cost is over $5000. The weighted rank of the technical performance measure was then obtained by multiplying the rank with its corresponding weight. The resulting product was shown in the appropriate cell on the table.

Table 4.3 - Ranking Criteria

Rank	Level of Contribution
0	No element contributes to the objective
4	More than one element contributes to the objective
9	All the elements contribute to the objective

Table 4.4 - Capabilities of Electrical Power Modeling Software

Performance Measure	Weight	TRNSYS (Weighted Rank)	PSCAD (Weighted Rank)	ID-Spec Large (Weighted Rank)	Energy Plus (Weighted Rank)	eQUEST (Weighted Rank)	ESP-r (Weighted Rank)
Electrical Modeling Performance							
Electrical Load Distribution & management	0.26						
On-site generation and utility electricity	0.13	1.17	1.17	1.17	1.17	1.17	1.17
Renewable Components	0.13	1.17	1.17	0.00	0.00	0.00	0.52
Power Generators	0.24						
Internal Combustion Engine Generator	0.04	0.36	0.36	0.36	0.36	0.36	0.36
Combustion Turbine	0.04	0.16	0.36	0.36	0.36	0.36	0.00
Micro generation integrated with thermal simulation	0.04	0.36	0.36	0.00	0.16	0.00	0.36
Grid connection	0.04	0.36	0.36	0.00	0.36	0.00	0.36
Electric Conductors	0.04	0.36	0.36	0.00	0.00	0.00	0.36
Building Power Loads	0.04	0.36	0.36	0.36	0.36	0.36	0.36
Integration with Other Packages							
Interface	0.10						
Command Line	0.08	0.72	0.72	0.00	0.00	0.00	0.00
GUI	0.02	0.18	0.18	0.18	0.18	0.18	0.18
Data File	0.3						
XMI File	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Text file	0.04	0.36	0.36	0.36	0.36	0.36	0.36
IGES File	0.04	0.00	0.00	0.00	0.00	0.00	0.00
DAT File	0.04	0.00	0.00	0.00	0.00	0.00	0.00
DWG File	0.04	0.36	0.00	0.36	0.00	0.36	0.00
Open Source	0.10	0.90	0.00	0.00	0.00	0.00	0.90
Cost	0.01	0.04	0.04	0.04	0.04	0.09	0.09
Computer Platform	0.09						
Windows	0.03	0.27	0.12	0.27	0.12	0.27	0.27
Mac OS	0.03	0.27	0.12	0.00	0.12	0.00	0.27
Linux	0.03	0.27	0.12	0.00	0.12	0.00	0.27
Weighted Total	1.00	7.67	6.16	3.46	3.71	3.51	5.83

The maximum total weighted rank that software could obtain is nine. The weighted matrix (Table 4.3) showed that TRANYS software package received the highest weighted total of 7.67 followed by PSCAD with a weighted total of 6.16.

4.6.1.4   A failed technique. In order to allow for successful integration into the base camp model, the software packages would need to fully meet all of the integration requirements and model the utilities as used in the military standard. Due to the flexibility and mobility required of military installations, commercial standards are not feasible. After analyzing the results of the weighted matrix as applied to the power modeling packages, the approach of a weighted matrix was determined not to be a good fit for this application. This led the analysis of the performance metrics for integration and the technical performance measures pertinent to each specific utility as more of a required checklist than a decision matrix. Thus, the remaining utilities were addressed in terms of technical performance measures required and the fit of the "best" package, but did not use a weighted matrix.

4.6.2   Water Modeling. Performance measures were determined using the same process as described with the power models in 4.6.1, a review of military standards and discussions with the customer about field application.

4.6.2.1   Determining water modeling performance measures. Water supply to forward area bases is a critical resource to campaign success. Consumable water for base camp operations is split into three classifications: potable, non-potable, and drinking water. The volumes of each classification will vary greatly upon a number of factors. For most base camps, water is kept on hand for only one day's operations. This method requires water to be resupplied daily (Headquarters, Department of the Army, July 1990).

Non-potable water may come from a local environmental source, a pre-existing well, or it could be trucked in. It is feasible to drill a well for these locations if one is not available, however circumstances may prevent this option.

Some locations can support water purification operations. In these situations, non-potable water can be processed into potable. Lakes, rivers, and wells can be subject to purification on demand. However, in theatre many tactical operations will not have access to water purification systems, to excess storage, or to distribution equipment. In these cases, potable water can also be trucked in.

Although it is officially a last resort source, in today's U.S. military, troops rely heavily upon bottled water for drinking supplies. This requires delivery through the same supply convoy that will distribute fuel to power generators the mentioned in the previous section, and is subject to the same risks. Bottled water also has the added downfall of adding significantly to the solid waste stream of the base camp (Anderson, 2011).

For patrol bases, only potable water is supplied to the base. Water is typically stored in five gallon cans. In some circumstances, bottled water is available for drinking. An occasional water buffalo (stainless steel or fiberglass water tanks on wheels, often in 400 gallon capacities) is deployable in some scenarios. A water buffalo can be outfitted with a wash station to provide for personal sanitation needs. For combat outposts, the same style of water buffalo is used consistently, and assigned a particular location within the camp.

When a base camp expands to the size of a Forward Operating Base (1000-2000 personnel), water supply starts getting more complicated. These base camps start out being serviced by a network of water buffalos for water distribution but may change to a water distribution system. Shower and laundry services start occurring on base and requiring additional water intake. For smaller camps, Meals Ready to Eat (MREs) are the

only option for day-to-day sustenance, but as the base camp grows, dining facilities

(DFACs) start to be used.

  4.6.2.2 COTS water modeling package. A satisfactory water model proved

difficult to locate in our survey of COTS software packages. Most of the software

packages billed as "water modeling" were actually troubleshooting software for old

leaking systems, or water quality control models without the capability of modeling

usage or distribution. However, one product was found that included open database

architecture and modeled the energy consumption of the distribution system.

WaterNetworks is used to extend the features of EPANet, a set of water modeling tools

by different municipal and military installations (Boss International, 2010).

WaterNetworks adds a graphical user interface, provides compatibility with AutoCAD

and Microstation, and communicates with ArcGIS databases. While this software

package integrates well, it should be noted that these modeling packages were intended to

model a more permanent in-ground set of pipes and equipment, which is rare for smaller

military installations.

  4.6.3 COTS Wastewater Modeling Package. Again, the search for a

wastewater treatment modeling software package began with the requirements stated in

the Red Book (United States Army, 2004). A variety of COTS software applications were

found to model sanitary sewer design and water treatment plants separately. However,

there was no one software package that could model both the drainage requirements for a

community and the requirements for processing and treatment of the waste products, and

so a combination of packages would be required for this effort. As with the water system,

these modeling packages were intended to model a more permanent in-ground set of

pipes and equipment, not the temporary and flexible equipment the military most often deploys to FOBs.

4.6.3.1 COTS sanitary sewer modeling package. HYDRA was a software program by Pizer (Pizer International, 2010) which claimed to already be in use by military bases to model and design urban drainage systems. Hydra prided itself on the ability to identify design problems before they become an issue to the public; issues like sewer overflows, street flooding, and surcharged pipes. HYDRA also offered the ability to evaluate new projects as extensions of an already calibrated model; such as evaluating the base as an extension to a pre-existing local sewer system.

For integration merit, Hydra had advantages and disadvantages. Hydra had the ability to provide output in the form of formal reports and/or tabular data, profiles and hydrographs, CAD files, and GIS files. The product included the ability to incorporate some user defined elements, but was not open source; it was also only functional on Windows platforms. The cost for a single license at time of evaluation was approximately $4500, and there was no guarantee that it would fit our needs.

4.6.3.2 COTS treatment plant modeling package design. GPS-X was the world's leading wastewater treatment plant modeling and simulation software package (Environmental Software Solutions, Inc., 2010). GPS-X had the ability to model many different types of wastewater treatment, from biological and settling treatment processes through influent, anaerobic, and filtration treatment methods. While the information available did not specifically include some of the elements needed for our complex integration project, GPS-X does claimed to provide dynamic cost operating models for various processes.

This Windows-based product claimed to have open-code models available for editing and the ability to customize the outputs. There was also a graphical drag and drop user interface that may prove helpful for the end users.

4.6.4   Force Protection & Security. A preliminary survey was performed for COTS software that could accurately model the security needs of a military base camp. As would be expected, there is not a huge market for this in the commercial world, and the initial survey turned up nothing worthwhile. A short search for security modeling software targeting gated communities and municipalities was also of little help, as did a search of private security companies and DoD contractors. Nobody executes security the way the Department of Defense does, so the expectation of finding accurate models available to the public was low from the start. One thing that was found that might be of use was a package for modeling the layout of a base camp with DRASH shelters, including requirements like stand-off distances. This was found in VTap2.0. This could be useful for the three dimensional layout capability and the user interface (DHS Technologies, LLC, 2010).

As a result of this discussion with the customer, force protection and security engineering was moved into the Department of Defense's area of effort in contribution to this project. While the inputs and outputs of the force protection arena remained a load taken into consideration when calculating the needs of the system, the force protection piece itself is being treated as a "black box" for the base camp model.

4.6.5   Other Software. In the process of searching for possible modeling packages, a few other areas were explored with no profitable results. The area of solid waste processing was surveyed, for example. This produced a few products used for

modeling the customer costs of waste processing, but nothing that could predict the volumes or the energy rates for processing a given volume of solid waste. As a further example, a search for software specific to community planning resulted in some interesting user interface designs, but no actual models for our use. CommunityViz was one package that had a very user-friendly approach to visualizing community planning and differentiating community zoning approaches (Placeways, LLC, 2010). However, CommunityViz did not have the level of engineering interaction needed for this project's needs.

      4.6.6   **Summary.** If COTS packages were required, the selection process could follow the suggestions of each package listed above. However, since none of the selected packages met all of the requirements for integration, the programming for each utility would need to be done as in in-house collaborative package. This allowed for improved accuracy of integration of utilities within the model.

4.7   **SUMMARY OF OTHER/ FUTURE WORK ON BASE CAMP MODEL**

      The efforts at Missouri S&T to create a virtual model of a base camp are ongoing. As a search for commercial off the shelf models of utilities turned up no solutions of value to the project, computational engines specific to the needs of a military base are being created for integration into the base camp model. The basic structure of the system has been captured in SysML. A baseline of the current utility usage has also been developed based on data provide from the customer. A rudimentary user interface has been developed for early-stage testing of the system. A preliminary piece has been tested with a small user group, but more testing will occur as further integration is added.

As a whole, the project has produced many lessons for the design group at Missouri S&T and for the customer. Five major project management lessons learned from the base camp work include the following:

Models need to be built specific to the requirements and real-world installations of the represented system. Using commercial modeling software for a military installation would not have provided an accurate view of a military-built system. Commercial utility models are used for permanent installations and managing long-term viability. Base camps are built with modular equipment that does not conform to American standards of commercial or residential construction.

In order for virtual models to be accurate to the true state of nature, a great deal of expert data is required to design and test these models. Sometimes those closest to the information do not realize the significance of the knowledge they have and do not speak up. Other times the data does not exist or is incomplete. The project team must be creative in bridging gaps in ways that provide accurate results.

Management of the project team requires application of some aspects of systems engineering as well. Subject matter experts must have experience and knowledge specific to the system on which they are working. They also need to be sufficiently knowledgeable in the application of systems engineering methodologies. This ensures that they have the basis to ask the right questions of the user organization to elicit the information most needed to the final project.

Due to the level of interaction needed with system experts, an effort of this nature requires a great deal of buy-in from the user community. If cooperation from the community is lacking and experts are unwilling to provide input to building the design

and feedback from testing a preliminary model, the product will not accurately reflect the real state of nature of the system.

To address this problem, having an advocate pushing the program from inside the user organization is a great asset. This individual must be high enough in the user organization and respected enough with in the informal culture to appropriately influence the flow of communication between the project team and the user group. The base camp has been blessed with just such an individual in Kurt Kinnevan.

As the project continues through integration, additional surveys will be conducted to further support the hypothesis that virtual modeling tools, such as the VFOB tool, reduce the appearance of complexity making the system easier to design and manage from a user perspective. Other testing will occur on the integration of other major subsytems and the final user interface.

5   MODELING EMERGENCY RESPONSE ORGANIZATIONS

In efforts to address large-scale natural and manmade emergencies, small crews of law enforcement officers, paramedics, firefighters, and other emergency personal join forces to minimize the impact on people, equipment, and the environment. This multi-agency collaboration has been referred to by many different names; for the purposes of this work the term Emergency Response Organizations (EROs) will be used.

The repercussions of failures within EROs often result in loss of lives, therefore the stakes are high to improve the effectiveness and efficiency of responses. Therefore, these organizations are an area of interest for many management and organizational researchers. Due to the type of collaboration and the environment in which these organizations function, they tend to exhibit behavior different from standard organizations. In order to improve understanding of the current state of these organizations, it is important to look at what problems have already been addressed and the state of the current organizational architecture.

5.1   LITERATURE REVIEW OF EROS

One of the first modern emergency response architectures was an interagency task force named the Fire Fighting Resources of Southern California Organized for Potential Emergencies (FIRESCOPE), formed in the early 1970s (FIRESCOPE, n.d.). This taskforce was created in response to disastrous and rampant wildfires in Southern California. The task set forth for this group was to "create and implement applications in fire service management, technology, and coordination, with an emphasis on incident command and multi-agency coordination (FIRESCOPE, n.d.)." Four essential

requirements needed to be met for the solution to be successful were: flexibility, scalability, consistency, and cost effectiveness.

The result of this effort was the Incident Command System (ICS). ICS creates what is generically referred to as a unified command. "The Unified Command… is a system whereby no agency or function will divest their authority or responsibility on any incident. All agencies [assigned] to the command or staff roles will share equally in the development of overall objectives and management of the entire incident." (Stumpf, 2001) ICS is the fundamental basis establishing a standardized response hierarchy for multi-organizational responses.

ICS experienced success in limited field testing through the late 1970s, before formally being adopted by the Los Angeles Fire Department in 1978. After further success, gradual implementation by various emergency response organizations was experienced (FIRESCOPE, 2003). ICS was adopted and/or endorsed by the Federal Emergency Management Agency, the National Fire Protection Association, the Occupational Safety and Health Administration, the Environmental Protection Agency, as well as many state and local governments on an organization by organization basis (History of ICS, 1994). ICS was becoming an unspoken standard for response architecture.

In 1980, FIRESCOPE's ICS program was incorporated as the backbone of a nationwide program known as the National Interagency Incident Management System (NIIMS). NIIMS still had a primary focus on multiagency firefighting, but allowed the principles of ICS to be applied to a variety of scenarios from natural disasters like floods and hurricanes to manmade events like bombings or major aircraft accidents. NIIMS

marked the first national standardization for response architectures. NIIMS incorporated

five major subsystems as components of an effective response architecture: ICS, training,

qualifications and certifications, publication management, and supporting technology

(National Wildfire Coordinating Group, 2004).

NIIMS existed as a voluntary standard across multiple disciplines of emergency

responders, remaining founded on the principle and structure of ICS. Standards for

training and for the issuing and maintaining of qualifications had not existed at this level

prior to NIIMS. The cross-functional nature of NIIMS training served as a template for

future discipline specific education. NIIMS remained the standard response architecture

for the U.S. for over twenty years, with piece-by-piece improvements, but no widespread

change. NIIMS was a standard, but it was a voluntary standard and not applied by all

response organizations. The terrorist attacks of September 11, 2001, highlighted the need

for standardization of emergency response methods (Comfort & Kapucu, 2006). As these

events unfolded, the highly emotional and chaotic response to this large scale emergency

showcased the weaknesses of the state of emergency response at federal and state levels.

The national and local responses to an event of this magnitude garnered a great deal of

attention, both positive and negative.

George W. Bush signed Homeland Security Presidential Directive 5 (HSPD-5),

Management of Domestic Incidents, directing the development and administration of the

National Incident Management System (NIMS) in February of 2003 (Bush, 2003). On

March 1, 2004, the Department of Homeland Security (DHS) issued NIMS to provide a

nationwide template for responsible entities to "work together to prevent, protect against,

respond to, recover from, and mitigate the effects of incidents." (United States Department of Homeland Security, 2008c)

NIMS revised the original NIIMS framework to allow for more flexibility in the command, and to provide a federally approved approach to a variety of emergency response efforts. NIMS expanded on the NIIMS subsystems. The six highlighted subsystems of NIMS (National Wildfire Coordinating Group, 2004) include:

1. Command and Management - an expansion on ICS

2. Preparedness - focused on planning, training, exercises, and qualifications

3. Resource Management - a process to describe, inventory, track, and dispatch resources before, during, and after an incident

4. Communications and Information Management - a standardized framework for communications and information management

5. Supporting Technologies - Technology and technological systems including specialized technologies that facilitate ongoing operations and incident management activities in situations that call for unique technology-based capabilities.

6. Ongoing Management and Maintenance - provide strategic direction for continuous refinement of the system over the long term.

As implemented, NIMS is the first time communications has been called out as an essential element in and of itself. Prior to NIMS, communications was wrapped up within the architecture and not stressed as a key integration component.

NIMS was tested by multiple large-scale responses in its first few years of existence. Perhaps the largest and most publicized response was that involving the

Hurricane Seasons of 2004 and 2005. The response to assist the City of New Orleans, Louisiana, during and after Hurricane Katrina made national headlines. However, Katrina did not affect just the city of New Orleans.

William Carwile was appointed as the Federal Coordinating Officer responding to Hurricane Katrina for the state of Mississippi. Carwile gives us his perspective and experiences in a paper he published in *Homeland Security Affairs* in 2005. He begins by establishing his role in the response: "The FCO has no authority to direct the state response, but does provide technical assistance, and expertise, and is authorized by the Stafford Act to mission-assign federal agencies, with or without reimbursement, to support the requests of the governor and his/her representatives." (Carwile, 2005) This implied that Carwile served as the federal lead to the response process, with the authority to call in and coordinate the response of various federal agencies for assistance. With multiple hurricane responses under his belt, including the 2004 hurricane season in Florida, Carwile is knowledgeable in the field he speaks about for this article. Carwile provides some experiential insight to the depth and breadth of the Unified Command concept as written and executed by various doctrines. For example, according to ICS as developed and implemented by FIRESCOPE in the 1970s, a Unified Command exists only at the top levels of the response. Independent organizations still manage their own responses, retain the responsibility and control of their resources, but work in coordination with other similarly independent organizations to accomplish the same set of objectives. This can cause issues when two simultaneous response organizations go about accomplishing the same task, but with conflicting methodologies. Carwile states that "'Pure' ICS may work well for fires and smaller disasters, but some substantial

modifications are required for large scale events." (Carwile, 2005) "Pure" ICS addresses the "What" of a response by emphasizing the need for common goals and targets. Carwile targets a lack of communication about the "How" of a response as being an essential weakness.

Carwile also noted an added level of complexity to be considered when ICS involves multiple jurisdictions. "In some states, the state constitution gives considerable authority to local jurisdictions; this can make things a bit murky when attempting to establish hierarchical arrangements in a unified command." (Carwile, 2005) Not only do the rules and regulations applicable to different organizations vary by location, but the terminology, roles, responsibilities, and authorities assigned to hierarchical roles within one individual organization can be drastically different from a second responding organization. NIMS had addressed this gap at the highest level by standardizing the titles and hierarchy of the unified command structure, but nothing addressed the conflicts at the working level.

Carwile's experiences are representative of other lessons learned from the Katrina and Rita responses. After such widespread consensus on the existence of substantial holes in the existing standard architecture, a revision was published in 2008 by the Department of Homeland Security. After the NIMS architecture was put through the ringer by gulf-coast hurricanes in 2004 and 2005, a series of lessons learned were collected and incorporated into a newly revised standard response architecture. The National Response Framework (a.k.a. *Framework*) published in 2008 (United States Department of Homeland Security, 2008e) has been designed for easier facilitation of large-scale multi-organizational responses.

> *"The National Incident Management System (NIMS) provides a systematic, proactive approach to guide departments and agencies at all levels of government, nongovernmental organizations, and the private sector to work seamlessly to prevent, protect against, respond to, recover from, and mitigate the effects of incidents, regardless of cause, size, location, or complexity, in order to reduce the loss of life and property and harm to the environment. NIMS works hand in hand with the National Response Framework (NRF). NIMS provides the template for the management of incidents, while the NRF provides the structure and mechanisms for national-level policy for incident management." (United States Department of Homeland Security, 2008d)*

The *Framework* is the overarching operational guide to responses to hazards of any kind in the United States of America. The *Framework* builds upon the NIMS template, using key lessons learned from wide-spread national catastrophes including Hurricanes Katrina and Rita. When revising the standard for emergency response architecture, the authors took into consideration feedback from after action reports (AARs) filed after actual emergencies of various sizes and severities, and from preparedness drills and exercises used as training for response personnel. This resulted in a new name that more accurately portrayed the intent of the architecture, and broader scope with a wider audience (United States Department of Homeland Security, 2008e).

Also key to this revision was the expanded focus on partnerships and multi-organizational responses. As noted by Carwile (2005), organizations within different jurisdictions implement differing levels of responsibility and authority to their individual hierarchical structures. Organizations use different terminology and are trained to respond in different ways to the same stimuli. The *Framework* reaffirms that the primary responsibility for the safety and security of citizens within any jurisdiction belongs to the local communities, tribes, and states. It attempts to address the need for multi-

organization cooperation by including clearer terminology with refined roles and responsibilities for federal response positions. Another key element of the *Framework* was the addition of "Guides for Response Partners." These new guides were instituted to help local and state responders, as well as non-government organizations, integrate the core principles and terminology, roles and responsibilities, and procedures for requests for assistance into the planning and preparedness documents for their individual response organizations. The goal of this effort is to provide a unified, coordinated, and effective national response. However, it should be noted that the *Framework* is still mandated only at the federal level. It is suggested for these smaller organizations, but not required.

A final alteration in the *Framework* was in major annex changes. This included 12 new or significantly revised sub-documents. One major addition is the development of a *Critical Infrastructure Key Resources (CIKR) Support Annex*. This provides responses to emergencies pertaining to loss of communications and infrastructure.

5.2   COMMUNICATION WEAKNESSES IN EROS

After over 40 years of development, the EROs are still experiencing dramatic malfunctions and constant revisions to address weaknesses. As with any system, the greater the complexity, the more likely there will be complications. There is no question that the standard emergency response architecture is a complex system, meeting all eight of Ciller's qualities for a Complex Adaptive System (1998). Further review was performed to determine areas of significant problems.

After real events and any of the training events, responders are surveyed, as an organization and as individuals, for any identified flaws and weaknesses of the response procedures and/or individual responses that vary from procedure. These AARs are used

to improve the emergency operating procedures of that organization. Due to the sensitivity of subject matter and risks of exposing organizational weaknesses, most of the AARs remain within each organization. There are opportunities for these AARs to be shared across organizations; however, they are required to be sanitized to a point that they lose much of the relevant information. As a result the lessons learned are either caught in an internal silo or diluted to a point of little utility.

In an attempt to encourage information sharing between organizations, the US Department of Homeland Security has established a lessons learned data base for sharing AARs. The information available is highly sanitized, but still allows for some key problems to be noted. While there are many areas where recurrent failures could occur, one area was chosen that could have substantial impact to the emergency response community: communications.

5.2.1   Communications in Emergencies. When the links between the components of any system breakdown, the system efficiency decreases and the system could fail altogether. This is the case with communications during an emergency response. The leading cause of many of these breakdowns in emergency response is a lack of unambiguous consistent communication, both between and within organizations.

The ability to communicate emergent information is essential to a unified command structure such as that proposed by the *Framework*. The best case scenario is to rely upon face-to-face communication when at all possible. A unified command post, appropriately equipped, securely located, and with the high-ranking officers from each of the responding organizations represented provides the ultimate situation for communication and joint information sharing. Though this is a preferable set-up, it is not

common. Many factors contribute to a more physically distributed command, including availability of space and resources, as well as a tendency of organizations to prefer to work in isolation during instability.

5.2.1.1 How communication is addressed by the *Framework*. The *Framework* includes two appendices that address Communications Infrastructure. The ESF#2 – Communications Annex provides the authorities, roles, responsibilities, and actions to re-establish communications infrastructure after a disaster strikes (United States Department of Homeland Security, 2008a). Coordination responsibilities of this piece are assigned to the Department of Homeland Security's National Communications System, while calling out the National Cyber Security Division for close coordination in cyber incidents.

Critical Infrastructure Key Resources (CIKR) Support Annex (United States Department of Homeland Security, 2008), focuses on incidents that result in the loss of Federally Identified Critical Infrastructure and Key Resources. Specifically, the focus is on (a) situational awareness, (b) impact assessments and analysis (c) information sharing, and (d) requests for assistance or information from private-sector CIKR owners and operators. The CIKR Support Annex designates specific federal departments and agencies as responsible for the oversight of CIKR areas.

As with the previous ESF, the CIKR Support Annex does not apply to communications used *during* a response. These documents target responses to emergencies pertaining to loss of communications and infrastructure, like the massive widespread power outage that affected the Northeast U.S. and Ontario, Canada in August of 2003. What is needed is a method to address communications failure during an event.

5.2.1.2 How communications fail. In most cases, the responding organizations will use radio communication as default during a response. This technology does not rely on the physical infrastructure that is most likely to fail (ie. power, telephone, and Internet) in times of crisis-level disasters. It has been established in past disasters that, in most cases, the existing radio infrastructure is not sufficient for large scale, multi-organizational responses. Reception can be blocked by traffic or by physical barriers. Giving a radio to an ambulance driver is wonderful in theory. However, if the radio signal cannot reach the hospital for the last 10 minutes of the commute, there is still a critical communication breakdown preventing essential information from reaching responders at the point where they need it the most. Due to resource availability and/or security issues, command centers in the past have been located in areas where there was no radio reception. Responders had to step outside of the facility to send and receive communications (Lessons Learned Information Sharing, 2006).

During multi-organizational responses, frequencies for internal communications and external communications can become overlapped by separate organizations. This results in channels becoming crowded, high-priority messages not being understood, and sometimes low-priority messages being assigned higher importance due to a misunderstood phrase or sheer repetition.

For example, if a sizeable earthquake hits the New Madrid fault in southern Missouri, there would be multiple response organizations from different jurisdictions involved in the response. It would be advantageous for there to be a cross-walk executed ahead of time to map the technical communications resources available to Missouri responders with the Kentucky, Tennessee, Arkansas, and Illinois responders. Each

responding organization could be assigned a set of frequencies for their internal uses. A set of frequencies for external communications (to the incident command post, to dispatchers, and to the various emergency operations centers) could be established ahead of time and programmed in to the radios for increased speed and usability.

Northern Illinois University (NIU) gives us an example where preplanning for communication between organizations has succeeded. After the Columbine High School incident in 1999, NIU worked with state and local agencies to establish and maintain a standard for interoperable communications. This teamwork resulted in the NIU police officers, on-scene at a campus shooting, being able to transmit critical information to emergency medical services personnel (Lessons Learned Information Sharing, 2011).

Another primary issue with communication between emergency response personnel is the varied vernacular employed by different response agencies. Some organizations use identical terms to communicate contradictory messages. As an example, the term "man-down" has multiple meanings to emergency responders (Lessons Learned Information Sharing). To a group of law enforcement officers, man-down means a member of their organization has been shot or otherwise removed from action. A mine rescue team can use "man down" to refer to any situation when a worker is below the surface. To paramedics, "man down" indicates a response is needed to an unknown situation. Some organizations use internally standardized 10 codes, while other organizations have never been trained on those codes and use a distinctive set of key words instead. It has been suggested that a singular set of response jargon be developed and used across disciplines, however this has not been addressed at the national level.

Interagency planning is something stressed within the *Framework*. This would assist in not only standardizing the technology for communication, but also some of the terminology and roles and responsibilities that become cloudy during a multi-organizational response. However, it will only work if all sides are in cooperation. Adaptation of the *Framework* is suggested for all responders, but only mandatory at the federal level. A secondary problem with this solution is that there are no boundaries between what is considered "interagency." This raises a lot of questions about response coordination. If your organization is capable and willing to respond to incidents in two different jurisdictions, should your response efforts change to meet the standard technology and terminology of the "local" responders? If so, does this restrict to whom you will respond? Will you respond to the municipality to your north, who follows very similar standards to your own, but not to the town to your south because they use a different set of standards? Where do the standards start taking precedence over helping save lives?

5.2.2 Humans as Responders. When considering problems with failed communications during emergency response, more than just setting standards needs to be considered. At the heart of communications failures is the fact that responders are human. The most common solution to any human-centered problem is training. Equally important and less examined are the areas of human system integration and human centered design.

Humans require training and exposure to excel in high-stress environments. Many responders will train constantly on their technical response pieces, even as far as emergency response exercises. While this refines many of the localized actions necessary

to address an emergency, most of this training does not adequately prepare the responders to communicate in emotional, adrenaline-pumped, high-stress scenarios.

Emergency medical technicians, for example, are trained in depth on how to provide cardio-pulmonary respiration, how to field dress a wound, and how to properly support a back injury while transporting the victim to a medical center. These are response actions they use every day; these responses are at the level of unconscious competence. They are trained on how to operate their communications equipment within the realms of their "normal" responses, but they are not trained on how those communications might need to change in a large-scale emergency. This contributes to the overload on the radio.

Enhanced training for all responders is needed to instruct them on how and when to alter standard procedures, how to change radio frequencies, and how to prioritize radio transmissions. With a plan for conducting this training available, the solution lies in choosing the right people for the job, and giving those individuals as much exposure and experience as is financially feasible. Various training methods require different levels of resources, and a different type of learning experience. Common training methods include:

- in-house exercises;

- multi-organization exercises in the field;

- tabletop drills, where a scenario is addressed by talking through the response step by step;

- classroom training;

- hands on training; and

- actual responses.

Each of these methods increases an individual responder's familiarity and expertise with response actions. Increased exposure reduces the level of emotional response and allows for a higher level of accuracy and comfort with response actions.

5.3   EROS AS SOCIOTECHNICAL COMPLEX ADAPTIVE SYSTEMS

EROs are traditionally not among the areas addressed by systems engineering. EROs are composed of people reliant on technology to perform their jobs, which makes EROs sociotechnical systems. A large-scale emergency response is a joint effort between multiple organizations, which adds to the complexity. An ERO is a CAS, and as such could be improved by applying standard systems engineering techniques. EROs meet all eight points of qualification for a CAS.

- SIZE – While ever response is different, large scale multi-agency responses are far beyond the scope of a traditional system design.

- INTERACTIONS – Multi-agency responses are integrated on many levels. These points of integration can range from radio frequencies, joint chains of command, or shared physical resources.

- CASCADING – Actions of one sub-organization/subsystem of an ERO have direct effects on the actions of other responders.

- REBOUND: When a change is made to one system, effects are triggered through surrounding systems that can cause the single change to reflect back on to the same subsystem, thus triggering another round of downstream effects.

- OPEN: EROs are open systems, constantly interacting with their environment.

- ENDOTHERMIC: EROs are resource intensive. A consistent flow of water, fuel, manpower, and money is essential.

- EVOLVING: An individual emergency response occurs in stages, one flowing into the next. The responding organization is also evolving, with new technologies, restrictions, and requirements constantly being added to the system.

- ISOLATION: ERO sub-organizations have a tendency to work in isolation, and interact only with their immediate surroundings, resulting in a stovepipe of information.

These and other similarities between EROs and military base camps allow us to predict that some of the same methods and tools that are being used successfully on modeling the base camp might be used to manage some of the problems caused by the complex nature of EROs.

5.4   EXAMPLE OF SYSTEM/SUBSYSTEM DESIGN FOR EROS

Based on limited experiential data of a multi-agency emergency response, an example was composed of what a flow diagram might possibly look like for a small wild-fire. Figure 5.1 shows the two segments of a response: the field responders (above the dotted line) and the Emergency Operations Center (EOC) and reserve resources (below the line). The information between the EOC and the Incident Commander (IC) is well outlined byfederal guidelines, as is the information between the field responding units and the IC. However, the information sharing between the individual response units, as well as the information between the EOC and the reserve units, are less well understood, and therefore designated as unknowns in this diagram.
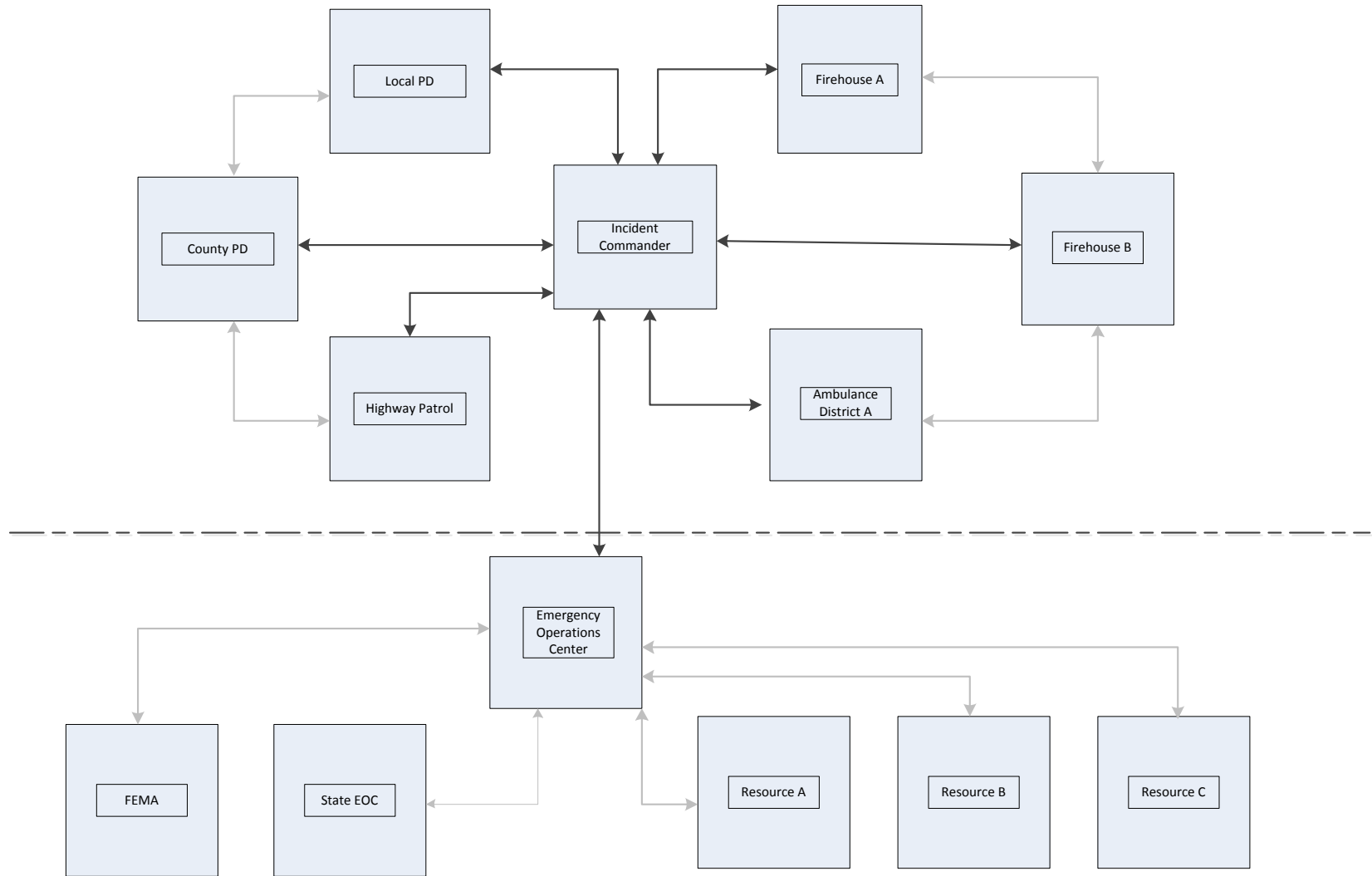
Figure 5.1 – Capturing Emergency Response Flows

The goal of this type of application is to move as many of the unknowns into known territory as possible. The information can be improved by bringing in subject matter experts, or by further development of guidelines and training to ensure that the information being shared between responders is a) clear b) concise and c) consistent.

5.5 DETERMINING THE LEVEL OF COMPLEXITY WITHIN EROS

The nature of a multi-agency emergency response will require a flexible approach to complexity. The number and type of responders are going to change based on the type of emergency to which they are responding. The organizations responding to a large wildfire are going to be potentially different than the organizations responding to a man-made disaster. Each response is unique, so the model will be required to be highly flexible and somewhat generic in nature. Treating Fire Station A like Fire Station B will induce some disparity between the model and reality, but it will improve the ability for initial modeling to be completed. In this example, one subject matter expert could be consulted on the communications needs of a fire station in their response efforts, providing input into the model. A working model could then provide training back to both Fire Stations A and B to make their response behaviors more closely correlated to the model.

As seen in Figure 5.2, the intent is not to lessen the number of interactions, but to improve the knowledge about and therefore the quality of those interactions. Understanding the current state of interactions between organizations will improve the ability to address the issues with technology, training, and the terminology used by the organizations. The two plotted points are for demonstration purposes only, not from data analysis.

Figure 5.2 – Two-factor Graph of ERO Complexity
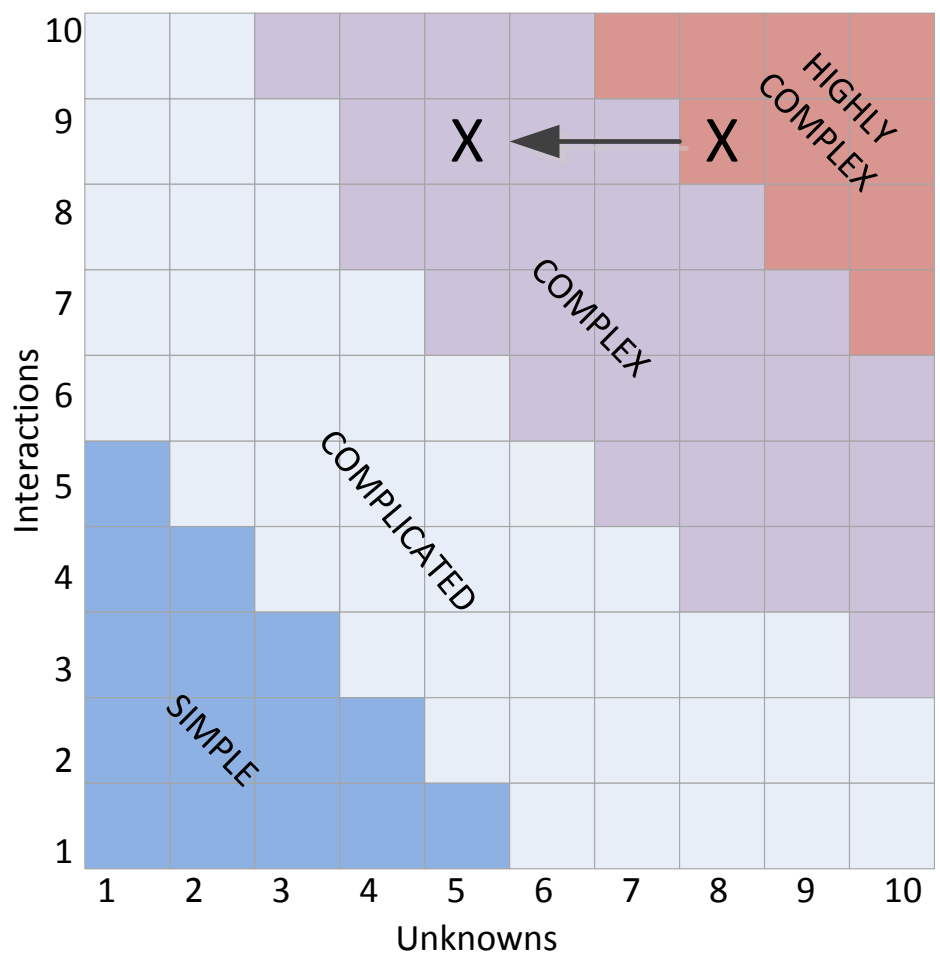
5.6   FUTURE WORK MODELING EROS

There were three major weaknesses identified in the earlier discussion on emergency communications: training, technology, and terminology. The overarching architecture and the three identified areas of weakness could potentially be addressed by application of systems theory techniques and/or complex adaptive systems management methodologies.

The ICS, which is the backbone of the ERO's architecture, should be expressed using SysML (Systems Modeling Language) to describe the ERO structure, incorporating specialized subclass generalizations and stereotypes in MBSE. This would help to introduce some much needed uniformity and could make it possible to have some level of common ground at a high level of abstraction. This architecting could then be shared with and evaluated by users to help achieve consistency in response management.

Research is active in pursuit of improvements to the specific technologies used by responders. However, the work is mostly focused on improving the modularity and mobility of replacements when the existing technology fails. Other gaps in the technological arena can be addressed through using MBSE to map the current capabilities of signal transmission and reception, of any and all technologies, whether radio, phone, or satellite. Modeling the communications capabilities of high risk areas as a preparatory measure before an emergency could allow for faster more efficient response actions after an outage. This could ensure that incident command posts are located in an area best suited for sending and receiving data. Additional integrated solvers can be included to map out radio and cell towers to reroute reception when one area of a grid is unavailable or overloaded, allowing responders in low signal areas to still be heard.

Training could also be improved by using virtual models. The ability to create realistic virtual training scenarios focused on the required communication skills of all responders, regardless of occupation, could ensure consistent distribution of essential knowledge when new standards are developed and dispersed. This would also allow for standardization of record keeping and training-based certifications. This type of training system can be made simple and uniform, as to apply to any size of responding

organization, from the volunteer firefighters in rural communities to the presidentially appointed federal coordinating officers on large scale emergencies.

Terminology is an area that is often overlooked in after-action scenarios, and therefore lacking in attention to the weaknesses. Recommendations for future work in this area include a look at using model based systems engineering to approach the breakdown in communications due to terminology. Work is currently being conducted using MBSE to address ontological differences in various technological fields. This approach shows potential as a method of bringing resolution to the lack of a single standard language for use by emergency responders.

6 CONCLUSIONS

An evaluation of literature relating to sociotechnical systems found a gap in the research regarding techniques used to manage the complex nature of these systems. Recognizing a sociotechnical system as a complex adaptive system suggested application of a model based systems engineering approach that is commonly applied to technical complex adaptive systems. Work toward this new application for sociotechnical systems included analysis of an ongoing project, the Virtual Forward Operating Base project funded by the United States Department of Defense. A two-factor complexity evaluation tool was developed for early analysis of the level of complexity in a given system. This scale uses perception of the number of unknowns and the degree of integration in a given system to help determine whether or not the application of a virtual model is appropriate. The same tool was also used to evaluate the perceived level of complexity within the virtual model by a user group. The results of the data analysis supported the hypothesis that a virtual model decreases the perception of complexity by the end user. The difference between the results provided by the systems experts designing the model and those taken from a sample of end-users was statistically significant. While the expert rated the system in the complex region on the two-factor scale, the sample of end-users rated a base camp in the complicated area, indicating a lower level of complexity.

Future work on this effort is required to validate assumptions tying the two-factors used in this test to the eight qualities of a complex adaptive system identified by Cilliers (1998). This will likely involve development of a multi-dimensional approach to address each of the eight qualities, and then testing against the two-factor model for validation of the simplified tool.

The two-factor survey should also be retested against a second user sample. A duelsurvey approach is proposed wherein the first survey will be given before the user-group is introduced to the tool, as a baseline for evaluation. The second survey will be taken later in the project, after the modeling tool is demonstrated and put to use for hands-on modeling of base camps. This second data set is proposed for application to the 2012-2013 Captain's Career Course at Fort Leonard Wood.

A third area of future work is to test the big picture hypothesis (virtual modeling reduces the perception of complexity and improves understanding of a system) against a different socio-technical system. One system identified for this second test is an emergency response organization (ERO). An ERO can be defined as a sociotechnical complex adaptive system, and meets preliminary estimates of applicability through using the two-factor complexity evaluation tool.

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