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Nuclear Weapons Mission Area Workshop: Strategy Enablers from a Systems Perspective

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Abstract

A one-day workshop was held on April 14, 2016 to explore Nuclear Weapons Mission Area (NWMA) strategy enablers from a systems perspective. This report documents the workshop and is intended to identify initiatives, based on the workshop exchanges, and catalyze these initiatives to enable implementation of the NWMA strategy using systems thinking and methodology. Topics explored include Model-based Engineering, Enabling Viable Capabilities, and Enterprise Decision Awareness. The morning of the workshop featured Dr. Dinesh Verma (Stevens Institute/SERC) as keynote and during the afternoon attendees participated in three facilitated sessions on the topics. There were over 70 participants from about 40 departments across Sandia National Laboratories.

Acknowledgments

This was made possible by support from the NWMA Center 200. We appreciate the attendance of all the participants. Special thanks to Dr. Dinesh Verma for working with us over a period of time to make this workshop successful. Thanks also to Casey Davis and Natasha Wilcox for taking care of all the logistics and coordination.

Contents

Figures

Tables

NOMENCLATURE

APL	Advance Physics Laboratory
ConOps	Concept of Operations
CoPs	Communities of Practice
COTS	commercial-off-the-shelf
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
ESA	European Space Agency
GIT	Georgia Institute of Technology
HR	human resources
INCOSE	International Council on Systems Engineering
JHU	The Johns Hopkins University
JPL	Jet Propulsion Laboratory
LMC	Lockheed Martin Corporation
M&S	modeling and simulation
MBE	model-based engineering
MBSE	model-based systems engineering
MOE	measure of effectiveness
NSE	Nuclear Security Enterprise
NW	nuclear weapon(s)
NWMA	Nuclear Weapons Mission Area
RPP	Realize Product Procedure
Sandia	Sandia National Laboratories
SERC	Systems Engineering Research Center
SME	subject matter expert

EXECUTIVE SUMMARY

A one-day workshop was held on April 14, 2016 to explore Nuclear Weapons Mission Area (NWMA) strategy enablers from a systems perspective. This report documents the workshop and is intended to identify initiatives, based on the workshop exchanges, and catalyze these initiatives to enable implementation of the NWMA strategy using systems thinking and methodology over time.

Topics explored include Model-based Engineering, Enabling Viable Capabilities, and Enterprise Decision Awareness. The morning of the workshop featured Dr. Dinesh Verma as keynote and during the afternoon attendees participated in three facilitated sessions on the topics. The keynote provided an industry landscape perspective of the state of systems and systems engineering, and addressed the topics of the workshop. Based on the keynote and the exchanges during the facilitated sessions the following initiatives are recommended.

1. Define the concept of operations for nuclear weapons and for Sandia capabilities to normalize the thinking, description, and communications.
2. Define a vision and roadmap for harmonizing and maturing model-centric engineering at Sandia to align efforts and create synergy between people that are endeavoring to advance our development methodology.
3. Develop a reference architecture for Sandia systems, capabilities, and enterprise that would enable a model-centric approach and enhance Sandia's future agility.
4. Map the current "information ecosystem" that supports decision making at the laboratory including interfaces, best practices, databases, and access control.

These initiatives will enable successful implementation of the NWMA strategy. The successful execution of these initiatives will require engagement from stakeholders and partners from across the Laboratories.

INTRODUCTION

Background and Motivation

The intent of the Nuclear Weapons Mission Area (NWMA) strategy is to promote focused leadership attention on several strategic objectives to ensure the success of the nuclear weapons (NW) mission and Sandia over the coming decades. The NWMA strategy does not cover the entire scope of the NW mission at Sandia, but rather focuses attention on some of the most significant organizational and technical challenges before the NWMA and the Laboratories as a whole. Many of these challenges derive from a persistent need for greater agility and affordability which, combined with the uncertainty within the geostrategic and national policy environment in which the NWMA operates, will require active and informed engagement from program management units, mission support, research and line organizations from across the Laboratories to solve.

On April 14, 2016 the NWMA Planning and Integration group held a workshop titled "NWMA workshop: strategy enablers from a systems perspective." The workshop examined systems engineering concepts in three key topic areas and elicited ideas and perspectives from subject matter experts (SMEs), technical staff, and management representing a broad cross section of the laboratory. These ideas and perspectives will likely benefit NW leadership and the workshop participants. The organizers anticipate that participants will engage in ongoing dialogue sessions at the center level regarding the implementation of the NWMA strategy.

Innovation is the primary enabler for sustained deterrence. The ultimate goal of the NWMA strategy and this workshop in particular, is to create an aligning force that will guide staff and management discretion. This alignment of discretion is expected to result in supporting innovative implementation of the NWMA strategy.

This report concludes with opportunities that can frame continued dialogue among the workshop participants and the broader NWMA-aligned community within the Laboratories. The goal of this report is to identify initiatives, based on the workshop exchanges, and catalyze these initiatives to enable implementation of the NWMA strategy using systems thinking and methodology over time.

Workshop Topics and Agenda

The systems engineering topics selected crosscut the strategy objectives and are enablers to the implementation of the strategy. They include the following:

Model-based engineering – Model-based engineering (MBE), as intended in the workshop, is the practice of centering the design, definition, analysis, and realization of a system or enterprise on models. Ideally, the models are related and maintained in a way to maximize the effective realization of solutions. Note that this definition includes the use of static or structural models as well as modeling and simulation (M&S) that allows dynamic analysis to evaluate performance objectives of systems or enterprises. This capability is perhaps most applicable to the Sustained Deterrence NWMA strategy objective but there is also relevance and application to the other NWMA strategy objectives.

A list of working definitions for terms used during the workshop and related to model-based approaches is included below.

> ***MBE*** *– Integrated use of 2D and 3D models to define the system technical architecture and design across the full life cycle, across all disciplines, across all program members [models are the authoritative definition of the system]*
>
> ***Model-based systems engineering*** *– A specialized type of descriptive modeling used to create and analyze systems engineering process information across the life cycle [the model is the authoritative definition for all systems engineering information]*
>
> ***Model-based enterprise*** *– The tools, models, and infrastructure used to share design information across the enterprise that develop and support the system*
>
> ***M&S*** *– Dynamic analyses to evaluate performance objectives of systems or enterprises*

Enabling viable capabilities – capabilities (included as Capabilities & Operations) are included as one of three elements in the NWMA elements shown in Figure 1. The concept of a capability is referenced multiple times in the NWMA strategy particularly in the *Foundation Objective* relating to "capability-based science and engineering foundation."[1] The working definition of "capability" used during the workshop was:

> ***Capability*** *– The potential to achieve a mission or business outcome through application of the knowledge, skills, or abilities of our people supported by the infrastructure, facilities, or tools of the laboratory.*

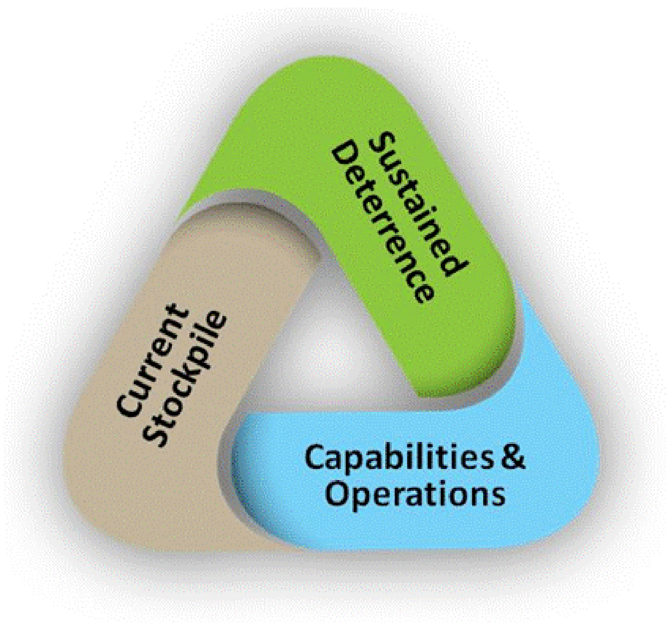

Figure 1 - Nuclear Weapons Mission Area Elements

Enterprise decision awareness –Sandia comprises two primary locations (California and New Mexico) and seven mission areas, realized collectively across a nested organizational structure guided by multiple strategies with often overlapping goals and objectives. The NWMA is the largest and core mission of the Laboratories and is symbiotically reliant on the entire

[1] Nuclear weapons meeting webstream New Mexico

Laboratories to "ensure a safe, secure, and effective U.S. nuclear deterrent in collaboration with sponsors, customers, partners, stakeholders, and other Sandia mission areas."[2] Decisions are the pulse of the work done at the Laboratories and shared decision awareness at the project team level through executive leadership has a first order impact on how effectively the Laboratories deliver value to the nation.

Table 1 contains the list of questions posed for each topic; these questions were also provided to the keynote speaker in preparation for the workshop.

Table 1- Systems Enablers Topics and Questions Posed

Model-Based Engineering	• What is the history and perspective of model-based engineering (MBE)? • How can MBE support product realization across an enterprise? • What is the difference and commitment of document-centric versus model-centric MBE? • How can traditionally non-technical viewpoints and information be incorporated in MBE?
Enabling Viable Capabilities	• What models exist by which to view capabilities? • What comprises the capability "ecosystem"? • How can capabilities be viewed as a system within systems?
Enterprise Decision Awareness	• How is situational awareness maintained at the enterprise level? • How do complex adaptive systems and systems-of-systems views relate to enterprises? • How does technical communication enable enterprise efficacy and responsiveness? • What governance models exist for technical enterprises?

[2] Nuclear Weapons Mission Area Strategy, version 1.0, 2016.

The workshop was a daylong event at an off-site location in Albuquerque, New Mexico. Table 2 presents the agenda for the workshop.

Table 2 - Strategy Enablers from a Systems Perspective Workshop Agenda

Time	Topic		Presenter
0800	Gathering, Check-in and Refreshments		Casey Davis and Natasha Wilcox
0830	Welcome and Orientation NWMA Strategy Introduction Motivation for Workshop Introduction of people including Dr. Verma		Shawn Burns
0900	Kickoff of Workshop Topics		Dr. Dinesh Verma
0945	Break		
1000	Kickoff of Workshop Topics with Q&A		Dr. Dinesh Verma
1100	Introduction of afternoon exercise (observers can depart at this point)		Regina Griego
1130	Lunch		
1215	Topical Breakouts – assignment to groups, movement and orientation to locations		
	Model-based Engineering	Enabling Viable Capabilities	Enterprise Decision Awareness
1230	Session 1 Groups, assignments are on “dance cards” for participants		
1320	Switch groups		
1330	Session 2 Groups, assignments are on “dance cards” for participants		
1420	Switch groups		
1430	Session 3 Groups, assignments are on “dance cards” for participants		
1520	Reconvene as large group		
1530	Readout of Topics (10 minutes per topic)		Facilitators for each topic
1600	Observations and Path Forward		Dinesh Verma, Shawn Burns, Regina Griego
1630	Adjourn		

WORKSHOP REPORT

Keynote Summary

Dr. Dinesh Verma[3] provided the keynote in two morning sessions with a break between sessions. The first session provided an industry landscape perspective of the state of systems and systems engineering. The second session addressed the topics of the conference, which support each other and are underpinned by many of the same practices. Below is a synthesized summary of both keynote sessions.

The value of systems engineering – systems engineering is fundamentally a way of looking at the world and approaching problems. Systems engineering requires a technical background and in most industries, it is a vector toward technical leadership. Systems engineers first seek to clarify a problem posed and the context for the problem. An example is that most engineers tend to think in noun form (motor, chassis, etc.) rather than in verbs (propel, cool, etc.), whereas systems engineers think in verbs. Systems engineers typically break things up functionally and functions are expressed using verbs. In general, systems engineering does not have an axiomatic basis as many other engineering disciplines do, for example, Maxwell's equations. Systems engineering relies primarily on principles and heuristics, backed up with some mathematical concepts from complexity science, graph theory, and other mathematical disciplines. Some of these principles and heuristics can be domain-centric. Examples of principles in the systems engineering toolkit include the concept of a boundary of a system, modularity that is based on cohesion and coupling of modules, system lifecycles, designing toward achieving a set of emergent properties at the system level that align with the purpose of the system, etc. Systems engineering is a relatively new discipline; it started in the 1940s and 1950s and the community developed a systems engineering graduate reference curriculum about 10 years ago. The essence of systems engineering can be described in layman's terms as an iterative cycle of deciding what to build and why, ensuring systems work and are robust, bringing solutions to life, and managing evolution/deciding what is next. The essence of systems engineering remains the same, but the evolution of systems engineering from mechanical and electrical elements, to the introduction of electronic elements with isolated software, to networked systems, is taxing the traditional systems engineering toolkit.

Trends in systems engineering – traditional systems engineering, which focuses on product development, has evolved a toolkit and set of practices that have allowed successful product realization for increasingly complex systems. The complexity of current systems does not permit a small number of engineers to understand the entire rationale and design of a system. These systems are challenging the current systems engineering toolkit. Some of the emerging trends in systems engineering driving complexity or used to manage complexity include:

[3] Dr. Dinesh Verma, Professor and Dean of the School of Systems and Enterprises at the Stevens Institute of Technology. Concurrently, Dr. Verma serves as the Executive Director of the Systems Engineering Research Center (SERC) established by the Department of Defense. Dr. Verma's professional and research activities emphasize systems engineering and design with a focus on conceptual design evaluation, preliminary design and system architecture, design decision-making, lifecycle costing, and supportability engineering. Dr. Verma has authored over 100 technical papers, book reviews, technical monographs, and he has co-authored two textbooks.

Modular systems and open-architectures – designing systems and families of systems such that they incorporate reusable parts, common platforms, and commercial off-the-shelf (COTS) components is necessary to achieve schedule, cost, and maintenance goals.

Systems of systems – emphasis on capabilities that require implementation of "system of systems" that are a network of heterogeneous systems. Systems are designed to readily plug into a communications network and are interoperable. At the system-of-systems level functionality is not systematically decomposed and assigned to component systems, for example, a directed tree view of systems, but rather each system has a set of capabilities that are networked together to achieve a set of missions. The interoperability at the network level gives a competitive advantage; an example is current telecommunications using cellular technology and smart phones.

Increasing need to extend the life of systems and assets – there are significant challenges with sustainment and little opportunity to start fresh with a blank sheet of paper, most development is constrained in government and industry by dependence on deployed systems.

Multiple partner and contractor teams and distributed development teams – this introduces the problem of distributing or partnering in a way that maintains the integrity of the architecture of a system. This can introduce significant complexity in the development of systems based on negotiated work-share boundaries.

Resource conscious environments – the time and cost of systems development for most significant systems requires management and prioritization based on resource constraints and drives decisions throughout government and industry.

Software intensive systems – functionality delivered through software is prevalent for most systems today. An example of this is the 4th generation fighter, which allocated 40% of functionality to software compared with the 5th generation fighter, which allocated 90%. All engineers require significant understanding of software. Organizations that have a rich history in mechanical design are having a tough time transitioning to successfully realizing systems that are software intensive.

Socio-technical systems – The complexity of traditional systems developed today tax our current systems engineering toolkit, but that toolkit becomes overshadowed when dealing with socio-technical systems and complex adaptive systems. An analogy would be the difference between Newtonian physics and Einstein's theory of relativity, Newtonian physics still applies at some level, but the application becomes revised and somewhat limited. Socio-technical systems and complex adaptive systems require other tools for analysis. In some cases, a reframing of traditional systems engineering principles is required. An example of the revisions is the introduction of the notion of paradoxes by John Boardman at Stevens Institute. He revises traditional systems engineering principles, such as systems have a defined boundary, systems require a deterministic command and control, all functionality emerges strictly by design, all elements of a system belong to a single component or subsystem, and every system should be designed based on what the customer wants. For socio-technical systems and complex adaptive systems John Boardman introduces paradoxes as an extension of what traditional systems engineering often teaches including:

- boundary paradox – a boundary is required…yet it must be permeable,

- control paradox – command and control hierarchy is required…yet information exists at the edges that must be given attention or may override command and control from the top,
- intelligence paradox – prescience is required…yet emergence must be allowed,
- crowd paradox – heterogeneity enhances the purpose of the whole…yet the diversity among parts cannot jeopardize belongingness, and
- customer paradox – listen to the customers…yet take advantage of disruptive technologies.

Complexity is not based simply on numbers, for example, number of interfaces or requirements, there are dimensions of systems that affect complexity, for example, humans in the loop or system of systems with autonomous actors. Complexity is a function of the degree of difficulty to accurately predict behavior over time. In fact, there are systems that defy predictable behavior. Complicated systems allow for decomposition, whereas decomposition does not work for complex adaptive systems. An example of a complex adaptive system cited in the keynote is the country of Sweden when it changed from right-hand to left-hand drive. They recognized the most difficult part of this change was the human and were successful because they messaged the change simply, consistently, using multiple means, and over a period prior to the change. Other examples of complex adaptive systems where humans and autonomous entities were pervasive actors include the introduction of a roundabout as shared space in Utrecht, Netherlands, and the economic collapse of 2008.

With all types of systems be it a traditional system, system of systems, complex adaptive system, or socio-technical system, new or revised systems engineering principles are being developed. Figure 2, discussed during the keynote, provides a simple pattern that can be applied to problems at all levels of complexity. The options for a solution to a problem is to develop an *optimized* system, a system that can *adapt*, a system (or solution) that uses a *hedge* strategy, or in some cases a system solution that *accepts* a certain amount of suboptimal behavior because there is no other feasible option. Traditional systems engineering is based on the ability to *optimize* the system because the assumption is that most product development efforts are based on tractable problems, that is the complexity still allows for inputs to be mapped to predictable outputs. With the emergence of system of systems and complex systems, there are solutions to problems that are not tractable, for example, autonomous vehicles. In this case, the system may be designed to *adapt* because the time constant of the environment (other cars, humans, etc.) is longer than the response time of an autonomous vehicle. If time constants for the system solution are exceeded, then redundancy may be required, which is a *hedging* strategy. An example is the internet or cellular systems that re-route traffic and are designed to meet the demand with redundancy. Often system solutions can only be designed to *accept* a certain amount of loss or downtime and that is the last alternative when faced with complex problems.

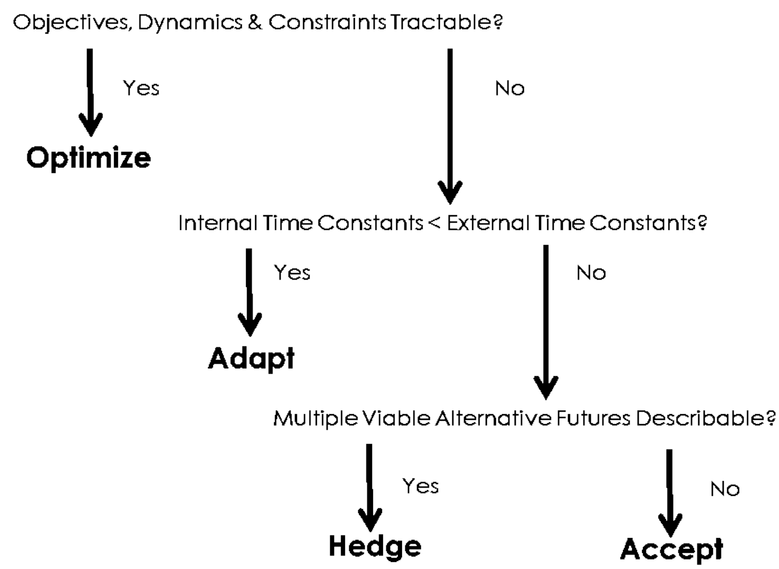

Figure 2 - Pattern Related to Tractability of a Problem and Time Constant To Adapt

Clarity of purpose/the essence of intent – Many studies including one done at the request of the Program Manager for Next-Generation Aviation, showed that most successful systems start with clarity of intent or purpose. A strategy that can be applied to clarify purpose is to start with the end in mind, for example, what is the intended use of a system by customers or stakeholders. Indeed, from a program manager's perspective, the purpose of systems engineering is to reduce risk by focusing on validation (customer acceptance) and verification (design quality). Another strategy to clarify purpose is to rapidly develop prototypes and enable early feedback from stakeholders.

Once the intended purpose of a system is established, there are key steps that enable further clarification of the purpose and ultimate success of systems at all levels of complexity. These include:

- Establishing measures of effectiveness (MOEs) as the criteria by which a system or endeavor achieves success. This is required for systems of all complexity, projects (separate from the system as a project usually has a shorter lifecycle), and even enterprises. These measures are few in number, 5 ± 2, and if these measures are compromised, then the endeavor is likely judged a failure.
- Developing a concept of operations (ConOps), which includes an analysis of stakeholders, operational scenarios, constraints, and performance measures results in a more detailed analysis of the problem and begins the transition to solution. As part of concept development for a solution, the use of capabilities (what the system does), and characteristics (what the system is) define expected behavior and properties. This is a recursive process and applies at the enterprise, for example, Nuclear Security Enterprise (NSE), or system level.
- Developing an architecture, which encapsulates the principles of behavior and structure for solutions. An architecture is a set guidelines and principles that can yield multiple designs, especially when reference architectures are developed first. When reference architectures are used to instantiate architectures and designs at the enterprise as well as

the system level, the ability to encode knowledge and realize product is enhanced multi-fold. When strict adherence of overly specified requirements is followed to realize a solution, less flexible and more brittle systems result. There are many examples of brittle systems whose architecture mirrors the enterprise that developed the system, for example, 12 subsystems and 12 technical directors. This happens especially when enterprises have a successful legacy (e.g., Scania Trucks). In many of these cases, the engineers do not know the rationale for the resulting architecture or design, even when good rationale was applied originally.

Architecture and model-centric development – For established systems, an approach to developing a reference architecture is to mine architecture patterns. Architecture patterns abstract the essence of the system structure and behavior. Architecture patterns capture institutional design knowledge, reduce cognitive workload of engineers, increase consistency and quality of the design, and contribute to model-centric engineering. There can be tremendous returns on investment if patterns are mined at the system and enterprise level. Reference architectures build from multiple architecture patterns. They become powerful assets. It is a way of encoding principals and minimizing complexity, reducing time to ramp staff up, and reducing time to market. There is value in looking at the tie between a reference architecture of an enterprise and that of the system that it develops. Instantiating architectures and designs based on reference architectures allows for agility and adaptability to respond to change, and enables both exploitation and exploration of system architecture and design, that is, the art of the practical versus the art of the possible.

Model-centric engineering based on reference architectures provides the next level of efficacy and agility for product development. It allows detailed analysis of designs based on defined architecture options and normalizes a disciplined approach to designing systems. Part of that discipline includes developing a consistent ontology, which gets an enterprise to a place where they speak the same language and leads to a more aware enterprise. Ontology is a formalized vocabulary that enables interoperability at the data level, and defining ontology is a prerequisite to model-centric engineering. *A focus on integrating tools will not achieve model-centric engineering.* The biggest prerequisite to achieving value from model-centric engineering is the ability to perform model-to-model transformation because often models are discipline-centric or developed for a specific purpose.

Even if an organization has a model-centric engineering enterprise, there is still a need for "sandboxes" that allow for the art of synthesis, as most architects require. Each enterprise must decide what will work for them when establishing a model-centric engineering capability. Some common themes in developing a model-centric enterprise include developing a defined ontology, applying the approach on a real example, and clarifying the methodology for rolling out model-centric approaches. The impact of model-centric engineering is error-avoidance and many more cycles of a design, that ends with a better design. The goal of model-centric engineering is to get to a single source of technical truth that provides different viewpoints based on the stakeholder.

Enterprises that use expedited development – Applying the principles and practices discussed so far, including starting with intent, defining architecture, and employing model-centric engineering leads to enterprises that are more agile and can expedite development of concepts and products. Based on a study of 25 organizations, common characteristics of enterprises that use expedited development include leveraging mature technology, making use of incremental development, and striving for stable requirements with a well-focused customer. Observation of these enterprises show the ability to exercise flexibility in reallocating staff, in acquisition, and in process tailoring. It is also inferred from observations that these enterprises have an intense knowledge sharing culture (often enhanced by model-centric engineering), are risk aware, and focus on both exploration and exploitation of system architectures and designs.

Facilitated Sessions Summary

In the afternoon the participants divided into three groups for facilitated sessions on each of the workshop topics. There were three concurrent sessions featuring one of the three topics. The participants rotated through each of the sessions using a "dance card" that was designed to shuffle the participants for each session. The sessions featured 50-minute discussions followed by 10 minutes to allow the participants to rotate.

The basis of the facilitated sessions is a method called "world café."[4] The premise of the world café is that "***People already have within them the wisdom and creativity to confront even the most difficult challenges; that the answers we need are available to us; and that we are wiser together than we are alone.***" The world café enables the conversation through group interaction ***"sharing our collective knowledge and shaping our future."*** To enable the conversation, tables were arranged in a conference configuration and the host-facilitators served as catalysts; they posed questions, but followed the energy of the group within topical bounds. Participants had available various means to share ideas: butcher-block paper on the tables, post-it-notes of various configurations, flip-charts, etc. Two roving facilitators listened from an aggregate perspective and influenced sessions as necessary.

The principles of the world café include the following:

- **Set the context:** the keynote and the host-facilitators set the context for the topics and each session, based on the previous session
- **Create hospitable space:** the sessions were set-up in separate rooms, there were snacks, and participants were free to take bio-breaks, get snacks, or stand/sit as necessary
- **Explore questions that matter:** knowledge emerges in response to compelling questions. Powerful questions that "travel well" help attract collective energy, insight, and action. Open-ended questions and exploration of ideas were encouraged
- **Encourage everyone's contribution:** most people want not only to participate, but also to actively contribute and make a difference; contribution of ideas, experiences, and perspectives was encouraged
- **Connect diverse perspectives:** there was the opportunity as participants moved between sessions to meet new people. There was a wealth of experience and background (Appendix A: Participant Variety across Sandia) in the workshop and the opportunity to connect perspectives
- **Listen together for patterns and insights:** listening is a gift the participants give to one another, participants were encouraged to pay attention to themes, patterns, and insights that emerged

[4] The World Café Community Foundation Creative Commons Attribution, *A Quick Reference Guide for Hosting World Café, 2015.*

- **Share collective discoveries:** participants were encouraged to share "ahh-haa" moments as they went through the afternoon. The facilitators harvested the ideas and discussion at the end of the exercise and shared the story that emerged with everyone

Model-based Engineering

The discussions during the MBE session of the NWMA workshop focused on areas of opportunities and potential solutions. The discussions spent a considerable amount of time explaining the difference between the terms model-based systems engineering (MBSE), MBE, and M&S. The interpretation is that defining terms is something that needs to occur in any implementation effort going forward.

The opportunities discussed included industry comparisons, foresight implementation, and partnerships. A consistent theme across the sessions was the need to reward and support staff through a change in approach to utilizing models with integrated simulations, instead of the current document-centric and manually directed tests. Participants felt as though leadership was not promoting the use of these approaches and thus not providing adequate support. The three groups generally agreed that Sandia is behind industry in the application and trust of engineering models and model analytics, but ahead of the industry in physics-based modeling and simulation.

For future growth, all participants felt that an opportunity existed for Sandia to lead the DOE/National Labs complex in the application of MBE for high-consequence systems. To obtain that goal, the groups recommended the establishment of an executive champion, preferably at the director level, who had funding authority, as well as leveraging the current grass-roots efforts (such as the internal partnering by Org.6923) to promote cross-project/application use of MBSE, in order to transform the engineering culture into an MBE-centric culture. Some suggested ideas included: promoting cross-lab and program management communication, partnerships with industry, nurturing collaboration with external partners (such as the discussions with Jet Propulsion Laboratory (JPL), or other near industry groups in aerospace, defense, and complex systems engineering – Boeing and Lockheed Martin Corporation (LMC)), and partnering with professional organizations such as INCOSE to build capabilities across Sandia.

The gaps in MBE implementation at Sandia are in the use of engineering models throughout the duration of technical development processes and the interfaces between engineering models and physics models. There were complaints that Sandia neither integrates models of core information nor standardizes approaches. Participants pointed out that Sandia's customer expectations and operating environment would have to change to not be so document reliant and to determine how to rely on models. The example was given that the structure of the NSE system acquisition process supports document-based deliverables.

Participants suggested implementation strategies toward a future path of MBE at Sandia, such as focusing training on educating the entire workforce in the benefits and use of MBE integrated with simulations. There was caution on the perception of models as "trusted" models. Retiring old processes and allowing for new modern approaches was encouraged. One suggestion to assure retention of technical knowledge was to rebuild the entire stockpile every 10 years. Also mentioned was that if DoD/DOE required a model Sandia would deliver the model in an MBE approach without question. A tactical suggestion was to make MBE tools more available and to share tool costs across programs. Participants suggested that Sandia should embrace similarities with industry rather than focus on differences. An example is Sandia's frequent tendency to customize tools because many at Sandia believe that our business is *so* different that we need to extensively customize tools or build our own, significantly increasing the cost of commercial tools.

Enabling Viable Capabilities

The enabling viable capabilities discussion centered on gaps and opportunities for improvement. At the highest level, the identified gaps and opportunities fell into two categories: "knowledge, skills, and abilities" and "tools." However, two suggestions were more general in nature: in addition to listing the capabilities it needs, a participant suggested that the NWMA begin by crisply explaining why it needs those capabilities. An extension of that suggestion, while not specifically cited, might be why the NWMA needs the capabilities to be resident at the Laboratory. Another participant suggested that Sandia conduct a benchmarking study of how others steward and manage their capabilities. The list of potential institutions for benchmark purposes included JPL, European Space Agency (ESA), The Johns Hopkins University Applied Physics Laboratory (JHU APL), MITRE, LMC, Ford, SpaceX, Georgia Institute of Technology (GIT), and Systems Engineering Research Center (SERC).

Knowledge, skills, abilities

Most of the energy in the capabilities discussion revolved around developing and sustaining the knowledge, skills, and abilities of staff in NW. Below is a summary of suggestions.

- Improve onboarding of staff new to NW work in order to communicate purpose and importance and to sustain capability. The context of this suggestion dovetails with Dr. Verma's discussion about reference frameworks: improving onboarding will provide better domain knowledge for staff. Participants stressed that this onboarding should not be limited to new hires, but rather all staff new to the NW mission should receive this training. Computer-based, on-demand, self-paced training was the preferred method; however, intentional pairing of new team members with more seasoned staff for mentoring purposes was also encouraged. Participants suggested that the content of the training consist of a reasonably comprehensive overview of the NW program in a way that communicates why we need sustained deterrence. Some participants felt that formal MBSE training should also be a part of this training.

- Increase cross-Lab teaming and strengthen communication pathways. This suggestion dovetails with Dr. Verma's discussion about model-to-model transformations (synthesis that can transform) and is one of the characteristics of expedited development that he spoke about: an intense knowledge sharing culture. Suggestions here included nurturing and leveraging Communities of Practice (CoPs) to help onboarding, mentoring, agility, and innovation; creating an online platform and network that encourages and nurtures communications across these communities to help create a fertile environment for innovation; exploiting dual use of people, technology, and skills; and rewarding staff for teaming, collaborating, and taking appropriate risks.

- Sustain capability through staff retention. Participants felt that the focus here should be on 5 to 10 year staff. Specific suggestions were to improve HR analysis of those leaving the Labs, to improve the ability of the Labs to compete with industry, and to speed up the hiring process.

- Improve the trust culture to increase agility and innovation. The rationale behind this suggestion was that trust drives innovation (it affects the willingness of staff to share information). A low trust factor limits robust relationships, teaming, and collaboration. Further, trusting relationships will create better output with existing workforce and add value to new hires. Specific suggestions included using performance management forms as a crosscutting strategy to strengthen trust by emphasizing behavior attributes taught in Speed of Trust training.
- Elevate "systems engineering discipline" at Sandia. Suggestions here included pushing systems engineering discipline out to Sandia domains other than hardware/software integration (e.g., systems engineering in research and technology or construction arenas) to accelerate the practice of systems engineering, and making Sandia more visible as an external systems engineering thought-leader. Potential opportunities could be increased collaborations with SERC, conducting more systems engineering research with commensurate published manuscripts, and increasing awareness of Sandia's capabilities. Another suggestion was to co-locate systems engineers with the purpose of creating a real-time, collective, collaborative systems engineering group as a Lab resource to help different organizations explore concepts. Examples for co-located collaborative engineering are the ESA's Concurrent Design Facility and JHU APL's Central Spark innovation center.

Tools

Although there was less energetic discussion about gaps and opportunities for the facilities and tools portion of capabilities, a few ideas arose. A summary of these suggestions is presented here.

- Re-architect processes/procedures to ensure added value. Participants suggested that NW consider RPPs (Realize Product Procedures) and classification guides as initial candidates. Another suggestion was to integrate engineering and project management processes. A further suggestion was to consider a less document-centric model to find agility through an automated system, possibly through COTS technology. Suggested tactical methodology for re-architecting included answering these questions:
    - How can we increase efficiency and cost-effectiveness through our processes/procedures?
    - Is the process schedule driven? Does it allow time to re-architect projects if necessary?
    - What is an acceptable (rather than perfect) end product?

  One participant wondered if it would be possible to remove the "risk" in re-architecting NW policies/procedures by piloting them in other Strategic Partnerships Projects work.
- Standardize and upgrade tools and resources. Specific suggestions here included:
    - Standardizing the way we do requirements/system engineering across systems (e.g., some are using the same tool, but doing requirements differently)
    - Creating a better repository for drawings and models
    - Improving training and resources to use tools effectively, including creating and defining roles and responsibilities among users, administrators, and SMEs who can apply tools appropriately and better integrate the business folks who support the projects so teams can speak the same language
    - Creating a coordinated MBSE strategy and integrated MBE toolset

Enterprise Decision Awareness

The enterprise decision awareness discussion at the workshop focused primarily on current challenges to and consideration of an ideal state for maintaining enterprise decision awareness. Although the discussion was diverse, it was possible to identify a couple areas of focus. In the context of challenges to enterprise decision awareness, the participant comments focused on information access and barriers to communication across the enterprise. In the context of the ideal state though, participant comments focused on management of communication and the decision process itself, particularly at the leadership level, rather than the mechanics of information access.

The following sections summarize the dialogue in this area in terms of the four questions posed at the beginning of the workshop.

How is situational awareness maintained at the enterprise level?

There was consensus among the workshop participants that access and communication of data and other information played an important part in maintaining enterprise situational awareness. Particular challenges to access and communication included both institutional and work culture barriers such as programmatic stovepipes, need-to-know, and willingness by owners to share information. The workshop participants also recognized that removing barriers and granting access is the first step, followed by the organization and timeliness of information. In the view of the workshop participants, an enterprise maintains decision awareness through access to timely and appropriately organized data and information sources.

The discussion regarding the ideal state of enterprise decision awareness focused heavily on decision making and communication processes. Deliberate efforts to 1) identify the correct participants in a decision, 2) identify roles and responsibilities of those participants, 3) surface and analyze assumptions, 4) formalize communication pathways, and 5) monitor outcomes were features of this discussion. As in the discussion regarding challenges to enterprise decision awareness, the participants also emphasized the importance of appropriate and timely information to the decision process but there was limited discussion on how to achieve this beyond an intriguing suggestion to use tools of social media and social networking. The participants also commented frequently on the importance of an increased tolerance for failure and risk in the decision-making process.

How do complex adaptive systems and systems-of-systems views relate to enterprises?

Reeves, Levin, and Ueda (2016)[5] assert that enterprises and business systems *are* complex adaptive systems (see Figure 3). The behavior of such systems is an emergent result of decisions made by the individual agents that make up the system and feedback from the overall system and its environment. The details of how a decision was made by one agent in a complex adaptive system is less important to other agents, and the system as a whole, than information relating to how that decision impacts the context in which decisions are made by other agents. The workshop participant comments reflected this view. When considering barriers to enterprise situational awareness and decision making the workshop participants focused on barriers to information flow. Conversely, when considering an ideal situation, the workshop participants focused on the process by which an agent would obtain and process information in order to make

[5] Reeves, M., Levin, S., and Ueda, D., 2016. "The Biology of Corporate Survival," *Harvard Business Review*, January 2016.

a decision. In short, environmental information and context needs to be available in an enterprise, not the details of decisions made by individual agents. For example, the workshop participants discussed developing databases and tools to optimize access to and processing of information to support decisions made by users of the information (information pull) rather than translation and broadcasting of information by generators (information push). Such an adaptive information exchange might depend more on establishing enterprise-level information and interface standards rather than a more rigid communication structure.

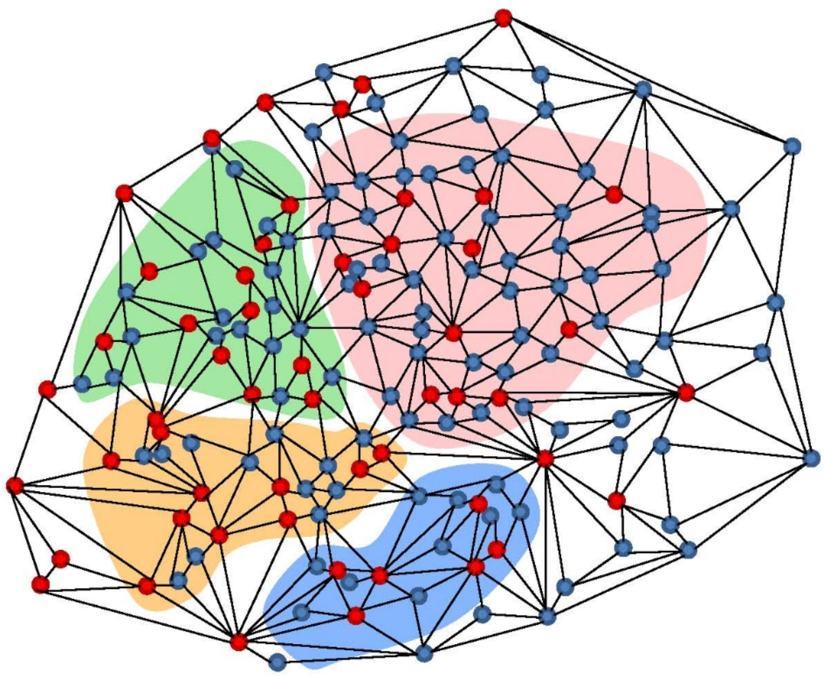

Figure 3 - Complex Adaptive System Communication Network Illustration

How does technical communication enable enterprise efficacy and responsiveness?

Technical reports are one instance of communication that consolidates decision information suggested in the complex-adaptive system described above. In this case, the technical report represents a technical decision made perhaps at a project level. The technical library archives and search engines are examples of the databases and tools suggested above that facilitate access by users of this data to support subsequent (technical) decisions. A system such as this is quite familiar to members of a research community. It does not require information push by developers based on sets of procedures or communication plans, and if it includes best practices or interface requirements, for example, report formatting rules, it facilitates information access and assembly of information.

It is not difficult to abstract such an information exchange infrastructure into an ecosystem that supports a much broader range of enterprise decision information, such as financial data, project execution data, M&S data, corporate procedures, governance decisions, to name a few. Indeed, some of the elements of this type of ecosystem already exist or are in development within Sandia, for example, the Oracle financial system, Sandia Enterprise Project Management, and Genesys, as well as the technical library systems already described. Focusing on the development of a comprehensive and integrated information system such as this may be more practical, adaptable, resilient, and effective in maintaining enterprise decision awareness, and may be more adaptable than a process-based approach focused on pushing information out to potential users.

The workshop participants recognize that such a comprehensive and broadly accessible ecosystem might result in unique security and need-to-know challenges. It would also be naïve to assume that cultural issues surrounding project execution and ownership would not also be a challenge in the establishment of this type of information ecosystem.

What governance models exist for technical enterprises?

Currently, a number of governance boards exist within the Laboratories that provide coordination at the senior manager and senior staff level. Examples of this governance structure include the Product Realization Governance Structure within Sandia's Weapons Engineering and Product Realization Division and the Research and Mission Foundation Investment Area teams within Sandia's Science and Technology Division. While governance boards such as these provide valuable coordination across multiple functional units at the Laboratories, their agility and reach is constrained by the realities of logistics and scheduling. An enterprise information exchange ecosystem system such as that imagined here would not only benefit the deliberations of this existing governance structure but would also potentially increase the influence of the structure by providing better information access and communication both into and out of the governance structure. Developing best practices and templates to maximize the utility of information sources across the enterprise could supplement the governance board role.

OPPORTUNITIES AND CONCLUSIONS

The workshop participants identified an array of questions and potential areas of inquiry during their discussions. However, these discussions also suggested a few fundamental initiatives that, if successful, could support the advancement of the NWMA strategy in a number of areas. These initiatives include:

1. Define the concept of operations for NW and for Sandia capabilities to normalize the thinking, description, and communications.
2. Define a vision and roadmap steps for harmonizing and maturing model-centric engineering at Sandia to align efforts and create synergy between people that are endeavoring to advance our development methodology.
3. Develop a reference architecture for Sandia systems, capabilities, and enterprise that would enable a model-centric approach and enhance Sandia's future agility.
4. Map the current "information ecosystem" that supports decision making at the laboratory including interfaces, best practices, databases, and access control.

The successful execution of these initiatives would require engagement from stakeholders and partners from across the Laboratories.

Appendix A Participant Variety across Sandia

Org.	Department Focus
151	NW Systems Analysis Department
153	Strategic Weapons Studies Department
155	National Security & Homeland Defense Studies
157	Nuclear Security Enterprise & Cost Analysis
158	NW & Labs Futures Analysis
159	Policy & Decision Analytics Department
260	NW Strategic Planning & Enterprise Integration Group
252	NSE Integration
253	NW Mission Area Planning
281	NNSA Enterprise Analytics Support
414	Prod Realization & Engineering Assessment
425	Comp & Tester Surety Engineering
427	System Surety Engineering II
1220	ASC Program
1341	Radiation Effects Theory Department
1382	Nuclear Quality & Requirements
1754	NW ASIC Product Realization
1911	CTO Programs Office
2124	B61-12 Non-WR System Engineering
2152	B61-12 Weapon System Engineering
2215	SE Technical Program/Project Management
2241	Advanced & Exploratory Systems
2242	Use Control Systems Engineering
2245	Surety Software Department
2626	Firing Sets & Controllers
2627	Advanced Fuzing Technology
2727	Neutron Gen Cyber Engineering & Technologies
2732	ELNG Lifecycle Engineering
5012	Systems Engineering & Engineering Management
5358	Inertial Integration/Qualification
5555	Systems for Development & Analysis
5568	Mission Data Processing Systems
6114	Military & Energy Systems Analysis
6923	High Confidence System Environment
8113	Advanced & Exploratory Systems
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9512	Lifecycle Management Solutions
9517	Engineering Infrastructure
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