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Managing Complex Systems Engineering and Acquisition Through Lead Systems Integration

30 September 2018

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Abstract

Modern complex mission capabilities are fundamentally achieved with multi-mission, highly interoperable system of systems (SoS). The acquisition and management of these mission capabilities across the SoS lifecycle require the complex integration of interdependent new and legacy systems from the lowest component level to the highest enterprise level. The challenge of integrating these disparate constituent systems into an SoS is that they are developed and procured asynchronously, usually by different program offices, and often across different enterprises. The System of Systems Engineering and Integration (SoSE&I) “Vee” process model was developed to provide details on the engineering activities required during the SoS lifecycle. However, the SoSE&I “Vee” does not specify the implementation details of the engineering activities.

Heretofore, Navy System Commands (SYSCOMs) have been using different approaches to address SoS issues. Two prevalent approaches are Navy Integration and Interoperability (I&I) and Lead Systems Integration (LSI). Navy I&I provides a framework for mission engineering and the collaboration between SYSCOMs; it focuses heavily on the engineering activities that occur early in the SoS lifecycle. LSI is an acquisition strategy that employs a series of methods, practices, and principles to increase the span of both management and engineering acquisition authority and control to acquire an SoS or highly complex systems. LSI is effectively a “marriage” of program management and multiple functional disciplines that must work together cooperatively to assert and execute trade space in the SoS given multiple constituent system acquisitions. Both of these approaches can use the SoSE&I “Vee” as their foundation. However, neither of these concepts address the engineering and acquisition problem in its entirety.

This research results in a correlation between the LSI and I&I processes, embedded on the SoSE&I “Vee,” and provides a blueprint for a more complete SoS governance approach with a more executable set of guidelines and results in an enhanced mission-based SoS development and LSI management model. The revised process model includes inputs, outputs, and guiding principles of each phase to yield an implementable solution that can be employed throughout the SoS lifecycle. The enhanced SoS/LSI process is then applied to explore architecture development. Defining the SoS architecture is one of the most critical activities within the SoS lifecycle because the architecture serves as the basis of many decisions to achieve the mission capabilities.

Keywords: Lead Systems Integration, System of Systems, Lead Systems Integration, Model-Based Systems Engineering

Acknowledgments

The Naval Postgraduate School (NPS) was established in 1909 as an institution to provide advanced education to naval officers and research opportunities to support the fleet. This was the era when the Navy was experiencing a multi-decade technological revolution in which wooden-hulled, sail-powered ships were being replaced by steel-hulled, steam-powered ships. The United States was becoming a strategic naval power, as demonstrated via the circumnavigation of the Great White Fleet. This voyage was not only the largest armada the world had ever seen; it was the largest integration and demonstration of technology. NPS was established in the wake of the lessons learned from the voyage of the Great White Fleet, where it was learned that engineering education and research was needed for the effective integration and operation of new technology.

During the past century, NPS has been providing relevant education and advanced research to address the most pressing issues of the Naval Service and the Department of Defense (DoD). Today, concepts such as “cyber warfare,” “internet of things,” and “system of systems” are prevalent across the Navy and the DoD. Similar to the voyage of the Great White Fleet, the net-centric technology that is being integrated into operations today requires a new engineering acumen, achieved through education and research, to be truly effective.

In supporting the NPS mission of providing relevant advanced education and research for the Naval personnel, and in the spirit of the earliest NPS faculty members, Dr. Paul Montgomery (retired Systems Engineering Associate Professor) and Professor Ron Carlson (Systems Engineering Professor of Practice), in conjunction with Mr. Mike Pearson (Naval Air Systems Command [NAVAIR]), initiated the Lead Systems Integration (LSI) Certificate Program to better engineer, acquire, and integrate new existing technology into a system of systems. This on-going certificate program supports the NPS core mission be providing the students with relevant and unique advanced education and the opportunity to participate in on-going research to further the LSI concept.

The first three LSI Certificate Cohorts included employees from NAVAIR, while the fourth cohort included employees from the Naval Undersea Warfare Center (NUWC), Newport, RI, and the Marine Corps Systems Command (MARCORSYSCOM), Orlando, FL. It is because of these cohorts that the LSI concept is able to be further developed to better support the needs of the Naval Service and the DoD.

Cohort #1 contributed to the ongoing research by exploring the concept and providing a new definition for LSI. LSI was mandated by Congress Public Law 110-181 in 2008. However, Congress did not define the term *Lead Systems Integration*. The efforts of Cohort #1 significantly advanced LSI by defining and exploring the LSI concept. The students in the cohort included Ryan Aaron, Christina Allee, Ferguson Ayers, Richard Cerrano, CDR Josh Dittmar, Jacqueline Dvorak, Silvia Faulstich, CDR Anthony Fortescue, Lissette Fortuno, Stephanie Frederiksen, Matthew Funk, LCDR Brian Hall, Lance Hernandez, Eric Johnsen, Tracey Johnston, Clifford Kangas, Robert Keeney, Janet Marks, Vinh Nuyen, Patric Roesch, Joseph Schmidt, Andrew Starn, Rozier Steinbach, CAPT Thomas Tennant, Michelle Vuaghn, William Wren, and James Young.

Cohort #2 contributed to the research by defining the LSI Enterprise Framework. This framework made significant contributions by defining the various LSI levels; key LSI activities; and the universal resources needed to enable LSI. The students in this cohort included Richard Bee, Kirk Bonnevier, Richard Braunbeck, Gary Evans, Andrew Fowler, Lindley Grubbs, Jennifer Horsley, Randel Langloss, CDR Paul Mitchell, Richard Muir, Michael Olszewski, David Rose, Jerome Roubieu, David Ruminski, Andrew Scavone, Lisa Smith, Matthew South, and Lorenda Walton.

Cohort #3 explored conducting configuration management with the LSI Enterprise Framework. The students in this cohort included Cynthia Davis, Kevin Dusch, Erik Eldridge, Gregory Gibbs, David Kaniss, Candida Olney, Peter Stauffer, Thomas Stubbs, Emily Stump, Dolan Tavarez, Ronald Walden, Kent Yen, and Peter Youssef.

Cohort #4 used the research from Cohorts 1 and 2 to further expand the LSI concept so that it could be implemented in Naval System Commands. Their research heavily supported this report. Students in this cohort included Lisa Banta, Tara Barnum, Thomas Barron, Martin Bushika, Christina Dao, Brennan Dugas, Simplice Gbedie, Jerin James, Caroline Lazar, Gregory Maguire, Dennis Ritaldato, Nathaniel Spurr, Gregory Travassos, and Meredith Yazzie-Ramos.

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Dr. Warren Vaneman is a Professor of Practice in the Systems Engineering Department at the Naval Postgraduate School, Monterey, CA. He has more than 30 years of leadership and technical positions within the U.S. Navy and the Intelligence Community. Dr. Vaneman has been conducting research in MBSE and systems and system of systems since July 2011. To enhance his research efforts, Dr. Vaneman teaches several courses in Model-Based Systems Engineering, Architecting, and System of Systems Engineering and Integration. Prior to joining NPS, Dr. Vaneman held various systems engineering positions within the Intelligence Community, including Chief, Architecture Analysis Division, and Chief Architect of the Enterprise Ground Architecture at the National Reconnaissance Office (NRO), and Lead Systems Engineer for Modeling and Simulation at the National-Geospatial Intelligence Agency (NGA).

Dr. Vaneman is also a Retired Navy Reserve Captain, where he was qualified as a Surface Warfare Officer, Information Dominance Warfare Officer, and Space Cadre Expert. He had the pleasure of serving in six command tours, including a command tour in Afghanistan, and as the Commanding Officer, and Deputy N2, U.S. Fleet Forces Command Maritime Intelligence Operations Cell. He also served as the Flag Advisor for Systems Engineering and Space for the SPAWAR Headquarters Chief Engineer. He has a BS from the State University of New York Maritime College, an MS in Systems Engineering, and a PhD in Industrial and Systems Engineering from Virginia Tech, and a Joint Professional Military Education Phase 1 Certificate from the Naval War College.

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Carlson's research interests are in Model Based Systems Engineering, Lead Systems Integration, and Systems of Systems. He is co-located with Naval Air Systems Command in Patuxent River, MD and has provided onsite research and instruction support to NAVAIR (Patuxent River, MD), NAVSEA (Dahlgren, VA; Carderock, MD), and NPS SE students in the Nation Capital Region.

Carlson served 26 years in naval aviation as a pilot, the last seven years of which were at NAVAIR where he was the Military Director of Systems Engineering and led NAVAIR Systems Engineers through several years of systems engineering revitalization.

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Executive Summary

To stay ahead of our adversaries, the military must improve the capability of its systems. These systems are becoming increasingly complex, and so has the effort to develop them. To achieve the improved capabilities, gaps/shortfalls in systems are being filled by integrating them with other systems that possess the required capability. Some of these systems are legacy systems, some are new systems, and some are systems still under development. Furthermore, these systems do not only need to be integrated, they also need to be interoperable. They need to speak the same language, use the same units, and if more than one system can sense the same things, they need to determine which data is more accurate.

In the early 2000s, a few high-visibility government projects were failing. They were strongly criticized because of cost and schedule overruns and apparent conflicts of interest. There are multiple contributing factors in these failures: SE practices were not adequate to define and manage these complex programs, they were producing unprecedented System of Systems (SoS) with constituent systems that were in various levels of development, and government procurement policies changed in the 1990s. Additionally, the government did not have the necessary visibility into these projects to foresee impending problems because contractors were performing the design and integration work. These contracted systems integrators often re-allocated resources or funding between disparate programs/program offices or even chose which programs (or contractors) would be used. This led to numerous potential conflicts of interest as well as a loss of control and oversight by the government.

In order to improve the Navy's ability to acquire and gain insight into these complex SoSs, new approaches and methodologies needed to be developed. The two most significant approaches are Lead Systems Integration (LSI) and Navy Integration and Interoperability (I&I). LSI is an acquisition strategy that employs a series of methods, practices, and principles to increase the span of both management and engineering acquisition authority and control to acquire an SoS or highly complex systems. The Navy I&I provides an SoS and governance process to identify gaps in Naval missions and to develop, and coordinate, solutions across system boundaries.

Navy I&I provides a more detailed strategy than LSI, but is focused primarily on the early phases of the SoS lifecycle. LSI is more broadly defined, but lacks the details sufficient for an implementation strategy that can be used across the SoS lifecycle. Each of these processes provide clarity to a portion of the challenges faced by government personnel conducting complex SoS integration. However, none stands alone as a prescriptive document to enable the full spectrum of activities required to engineer and manage an SoS.

The LSI and Navy I&I processes can each use the System of Systems Engineering and Integration (SoSE&I) "Vee" as a foundation. The SoSE&I "Vee" provides a model of the high-level activities that need to be performed in the engineering and management throughout the SoS lifecycle, but fails to provide implementation guidance, and, equally important, it doesn't suggest who performs these activities. Neither LSI or Navy I&I address the full spectrum of the problem. However, LSI provides the broadest framework to address the SoSE&I "Vee." Given that the LSI Enterprise Framework offers the broadest perspective, further defining, and enhancing, LSI activities using the SoSE&I "Vee" as the foundation, is the premise of this research.

The SoSE&I "Vee" is depicted in Figure ES1 (Vaneman, 2016). This high-level depiction of the SoSE&I "Vee" provides useful context in using the overall SoS architecture for performing top-down engineering (as in traditional systems engineering [SE]) and performing bottom-up verification and validation.

Using the Integrated Definition (IDEF) function model (IDEF0), the SoSE&I processes can be expanded to incorporate both the LSI and Navy I&I processes. The functional activities are represented in the IDEF0 model by the SoSE&I functional activities; the inputs and outputs are represented by the inputs to, and outputs from each SoSE&I functional activity; the controls are represented by SoS acquisition policies, Navy SoS acquisition position mechanisms, LSI touchpoints, and Navy I&I ICF; and the mechanisms represent the SoS acquisition position descriptions (knowledge, skills, and abilities) needed to perform the functional activities.

Each of the SoSE&I functions were analyzed for inputs, outputs, controls, and position descriptions. Using this construct, the Navy I&I and LSI processes were analyzed to determine how they may further govern the SoSE&I functions. Figure ES2 shows the SoSE&I “Vee” as an IDEF0 model (Level 1). The model illustrates the interdependencies throughout the entire process flow from initial requirements through support of the fielded systems. The correlation between the LSI and I&I processes (embedded on the SoSE&I “VEE”) provides the blueprint for a more complete SoS governance approach with a more executable set of guidelines and should result in an enhanced mission-based SoS development and LSI management effort.

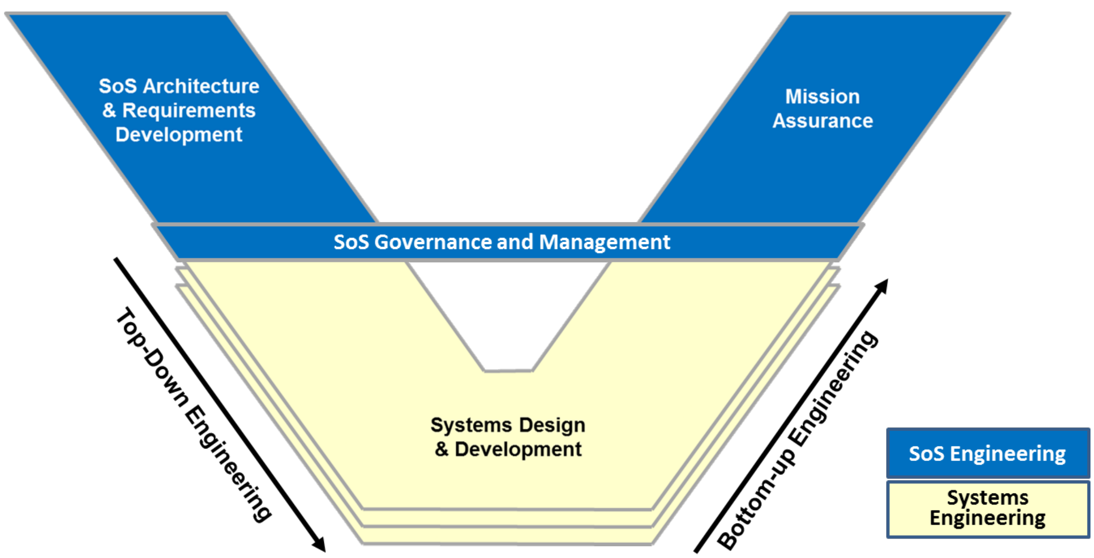

Figure ES1. Abridged SoSE&I “Vee” (Vaneman, 2016)

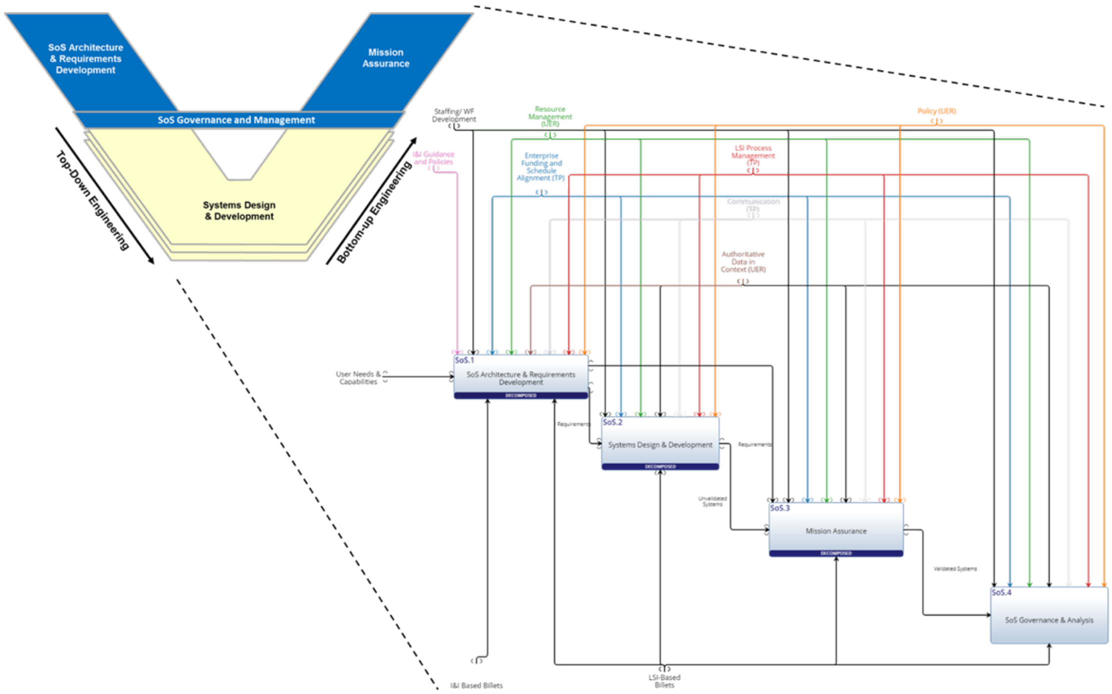

Figure ES2. SoSE&I "Vee" Viewed as an IDEF0 (Level 1) Model

This enhanced SoS/LSI Enterprise Framework, used in current and future government LSI efforts, seeks to reduce risk in the affordable optimization of integrated warfighting capability acquisition efforts across the SoS lifecycle, and to increase the speed of capability delivery to the warfighter. LSI can be executed by the government within existing organizations via enhancements to legacy processes, methods, and practices if the workforce is trained and motivated to think and act differently. The LSI Enterprise Framework provides an effective set of tools, resources, and concepts to help incrementally incentivize this cultural evolution.

To achieve this goal, the Navy should increase systems engineering and SoSE&I technical and management depth and breadth across the workforce by hiring professionals trained in advanced systems engineering concepts. Additionally, the adoption of a directed universal approach to SoS management, such as that presented in this report, should be implemented across the Navy enterprise in order for LSI to be truly successful. Not only are well-trained personnel required to ensure success, but top-down directed guidance that is common to all Naval Systems Commands for LSI in SoS will enable this approach.

Additionally, a directed universal approach to SoS management, such as that presented in this report, should be implemented and enforced across the Navy enterprise in order for LSI to be truly successful. Not only are well-trained personnel required to ensure success, but top-down directed guidance that is common to all Naval SYSCOMs for LSI in SoS will enable this approach.

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I. Introduction

> Our current system is like a machine to which we just keep adding important and wanted items, but without a cohesive strategy for an elegant, interwoven system. Considered on their own, the addition and growth of individual elements may be useful. But when ownership organizations do not see how their contribution fits into the whole and think their element is an end-state in itself, effective communication and execution are inhibited.
>
> —ADM William Gortney & ADM Harry Harris (2014)

To stay ahead of our adversaries, the military must improve the capability of its systems. These systems are becoming increasingly complex and so has the effort to develop them. To achieve the improved capabilities, gaps/shortfalls in systems are being filled by integrating them with other systems that possess the required capability. Some of these systems are legacy systems, some are new systems, and some are systems still under development. Furthermore, these systems do not just need to be integrated, they need to be interoperable. They need to speak the same language, use the same units, and if more than one system can sense the same things, they need to determine which data is more accurate. All of this further adds to the complexity.

Processes developed for systems engineering (SE) were useful for developing individual systems. However, as these systems became System of Systems (SoS), the traditional SE processes were found lacking. The creation of an SoS adds additional layers of complexity with technology developments at various levels, along with more stakeholders with differing views, all leading to less centralized control over the SoS development. To handle these complex tasks, more of the integration work was contracted to the private sector as it was thought to be easier for the private sector to hire (and fire) the right employees to accomplish these complex tasks. The contracting of this work led to a loss of capability and insight by the government in complex SoS integration, interoperability, interaction, and interfaces.

In the early 2000s a few high-visibility government projects were failing, including the U.S. Army's Future Combat System (FCS; U.S. Government Accountability Office [GAO], 2007) and the U.S. Coast Guard's Deepwater program.

They were strongly criticized by some observers because of cost and schedule overruns and apparent conflicts of interest. One area that the Army focused on, while doing an autopsy on the failed program, was the role of the Lead Systems Integrator (LSI), which was performed by a contractor. The Army cancelled the FCS program in 2009 and the replacement programs did not use an LSI to represent the government's interests. There are multiple contributing factors in these failures: SE practices were not adequate to define and manage these complex programs, they were producing unprecedented SoS with constituent systems that were in various levels of development, and government procurement policies changed in the 1990s. Additionally, the government did not have the necessary visibility into these projects to foresee impending problems because contractors were performing the design and integration work. These contracted systems integrators often re-allocated resources or funding between disparate programs and/or program offices or even chose which programs (or contractors) would be used. This led to numerous potential conflicts of interest as well as a loss of control and oversight by the government. As a result, the government sought to eliminate the use of contractors as LSIs.

To achieve the goal of bringing the LSI role into the government, a number of laws were passed. In 2008, Public Law 110-181, Congress directed the Secretary of Defense to properly size and train the Department of Defense (DoD) workforce to perform inherently governmental functions, specifically to eliminate contractors as LSIs (Grasso, 2010). Public Law 111-23, the Weapons System Acquisition Reform Act of 2009, required the Secretary of Defense to revise the Defense Federal Acquisition Regulation Supplement (DFARS) to reflect any organizational conflicts of interest that may arise from the use of private-sector LSIs. On September 30, 2010, the House and Senate conferees for the proposed Fiscal Year 2010 and 2011 Coast Guard Authorization Act resolved their differences, and the bill was sent to the President on October 4, 2010. One provision in the bill, Section 565, prohibits the use of LSIs within the Coast Guard, with some exceptions, and would require the use of full and open competition for any future acquisition contract.

To further assist in achieving this goal, the Navy has been conducting research to define the general strategy or approach to define the challenges of SoS integration.

Four documented processes for engineering and management of Navy SoS were discovered that appeared to add additional processes and details to the LSI effort and were examined during this research. The processes these documents discuss and the primary users of them are listed in Table 1. As part of an LSI Certificate Program, Naval Postgraduate School (NPS) cohorts researched the processes an LSI should adhere to in order to be successful and the result was an Enterprise LSI framework for the development of a large SoS. Another of the reviewed documents identifies a framework for SoS development to ensure Navy systems are both integrated and interoperable, another discusses developing a System of Systems Engineering and Integration (SoSE&I) approach to handling information technology (IT/TA), and the final one discussed the Marine Corps approach to Integration and Interoperability (I&I).

The final document, which addressed the Marine Corps approach to I&I, lacked sufficient detail and was eliminated from the study. The remaining three documents contributed to the generalized strategy or approach for SoS integration and were

Table 1. Naval Instructions Related to Lead Systems Integration

Process	Primary Use	Notes
Lead Systems Integration (LSI)	NAVAIR	1. NUWC, Newport and MARCORSYSCOM (Orlando) have employees in NPS LSI Cohort #4. 2. SPAWAR, MARCORSYSCOM (Quantico), and Strategic Systems Program (SSP) have expresses interest in LSI process and certificate. 3. NPS LSI certificate program is going to be presented to NAVSEA CHENGs on 16 Nov. 4. SSP has not adopted any of the Navy processes, therefore may be ripe for LSI adoption.
Navy Integration and Interoperability (I&I)	SPAWAR	1. NAVAIR, NAVSEA, SPAWAR, and MARCORSYSCOM are Navy I&I signatories. 2. Each signatory has an I&I lead. However, only SPAWAR appears to employ the process.
Marine Corps Integration and Interoperability	MARCORSYSCOM	1. MARCOSYSCOM has identified that there are significant differences between USMC I&I and Navy I&I. Currently, no I&I process is used. 2. USMC Combat Development & Integration (CD&I) is focusing efforts on implementing the Marine Corps Operating Concept (MOC). 3. USMC does not have a standardized process for developing SoS or complex systems, therefore LSI may be ripe for adoption.
Information Technology Technical Authority (ITTA)	SPAWAR HQ	1. SPAWAR HQ defined ITTA for acquisition and development of SoS during the 2010–2012 timeframe. 2. The current status of IT TA is unknown.

utilized in the study. The following are the titles of the two documents, which are discussed further in the next chapter:

- The Enterprise Lead Systems Integration (LSI) Framework
- The Navy Integration and Interoperability (I&I) Integrated Capability Framework (ICF) Operational Concept Document

Each of these processes provide clarity to a portion of the challenges faced by government personnel conducting complex SoS integration. However, none stands alone as a prescriptive document to enable LSI. As stated in the quote from ADM William Gortney, U.S. Fleet Forces Command, and ADM Harry Harris, Commander U.S. Pacific Fleet, at the beginning of this report, the government cannot continue to put systems together in an effort to achieve required capabilities without an overarching strategy or framework. SoS are becoming increasingly complex, and the aforementioned documents represent a first step in achieving such an overarching strategy.

The System of Systems Engineering and Integration (SoSE&I) "Vee," which is described in Chapter II, is an expansion of the SE "Vee" and is a good visualization of the acquisition process/steps. The previously mentioned documents cover portions of the SoSE&I process, but are incomplete and do not integrate with one another. The strengths and weaknesses of each of these documents will be reviewed and the information contained therein will be used to provide a framework to more clearly define LSI activities across the SoS lifecycle, further improving the model.

The primary purpose of this research is to develop an operational process for SoSE&I that flows efficiently through SoS development, deployment, and disposal. The overarching questions for this research are as follows:

1. What is the correlation between Navy I&I, IT/TA, and LSI?
2. How can correlating the various development and acquisition processes for SoS and complex systems facilitate acquisition strategies that improve their belonging, connectivity, and integration to better satisfy mission objectives?

The expansion of the SE “Vee” into a SoSE&I “Vee” (Vaneman, 2016) provides a common foundation on which to compare and combine the disparate strategies researched and will be used to present the results in a manner familiar to those in the SE discipline. Just as the SoSE&I “Vee” added to the well-established SE “Vee,” this research combines the aforementioned documents with SE knowledge and SoSE&I research to develop a model and framework for future SoS development. The approach, methodology, results, and conclusions of this research are provided in the following chapters and are intended to further the discussion of the LSI role in the Navy, serve as a resource for LSIs, and add to the existing LSI/I&I repositories.

This chapter has discussed the need for an operational-level guide for Lead Systems Integration in developing SoS. Chapter II provides an overview of the SoSE&I “Vee,” NPS’s Enterprise LSI Framework, Navy I&I, and IT/TA. Chapter III discusses the methodology of this research, while Chapter IV provides an example of how to apply these strategies to a current naval program. The final chapter discusses the conclusions and recommendations from this research to enable further work in refining the inherently government functions of the LSI.

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II. Review of Existing System of Systems Concepts

> It is when we have reached agreement on the names and concepts that we can hope to progress with clearness and ease in the examination of the topic, and be assured of finding ourselves on the same platform with our readers.
>
> –Carl von Clausewitz (1832)

As stated in Chapter I, this research is based upon two primary strategies: the LSI Enterprise Framework and the Navy I&I ICF Operational Concept Document. These strategies are critical in establishing the foundation of this research and will be explained in further detail below. This research has considered these strategies in relation to the SoSE&I "Vee" to address the Navy's overall problem with LSI. Systems and SoS are becoming more complex, and emerging threats are proving themselves to be more pressing. As a result, a critical need for integrated and interconnected systems has emerged. The implementation of SoSE&I using LSI techniques must be developed to adequately influence the ever-increasing complexity of the national defense enterprise.

A. SoSE&I "Vee"

Essential to the understanding of this research is an understanding of the SoSE&I "Vee." An SoS is "a set or arrangement of systems that results when independent and task-oriented systems are integrated into a larger system that delivers unique capabilities" (Vaneman & Budka, 2013, p. 2). Further defining an SoS is the attribute where the whole is greater than the sum of its parts (Office of the Deputy Under Secretary of Defense for Acquisition and Technology, Systems and Software Engineering [ODUSD(A&T)SSE], 2008). SoSE&I incorporates the basic tenants of SE within the SoS framework and results in "planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new constituent systems into an SoS capability greater than the sum of the capabilities of the constituent systems" (Vaneman, 2016). SoSE&I thus becomes the framework of choice for solving tomorrow's problems as they relate to pressing and emerging threats to the United States. The SoS approach to national defense provides the structure to develop new capabilities through the integration of new and constituent systems. A common foundation for delivering these complex systems is captured in the SoSE&I "Vee," which has built upon the traditional SE "Vee."

As depicted in Figure 1, the multiple layers of the customary SE "Vee" within the SoSE&I "Vee" illustrate the concept of concurrent development and management of constituent systems. This high-level depiction of the SoSE&I "Vee" provides useful context in using the overall SoS architecture for performing top-down engineering (as in traditional SE) and performing bottom-up verification and validation.

Figure 2 provides a decomposition of the processes shown in the abridged SoSE&I "Vee." This chapter provides a discussion of the Abridged SoSE&I "Vee" only. A detailed discussion of the decomposed processes will be central to the discussion in Chapter III.

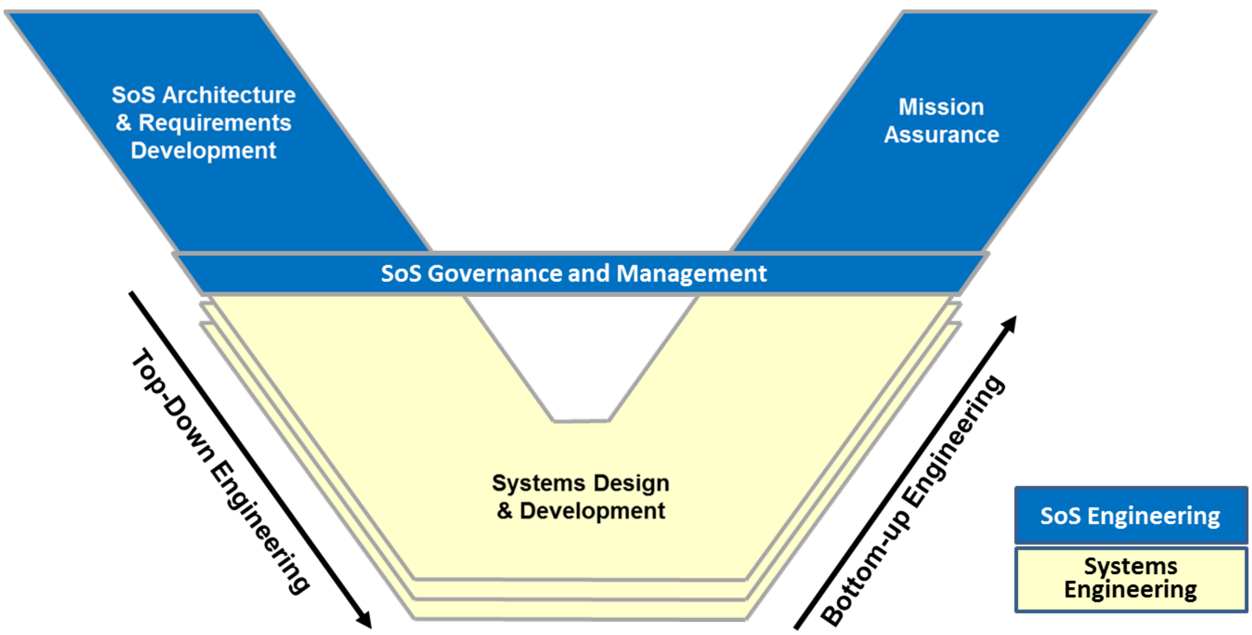

Figure 1. Abridged SoSE&I "Vee" (Vaneman, 2016)

SoS Architecture and Requirements Development

The SoSE&I "Vee" begins at the upper-left side with SoS Architecture & Requirements Development. In this phase the user needs are defined, and then transformed into technical requirements that can be executed by the system program office (Vaneman, 2016). The purpose of Architecture and Requirements Development is not only to understand the overall mission needs and establish the boundary of the SoS of interest, but also to uncover the requirements for the individual constituent systems needed to achieve the mission capabilities, their respective interfaces, and to manage and implement SoSE&I processes. It is equally important to develop a comprehensive plan to align systems that are meant to work together for mission success, provide a foundation from which resources can be prioritized to maximize user needs and budget issues, and establish an overarching requirements baseline to improve integration and interoperability across the SoS (Vaneman, 2017).

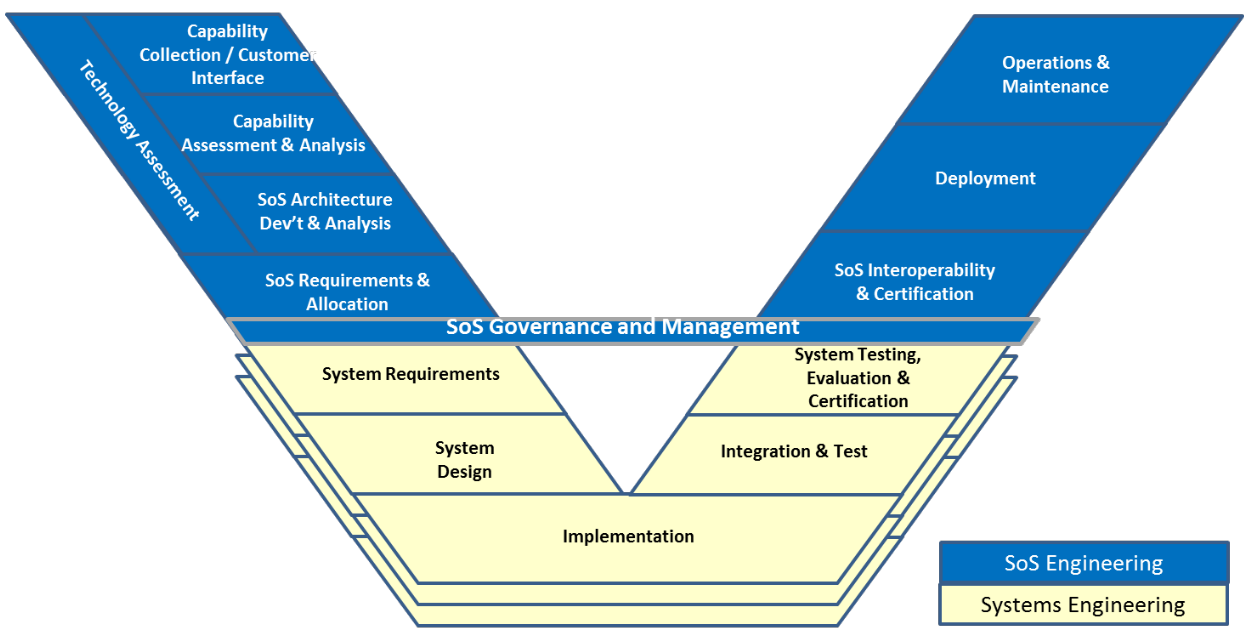

Figure 2. Unabridged SoSE&I "Vee" (Vaneman, 2016)

Due to the complexity of an SoS, Model-Based Systems Engineering (MBSE) methods are used to manage relationships between the functional, physical, parametric, and program perspectives in a variety of operational contexts to efficiently evaluate the SoS. Dynamic architectural views are constructed and used to analyze and forecast SoS performance; identify gaps, bottlenecks, and other constraints within the architecture; and explore solution alternatives to mitigate the issues found. These activities are performed in the context of the defined and approved mission threads and relate back to the goals and objectives to meet the stakeholder's mission needs (Vaneman, 2016).

Systems Design and Development

The bottom of the SE "Vee," depicted in Figure 2, represents the systems engineering activities that are performed by the program offices of the constituent systems. Several individual system SE "Vees" are depicted to illustrate that many constituent systems are developed and managed concurrently, with each system at different maturity levels within its own lifecycle. In this phase, the focus is on the development, sustainment, and management of individual systems (Vaneman, 2016).

Two important LSI activities must occur to ensure a successful SoS. First, the LSI must have sufficient insight into the constituent system's development, sustainment, and management to ensure the systems are compatible with the SoS. This is an important point because as decisions are made for individual systems, it is easy for those decisions to be contrary to the stated mission of the SoS. When individual system decisions impact the interoperability of the system to be able to work with the SoS, the decision must be elevated to the "SoS" or "Mission Capability Level" for resolution through the governance process (Vaneman, 2016).

Second, understanding constituent system functionality and programmatic issues is critical since constituent systems in an SoS rely on each other to achieve mission success. Issues such as system schedule delays, or technology issues leading to capability shortfalls, are critical since other systems that depend on upstream information may not be able to fulfill their missions within an SoS. System retirements are also an area of concern because a premature decommissioning may yield gaps that inhibit the SoS. A strong governance process must be in place to communicate and manage changes during the development cycle while maximizing SoS and mission effectiveness (Vaneman, 2016).

When developing an SoS it is important to understand that not all systems are in the same phase of acquisition at the same time. While some systems may be in the design phase, others may be in the sustainment or even retirement phase. Figure 3 (Herdlick, 2011) depicts how various systems acquisition phases may align as part of a larger SoS. Due to this asynchronous nature of the constituent systems, LSIs at every level of the organization must understand the need for flexibility in the process to achieve the overall interoperability of the system and SoS.

Mission Assurance

The upper-right side of the SoSE&I "Vee" represents the SoS Mission Assurance activities. Mission Assurance is defined as "the part of systems engineering and integration activities which, by means of a combination of design validation, product verification, and systems test, provides the systems engineers, design team, and customer with a high degree of confidence in the successful execution of the

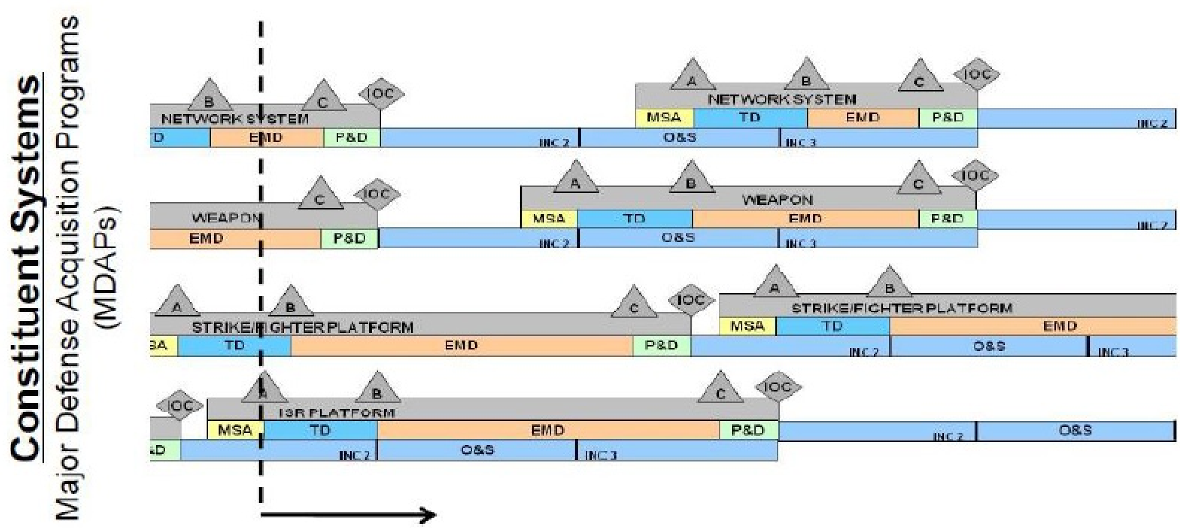

Figure 3. SoS Timelines (Herdlick, 2011)

required system functions" (Guarro, 2007, p. 14). More plainly, as one moves along the right side of the SoS "Vee," the Mission Assurance process ensures SoS success is documented in the context of mission success from the integration of systems to the operations and sustainment of the SoS. If individual systems meet their individual requirements but SoS interoperability and certification are not achieved, a reassessment of the requirements that were flowed down to the constituent systems is required to be performed in order to ensure individual capabilities combine to provide a more useful SoS capability. Similarly, if the SoS performs adequately but is unsupportable or unsustainable, its requirements will need to be reassessed. Another critical step in this process is the integration of the SoS's constituent systems.

The complexity of integrating systems in differing phases of acquisition illustrates that one of the most challenging roles of the LSI in SoSE&I is the integration of new capabilities with existing systems to support the SoS. While this integration has likely been planned, simulated, and tested in an MBSE environment, this is the first time when true system performance is experienced. Integration of the SoS is challenging even when it is controlled (Vaneman, 2016).

SoS Governance and Management

The final component of the SoSE&I "Vee" is SoS Governance and Management. While not formally described as a process, Governance and Management is a cornerstone of an effective SoS and is comprised of the set of rules, policies, and decision-making criteria that will guide the SoS team to achieve its goals and objectives (Vaneman, 2016). As the complexity of modern SoS increases, the multitude of technical and managerial activities involved become more entangled. As a result, a strong SoS governance and management approach is imperative to address complex emergent issues and those directly related to the triple constraint of cost, schedule, and performance.

Governance asks three fundamental questions. First, what will be managed at the SoS level? The SoS architecture and requirements provide some insights to the answers to this question. Being able to distinguish which SoS elements should be governed at the system level and which should be governed at the SoS level will help prevent an over-prescriptive governance structure (Vaneman & Jaskot, 2013).

The second question is, who has the accountability and decision rights across a broad set of stakeholders? This question determines the degree of participation, responsiveness, consensus, inclusiveness, and accountability needed in the governance strategy. It also guides how enforcement is managed within the SoS (Vaneman & Jaskot, 2013).

The third question is, how to implement the SoS governance structure effectively? The organizational structure, standards, policies, and the management environment must be understood to develop and implement effective governance. Governance must be consistent with the organization (Vaneman & Jaskot, 2013).

B. The Lead Systems Integration (LSI) Enterprise Framework

Lead Systems Integration is an acquisition strategy that employs a series of methods, practices, and principles to increase the span of both management and engineering acquisition authority and control to acquire an SoS or highly complex systems. LSI is effectively a marriage of program management and multiple functional disciplines that must work together cooperatively to assert and execute trade space in the SoS given multiple constituent system acquisitions. The LSI function is to assert and execute SoS and stakeholder trade space to affordably optimize integrated mission capabilities across the SoS lifecycle (Naval Postgraduate School Lead Systems Integrator [NPS LSI] Cohort #1, 2014). The roles of the LSI are similar to the roles of any systems engineer or system integrator within a program office. The primary difference is the span of LSI design and integration authority that persists throughout the SoS lifecycle (Vaneman & Carlson, 2017).

Levels of the LSI Enterprise Framework

To successfully plan, develop, and manage an SoS, a comprehensive development, acquisition, and implementation strategy is required. The SoSE&I "Vee" defines the activities required to engineer and manage an SoS throughout the lifecycle (Vaneman, 2016). The LSI Enterprise Framework defines a means to engineer and manage the capabilities and interdependencies of an SoS, that can be executed by the government LSI, across multiple systems, programs, and stakeholder levels. The LSI Enterprise Framework (hereafter known as the LSI Framework) captures the complex, interdependent, and mission capability areas through four enterprise levels to characterize the systems from the enterprise to the component level (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

Figure 4 depicts the levels of the LSI Framework. The Enterprise Level is the top layer of the LSI Framework that consists of a variety of stakeholders, from one or many organizations that represent the complex, socio-technical systems that comprises interdependent resources of people, information, and systems that must interact with each other and their environment to achieve mission success (Giachetti, 2010). It is at this level where the capabilities required to achieve enterprise mission success are defined, decomposed into mission capabilities, and allocated to the SoS level to be satisfied as mission capabilities (Vaneman & Carlson, 2018).

While the majority of the LSI engineering and management activities occur below the enterprise level, this level is important because this is where organizational, policy, and resource decisions are made for the LSI (Vaneman & Carlson, 2018).

The System of Systems Level is where a collection of supporting constituent systems and programs are brought together to support end-to-end capability effectiveness for the designated mission areas. Accomplishing a mission that cannot be satisfied by a single system alone has always been an SoS endeavor, but integrating the multiple systems together has frequently been left to small communities consisting of a few systems or the operators themselves (Department of the Navy, 2013). Many LSI governing efforts, at the System of Systems Level, involve a collaborative partnership of multiple program offices, versus a more directive effort that may occur at lower program levels (NPS LSI Cohort #1, 2015). Individual capabilities and functions are allocated to constituent systems for implementation (Vaneman & Carlson, 2018).

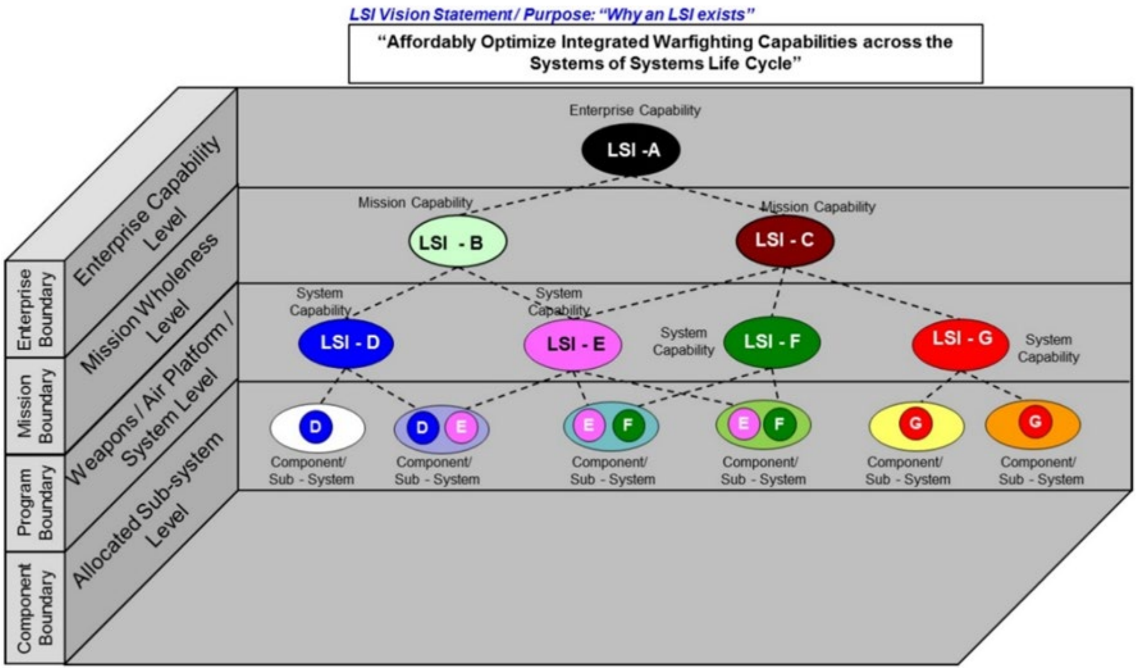

Figure 4. Lead System Integration Levels (NPS LSI Cohort #2, 2015)

The System Level is where a combination of functionally related physical elements are integrated into a usable system to achieve the system capability. In this level, the emphasis is on traditional systems engineering and development activities. However, two significant roles are important to the LSI. First, the LSI must ensure that the SoS level organization has sufficient insight into the individual programs within the SoS to understand the functionality and interoperability that will result from the engineering and design effort. Second, the LSI must ensure a strong governance model is in place that provides the technical authority to govern system baselines so that the system delivered for integration into an SoS meets the requirements that were allocated to it (Vaneman, 2016). In addition to the LSI's role in ensuring system integration to an SoS, an LSI may be used for the engineering and development of a complex system, where the system is composed of major sub-systems, and a large number of interacting components (Vaneman & Carlson, 2018).

The lowest level of the LSI Enterprise Framework is the subsystem/component level. This level consists of the allocated sub-systems and components that by themselves may, or may not, provide a usable standalone end product. These are the lowest level building blocks required for any LSI effort and may be managed by a team in a larger program office, or may be managed separately by sub-system program offices (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2018).

LSI functions in various levels occur at different places within an organization. For complex systems, these activities often occur within the program office. For SoS, the LSI function may occur as an executive level above the program office where they can exercise technical governance. Within each level, various types of LSI interactions and complexities are captured, and have multiple interfaces between program offices at the next lower and next higher levels to ensure proper communication and coordination is occurring throughout the SoS (Vaneman & Carlson, 2018).

The LSI has three especially important roles across the framework levels. First, the LSI must have sufficient insight of lower level of system decomposition. Second, the LSI must understand the role of the constituent systems in the SoS capabilities and requirements. And, third, the LSI must ensure there is a strong governance model that provides technical authority with a strong voice within the development and acquisition of constituent systems (Vaneman & Carlson, 2017).

LSI Touchpoints

Given the breadth of an SoS acquisition effort and recognizing that a government LSI's resources to manage an effort are limited, an LSI must be able to efficiently focus on the highest payoff "touchpoints" of control or influence to assert and execute trade space—aligned across the enterprise—to enable organizational agility. Although previous research has discussed inherently governmental functions for an LSI at a high level, there has been unclear specific applicability to current program processes and organizations—and some definitions also did not fully account for multidisciplinary functions that extend beyond systems engineering (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

The LSI Enterprise Framework defines 12 key touchpoints that apply across all domains as the essential high-payoff functions and activities. These LSI touchpoints are the functions that assert and execute SoS, complex system, and stakeholder trade space to affordably optimize integrated war fighting capabilities across the system of systems lifecycle. These touchpoints do not necessarily define new processes, but do identify how existing processes can be enhanced and used more efficiently (NPS LSI Cohort #2, 2015). Figure 5 depicts the traditional program office functions versus touchpoints required for an LSI (Vaneman & Carlson, 2017).

a. LSI Process Management. Responsible for mission wholeness, the LSI defines how their processes interface and interact with legacy processes across multiple stakeholders to meet unique SoS mission capabilities and trade space objectives. These standard work processes document the most efficient known method to produce a system or service, eliminating procedural waste and establishing a baseline for future process improvement initiatives. Standard work packages define process trigger conditions, objectives, enabling factors, inputs, functions, outputs, interfaces, and process time. Furthermore, these standard work processes are the foundation of effects-based staffing, which is critical to defining the skills and resources required to build and maintain an acquisition workforce capable of executing an LSI acquisition strategy (Vaneman & Carlson, 2017).

b. Communication. The LSI serves as the primary interface and facilitator across a diverse stakeholder constituency. Communications for the LSI is essential to manage multiple stakeholders and enable the organization to react with agility to requirements, design, or emerging stakeholder needs. All members of the LSI team should have a common understanding of assumptions, limitations, and constraints across the SoS (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

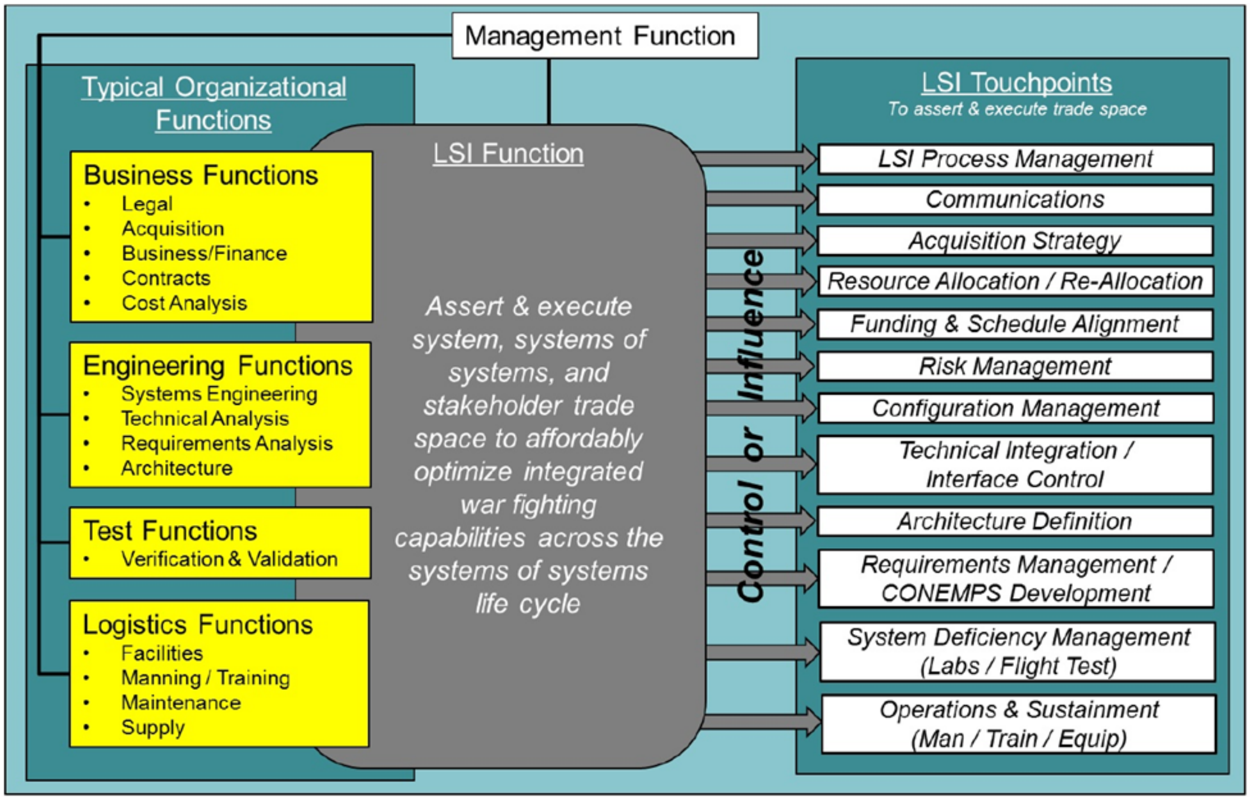

Figure 5. Program Office Functions vs. Lead System Integration Touchpoints (NPS LSI Cohort #2, 2015)

The continuous evolution of SoS capabilities, priorities, mission environments, assumptions, constraints, and threats, mandates unprecedented organizational alignment and enterprise agility. Due to the number of typically “stove-piped” teams and program offices, the need to communicate effectively is a key to success. The desired end state of this communication touchpoint is full programmatic, technical, and organizational alignment between the LSI acquisition objectives, and the objectives of the constituent systems (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

c. Acquisition Strategy. The LSI should serve as the principal SoS acquisition strategist. While the U.S. government has been assembling SoS for decades, there is often no overarching acquisition strategy. Given their broad responsibilities, the LSI is often in the best position to develop an overarching acquisition strategy that can be implemented across multiple independent and asynchronous programs and stakeholders to achieve the desired mission capabilities within the resource constraints (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

d. Resource Allocation/Re-allocation. The LSI is the primary arbitrator of enterprise resource allocations and re-allocations between constituent SoS elements and stakeholders. Requirements and risk mitigation plans should be properly funded across the integrated mission architecture in accordance with an LSI value maximization strategy to achieve the desired capability outcomes. Given the inherent volatility, uncertainty, complexity, and ambiguity of SoS mission environments, allocation of requirements and resources is an iterative process that occurs throughout the mission lifecycle (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

System of Systems asynchronous development schedules add a new degree of complexity to LSI resource allocation and re-allocation functions. Given the broad scope of constituent systems encompassed within many SoS mission architectures, it is unlikely that all elements will be in the same acquisition phase. In order to optimize SoS mission value across the SoS trade space, the LSI should also consider the overall mission readiness throughout the SoS lifecycle, including existing legacy operations and sustainment activities (NPS LSI Cohort #1, 2014; Vaneman, 2016; Vaneman & Carlson, 2017).

e. Enterprise Funding and Schedule Alignment. The handling of funding is an inherently governmental function. Enterprise funding and schedule alignment is especially challenging for the LSI since resources are usually budgeted by the resource sponsors to specific programs and systems, and not the SoS to satisfy enterprise or mission level capabilities. The LSI should be aware of dynamic funding, and schedule changes across multiple programs, and must align multiple asynchronous schedules of the constituent systems it may control (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

f. Risk Management. Risk management for an SoS is more complex than for traditional systems. Since there are likely many interdependent stakeholders and constituent systems in this effort, the LSI should expand the traditional definition of risk management from the system level and focus on risks at the SoS level. LSI risk management must maintain visibility of risks and opportunities of all systems and critical subsystems across the SoS trade space. The LSI defines alternative mitigation strategies to combine and normalize these risks across the SoS trade space (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

g. Configuration Management. Configuration management (CM) is the application of appropriate resources, processes, and tools to establish and maintain consistency between the system requirements, the system, and the associated system configuration information. This CM definition must be expanded to address the asynchronous CM across multiple interdependent stakeholders and constituent systems. This asynchronous CM is especially complex for an LSI that must establish and maintain the overall SoS CM baseline throughout the lifecycles for all system baselines. Since multiple system program baselines contribute to mission success, the LSI's CM baseline may change dynamically (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

Another challenging characteristic for the LSI is that each system may have a different way of managing its CM. Within each system there may be multiple "as designed," "as built," and "as delivered" configurations that may not be evident during the verification and validation phase. The LSI should be able to adjust for dynamic SoS loading to accommodate for these changes and constantly monitor and communicate within the team to ensure the SoS capability is still maintained (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

h. Technical Integration and Interface Control. Technical integration and interface control has a more significant role for the LSI bringing together an SoS, or complex system, than in traditional systems engineering. Since technical trade space management for an SoS occurs at the interfaces between constituent systems, the LSI should focus on enterprise technical integration and interface control. This effort is far more complicated than a traditional acquisition effort, since the technical maturity of the constituent systems within the SoS may be at different levels, and may also be changing at different rates (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

For systems early in the design lifecycle, the LSI should strive to ensure that the widest degree of interoperability is planned so that the system can participate to satisfy a wide range of mission capabilities. The LSI should work to influence design trade space decisions in systems that are in-development to promote risk reduction for interoperability issues. For the legacy systems, that may have been developed and fielded without consideration for inclusion into an SoS, the LSI should evaluate the system capabilities and technical scope to determine if the system can be used in an SoS to support mission capabilities and recommend potential solutions that would enable the legacy system to contribute to the SoS (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

i. Architecture Definition. An architectural definition for an SoS, preferably developed and hosted in a Model-Based Systems Engineering (MBSE) environment, is essential for engineering, analysis, and management of the SoS. The SoS architecture provides a technical blueprint of the SoS, showing the traceability of functional and derived relationships among all constituent systems. The architectural viewpoints enable stakeholders to visualize, define, and bound the component systems, and SoS, to identify integration points both inside and outside the systems. From these views, system interoperability issues can be identified. With proper CM, and use of compatible databases, new systems entering the SoS family may more easily integrate from an LSI standpoint and where all disciplines can see integration impacts, dependencies, and interoperability concerns (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

The LSI should place significant effort and value in the overall SoS architecture, since this architecture defines the interfaces for trade space management across the SoS. When defining and maintaining this SoS architecture, the LSI may be required to integrate the architectural data in various architecture tools used by different stakeholders and establish some method for overall architecture configuration management across these multiple databases and stakeholders (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

j. Requirements Management and Concepts of Employment. Once a preferred SoS concept is established, the LSI allocates requirements, functions, interfaces, and constraints across constituent systems. This task is especially challenging since the LSI must consider enterprise requirements management and concepts of employment (CONEMPS) across multiple systems and stakeholders. The stakeholders may each hold different assumptions, limitations, or constraints about the expected use of systems, and the mission requirements for the SoS. Constituent system decomposition and integration may also change dynamically or emerge during the evolution of the mission capabilities during SoS lifecycle. Requirements management for the LSI is further complicated since the allocation of requirements and resources may be iterative and ongoing across elements that the LSI may not control. The LSI should align requirements, assumptions, limitations, and constraints at the capability level for the overall SoS effort. The CONEMPS may be used as one tool to energize early user and resource sponsor involvement to align stakeholders (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

k. System Deficiency Management. Systems of systems deficiency management, supported by laboratory and operational verification and validation activities, is challenging for LSIs in complex mission environments involving multiple programs and stakeholders. The LSI should determine the impact of constituent systems deficiencies at the SoS level. The LSI should also determine the best way to mitigate these deficiencies. The use of simulations and prototypes representing each constituent system that comprises the SoS is a cost effective method that can be used for early integration risk reduction, may help to refine requirements, and identify additional requirements and constraints at the SoS level that may not be apparent at the system level (Vaneman & Carlson, 2017).

Another approach the LSI may employ to manage system deficiencies is to leverage simulations in live, virtual, and constructive environments. The live, virtual, and constructive test and evaluation approach permits "confidence" evaluations of SoS capabilities and allows for systems, weapons, networks, and sensors to be tested against the most realistic environments and concepts of operationally-based scenarios (Vaneman & Carlson, 2017).

l. Operations and Sustainment. The LSI's challenge of affordably optimizing integrated system capabilities across the SoS lifecycle is more complex than in a traditional acquisition effort since it may involve multiple independently developed support strategies, or existing legacy system support strategies, across the systems in the SoS which may also be at different levels of maturity. The LSI must understand the support requirements for the entire SoS so that the logistical requirements can be allocated effectively to the constituent systems and supporting stakeholders. The logistics support system should be evaluated across the SoS lifecycle to ensure operational supportability with specific attention to minimizing the logistics footprint. Sustainment costs should also be considered during system development and evaluated during testing to ensure that when the SoS capability is fielded, the sustainment costs to support the system are within the constituent systems and/or the LSI's SoS budget (NPS LSI Cohort #2, 2015; Vaneman & Carlson 2017).

Universal Enabling Resources

Universal enabling resources are those resources that support LSI-unique execution at any of the touchpoints to assert and execute the trade space. The four enabling resources and inter-related enablers apply at all levels in the LSI Enterprise Framework, and are outside the responsibilities of the typical program offices. However, the LSI must be aware of these activities and navigate within them. The four enabling resources are hereby introduced to ensure completeness in the discussion, and are shown in Figure 6 (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

a. Staffing and Workforce Development. Due to the unique nature of operating in a complex SoS environment and executing LSI efforts, staffing and workforce development requires an additional depth of focus and tailored enhanced knowledge, skills, and experiences beyond that required in traditional acquisition programs. Typical organizational functions supporting the touchpoints should be staffed by personnel trained with the requisite expertise and knowledge of operationally relevant environments at the various LSI Enterprise Framework levels (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

b. Authoritative Data in Context. The complex nature of the SoS environment makes asserting and executing the trade space essential, and creates the need for sound, authoritative data across systems. In any LSI effort, everyone must have the same data, and have a way to validate the authenticity, and accuracy, of the data to be used for decisions. "Authoritative Data in Context" includes a comprehensive integrated set of programmatic, technical, and stakeholder data that enables a shared common understanding of the trade space (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

c. Policy. Policy consists of the technical, organizational, and legal guidance and constraints of the LSI organization. This may include public law, civil mandates, legal rulings, competency policies, certification requirements, and other overarching guidance that must be accounted for by an LSI when executing any of the touchpoints at any level. These policies provide common guidance across the organizational levels, though the relative impact and flexibility of these policies may vary (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

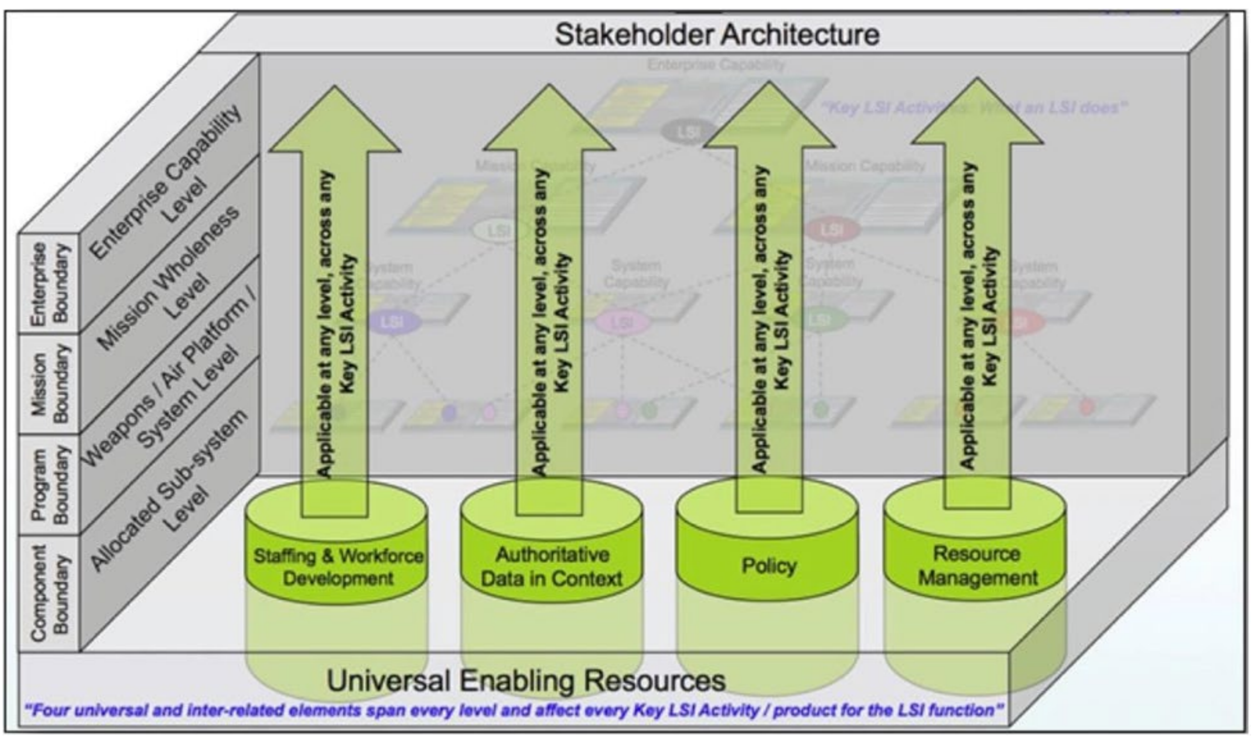

Figure 6. Lead Systems Integration Universal Enabling Resources (NPS LSI Cohort #2, 2015)

d. Resource Management. Resource management includes a cost, schedule, and performance resource triad that captures the relationship between the financial, timing, and capability aspects of the total system. When considered against a set of requirements, the resource triad is necessarily constrained by limiting the available resources to a bounded set (NPS LSI Cohort #2, 2015; Vaneman & Carlson, 2017).

The LSI Framework Assembled

Figure 7 (NPS LSI Cohort #2, 2015) depicts the LSI Enterprise Framework assembled from the four layers, the LSI Touchpoints, stakeholder architecture and governance, and the universal enabling resources. This framework allows for the alignment of key LSI activities across the enterprise be aligning the appropriate touchpoint to the various LSI levels and tasks. The framework identifies the internal and external organizational dependencies through the stakeholder architecture. Through the universal enabling resource, staffing and workforce development, policies, resource management, and the authoritative data context can be applied as required throughout the enterprise. Finally, governance empowers decisions across the enterprise by providing a set of decision-making criteria, policies, processes, and actions that guide the stakeholder architecture to achieve the enterprise goals and objectives (Vaneman & Carlson, 2018).

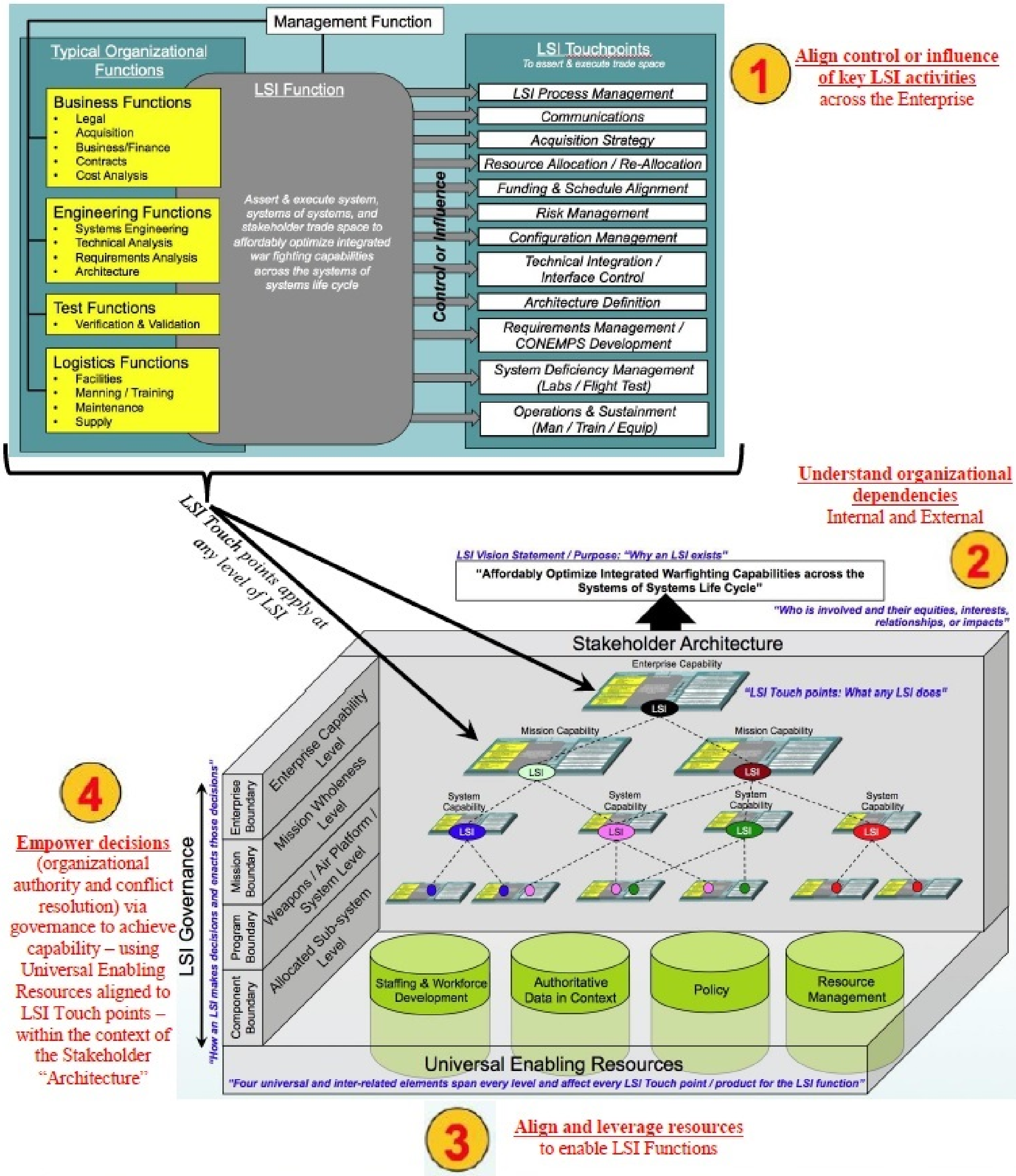

Figure 7. Enterprise Lead Systems Integration Framework (NPS LSI Cohort #2 2015)

C. Navy Integration and Interoperability

The Navy Integration and Interoperability (I&I) documentation provides SoS and governance processes to identify gaps in naval missions, and to develop, and coordinate, solutions across system boundaries. To identify the mission gaps, system interaction and behaviors are derived from and enterprise view of naval operational environments and mission objectives (Department of the Navy, 2016). Navy I&I is an important concept to this LSI research because, I&I provides detailed processes in the SoS Architecture and Requirements phase of the SoSE&I "Vee." The LSI Enterprise Framework only provides a general overview of the needed processes.

The process is largely focused on the Mission Engineering "Vee," as depicted in Figure 8 which is very similar to the SoSE&I "Vee," and the process can easily be extrapolated to SoSE&I.

The Integrated Capability Framework

The Integrated Capability Framework (ICF) was developed to provide the backbone for I&I. The guidelines established by the ICF are as follows:

- Defines the mission capabilities, measures of effectiveness, and associated operational conditions and constraints;

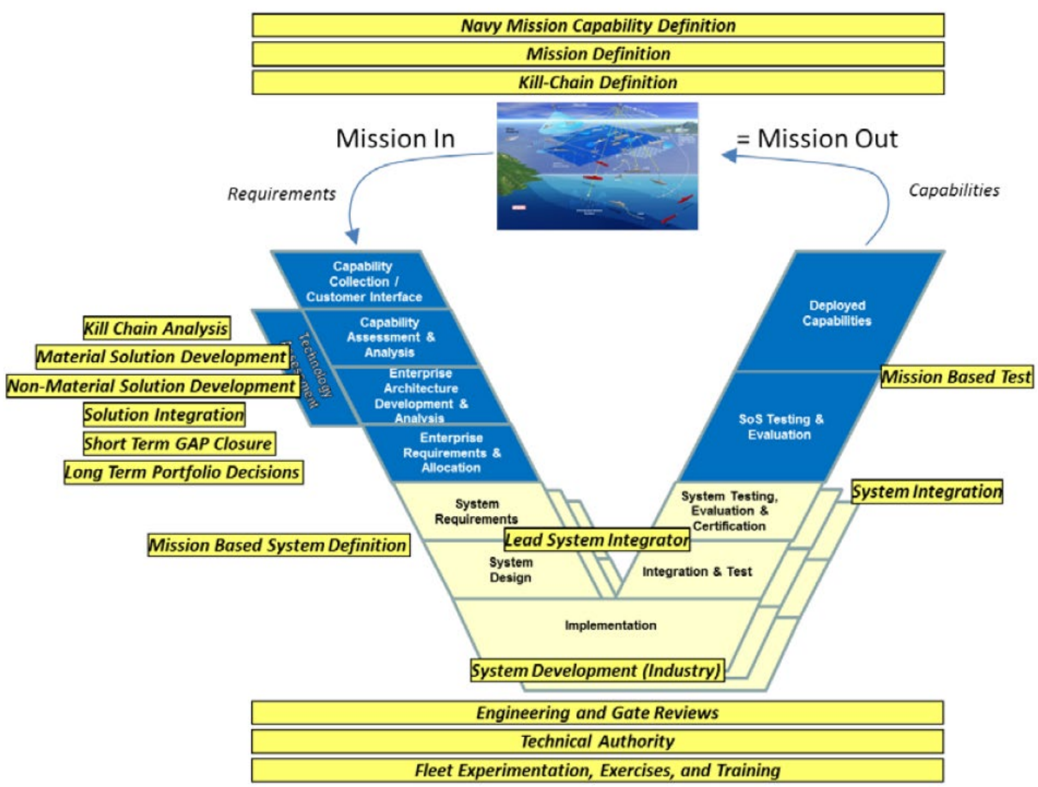

Figure 8. ICF Use Cases Applied to Mission Engineering

- Aligns mission requirement to system capabilities;
- Identifies SoS interfaces and measures of performance through the structured decompositions of the mission capabilities;
- Provides a common framework that facilitates enterprise level engineering across Naval System Command and Program Executive Offices;
- Establishes enterprise data structures and implementation guidance to facilitate a disciplined, and iterative, development of enterprise architectures;
- Provides constituent system program managers with a comprehensive set of interoperability requirements, and the knowledge of which systems, interfaces, and behaviors need to be designed and developed to support mission requirements. (Department of the Navy, 2016)

A discussion of the ICF elements follows.

a. ICF Data Model. The ICF Data Model provides the data structure, taxonomy, and relationships needed to define a Naval mission. The data model ensures commonality among the products, views, and data, and helps communication and collaboration by using a common taxonomy from authoritative sources such as Navy and Joint Policy and Guidance (Department of the Navy, 2016).

b. ICF Mission Model. The ICF Mission Model defines the operational perspective of the mission. The Mission Model captures the required operational capabilities, and uses the relationships captured the systems functional, interface, and performance requirement that were identified in the ICF Data Model. The Mission Model includes the tactical situation (TACSIT) or operational situation (OPSIT), mission threads including the rules and measures of performance, and the required information exchanges and system functions (Department of the Navy, 2016).

c. ICF System Baselines. The ICF System Baselines define functional capabilities and associated measures of performance; mapping IT system to nodes (e.g., ships, aircraft), networks, and communication paths between systems and nodes; and the established baseline or technical standard (Department of the Navy, 2016).

d. ICF System-Mission Alignment Module. The ICF Systems-Mission Alignment Module uses the relationships established in the ICF Data Model to link System Baselines to Mission Models to completely describe one or more missions. The output is a linked set of products and views, that provide the context needed for definition, analysis, and evaluation of mission capability, definition of mission need, and identification of potential I&I issues (Department of the Navy, 2016).

The I&I Process

The I&I process begins with a Warfare Capability Baseline (WCB) assessment which "uses the concept of a kill chain to organize, or model, the functions performed in the execution of a mission" (Department of the Navy, 2016, p. 12). The goal of the I&I process is to accomplish four distinct tasks:

- Address materiel gaps identified by the WCB;
- Build mission-based architectures as a basis for system acquisition;
- Use I&I decisions as a driver to SE reviews and gate processes; and
- Share mission related information across Systems Commands (SYSCOMs).

Through the I&I process, the Navy can improve their ability to effectively assess missions from an end-to-end perspective, across system boundaries, whether operating in as single service, or as part of a Joint or Coalition Force (Department of the Navy, 2016).

As it relates to the SoSE&I "Vee," the first step in the I&I process is the definition of the mission needs and requirements. The significance of this important first step is that it establishes the needs for system development or the constituent systems within the SoS. The mission needs and requirements serve as the primary input to the SoS Architecture and Requirements Development portion of the SoSE&I "Vee," and provide a constant reference for technological progress checks. Figure 9 depicts this mapping of the Mission Capability Objective to the SoS Technical Performance Requirements.

Following Mission Definition, I&I establishes the SoS interfaces involved based on the required mission parameters, requirements, and capabilities. This accounts for organizational relationships and helps to define SoS capabilities and needs. The common framework provided by I&I seeks to "facilitate enterprise level engineering across the SYSCOMs and enables efficient system integration and effective force interoperability" (Department of the Navy, 2016, p.5). This helps lay the ground work needed for individual system design and development.

The vision for the ICF includes an I&I Engineering Environment, as depicted in Figure 10 (Department of the Navy, 2016). This environment would be a repository for all data sources, products, and analysis/use cases from the I&I process. Having a single repository would enable "common implementation of framework (products), manage interfaces, behavior, and engineering standards across I&I communities, and support I&I analysis" (Department of the Navy, 2016).

The I&I ICF is intended to support the warfighter through a mission-based focus on SE, support to the acquisition process by identifying consistent requirements for the SoS early in the process and assisting with analysis efforts through a common I&I repository. Though the I&I ICF is intended to span the Mission Engineering "Vee" (or

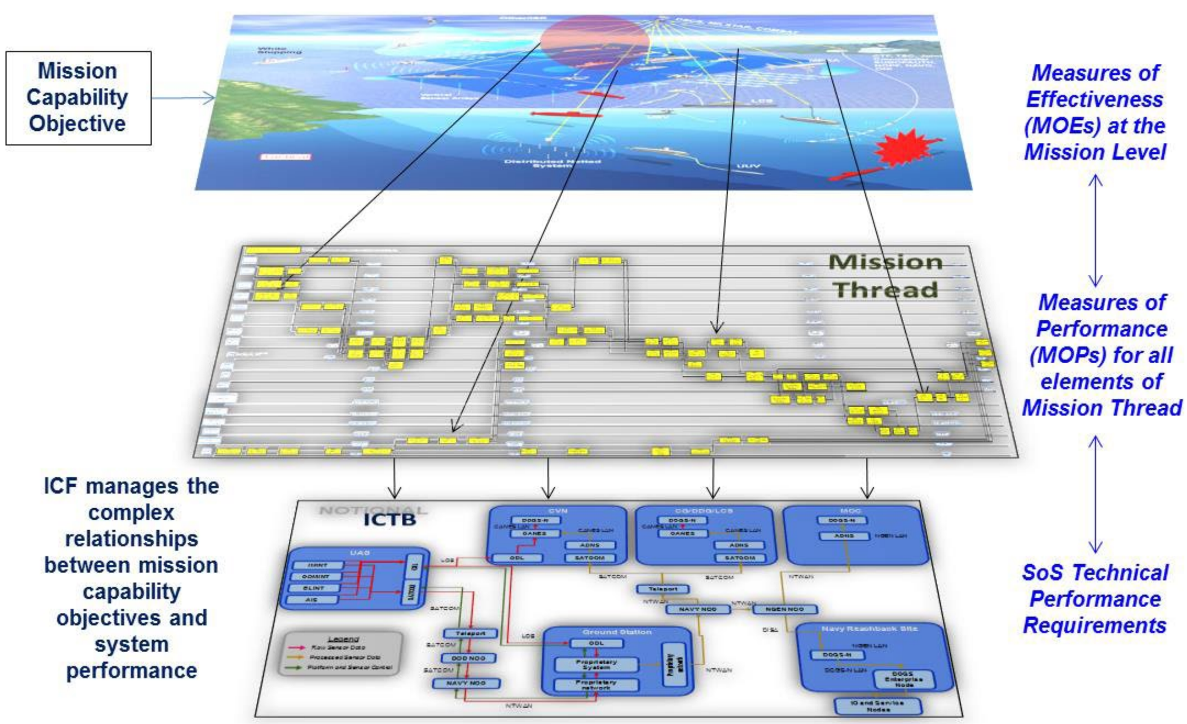

Figure 9. I&I ICF Vision (Department of the Navy, 2016)

SoSE&I "Vee"), it is largely focused on requirements and interface definition and does not provide much SoSE&I detail. As such, the process does not stand on its own. This research intends to incorporate the I&I ICF into the larger LSI process.

Use of the ICF enables consistent and more complete definition of Naval warfighter needs, and ensures that all stakeholders from initial concept to test and training understand what the definition of success is for any new or upgraded system. Additionally, training and testing efforts can use the same missions defined in the front end to perform the operational tests and training exercises, ensuring that the systems and sailors are tested and trained in accordance with planned missions. Use of Fleet-defined operational requirements, captured through ICF Mission Models, helps system and platform requirement definition and design, providing a validated and complete mission context including planned operational use during system

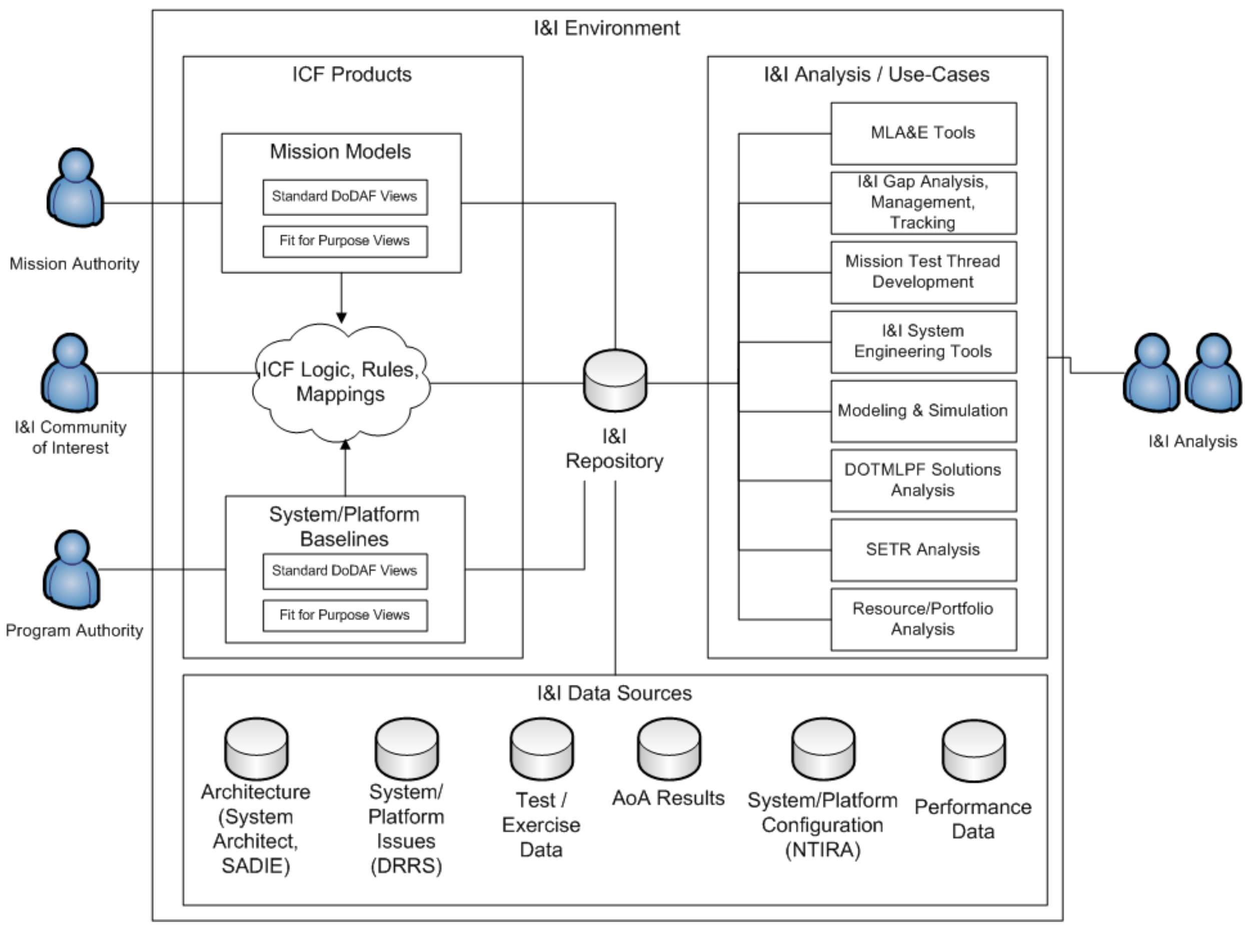

Figure 10. I&I Repository Vision (Department of the Navy, 2016)

development. The mission definition also provides system and platform owners with a thorough set of interoperability requirements and ensures existing capabilities are not duplicated. Finally, when completed with operational and system/platform measures tied to mission desired effects, the ICF enables analysis of I&I issues and mission gaps, and the tracking of closure for each one within the SoS (Department of the Navy, 2016).

D. Relationships Between Processes

LSI and Navy I&I touch on various aspects of the LSI process, but neither are complete or highly correlated. The LSI Enterprise Framework represents the process, at a high level, so it can be used to better understand, engineer, and manage an SoS. However, it does not provide the necessary detail for operational use. Navy I&I discusses portions of the SoSE&I "Vee," in more detail than is offered by the LSI Framework, and could be used to better define the SoS. However, Navy I&I is mostly concerned with the SoS Architecture and Requirements Development Phase of the SoSE&I "Vee." However, I&I includes the only discussion of test and evaluation that is found in the Mission Assurance Phase of the SoSE&I "Vee," and minimally at that.

The concepts in this chapter are analogous to the strategic level of planning in the military sense. They provide good definitions and guidance, but lack specific operational details. Chapter III expands these concepts, to be analogous to the operational level in a military sense, so that they can be better used to engineer and manage SoS, to provide better mission support.

III. Methodology

> Twenty-first century acquisition is fundamentally more complex than previous acquisition approaches, in that today's systems not only need to be more highly capable than before, they need to be built more quickly, and at less cost.
>
> —Rosenthal, Sheard, & Neuendorf (2012)

As discussed in Chapter II, the Navy has been exploring, and developing, strategies and approaches to address the engineering and acquisition challenges associated with SoS development, composability, and sustainment. Lead Systems Integration, and Navy I&I, have emerged as the leading strategies. While each strategy offers insights, and partial solutions, to the challenges posed by the SoS engineering and acquisition environment, neither addresses the problem that spans the entire SoS lifecycle. One of the goals of this research is to expand the LSI concept by defining an implementation strategy that can used across SoS lifecycle phases and organizational boundaries.

The common denominator between LSI, Navy I&I, and IT/TA (discussed briefly Chapter I), is that each uses the SoSE&I "Vee" as it's foundation. Navy I&I provides a more detailed strategy than LSI, but is focused primarily on the SoS Architecture and Requirements Development phases. LSI is more broadly defined, but lacks the details sufficient for an implementation strategy that can be used across the SoS lifecycle. The LSI implementation strategy, developed in this chapter, capitalizes on the strengths of Navy I&I and LSI, while continuing to use the SoSE&I "Vee" as the foundation.

A. Developing a Common LSI Implementation Strategy

As shown in Chapter II, the SoSE&I "Vee" can be portrayed as the abridged "Vee," showing the four top level in phases (Figure 1), and the unabridged "Vee" (Figure 2), showing the decomposed functional activities for each phase. However, these decomposed activities are where the SoSE&I "Vee" detail stops. The "Vee" model does not include the inputs and outputs for each phase, the rules and policies governing the activities, or the skills needed to perform those activities. These elements are needed to develop an LSI implementation strategy.

The Integrated DEFinition (IDEF) function model (IDEF0) was selected to help define the LSI implementation strategy since the model includes the system function, inputs and outputs, controls or governing rules and policies, and mechanisms that represent the elements that perform the function.

Using IDEF0, the SoSE&I process can be represented by IDEF0: the functional activities are represented by the SoSE&I functional activities; the inputs and outputs are represented by the inputs to, and outputs from, each SoSE&I functional activity; the controls are represented by SoS Acquisition Policies, Navy SoS Acquisition Position Mechanisms, LSI touchpoints, and Navy I&I ICF; and the mechanisms represent the SoS acquisition position descriptions (knowledge, skills, and abilities) needed to perform the functional activities. Figure 11 illustrates the Level 0 SoSE&I IDEF0 model.

Each of the SoSE&I functions were analyzed for inputs, outputs, controls, and position descriptions. (The position descriptions shown in the models throughout this report are generic because this aspect of the model was outside the scope of this research.) Using this construct, the Navy I&I and LSI processes were analyzed to determine how they may further govern the SoSE&I functions. Figure 12 shows the SoSE&I “Vee” as an IDEF0 model (Level 1).

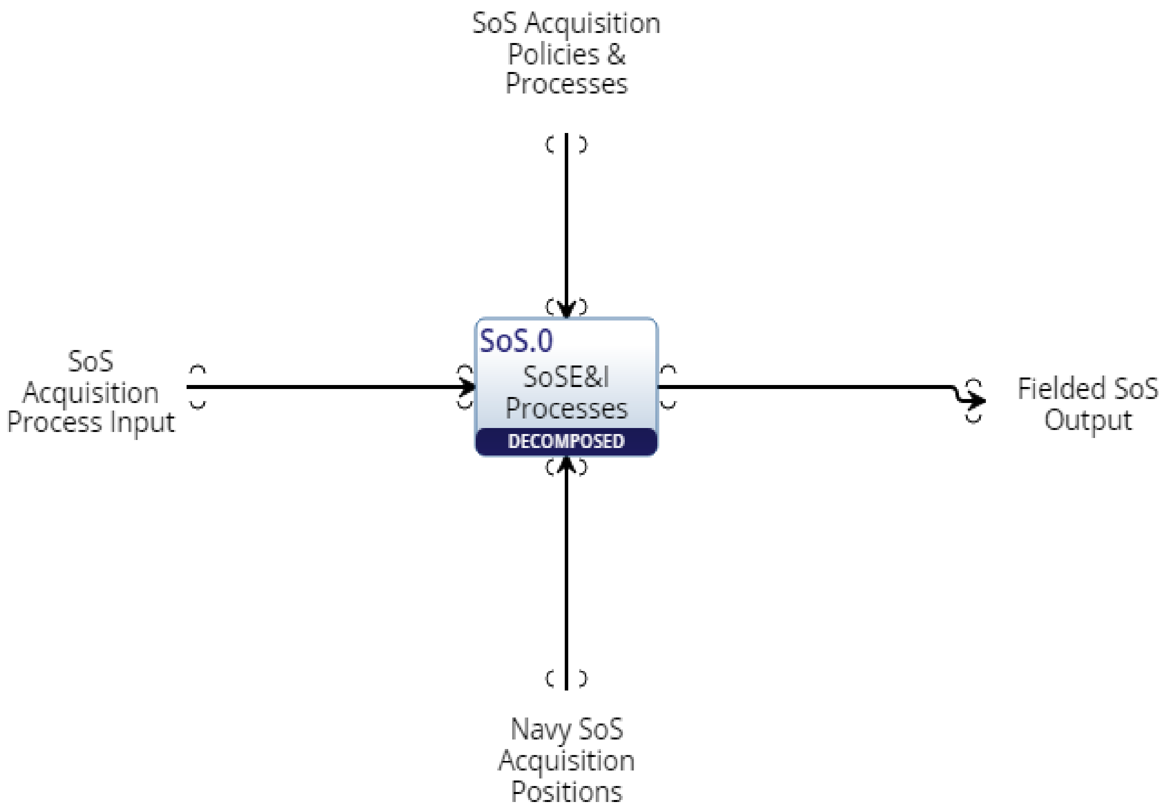

Figure 11. SoSE&I IDEF0 (Level 0) Model

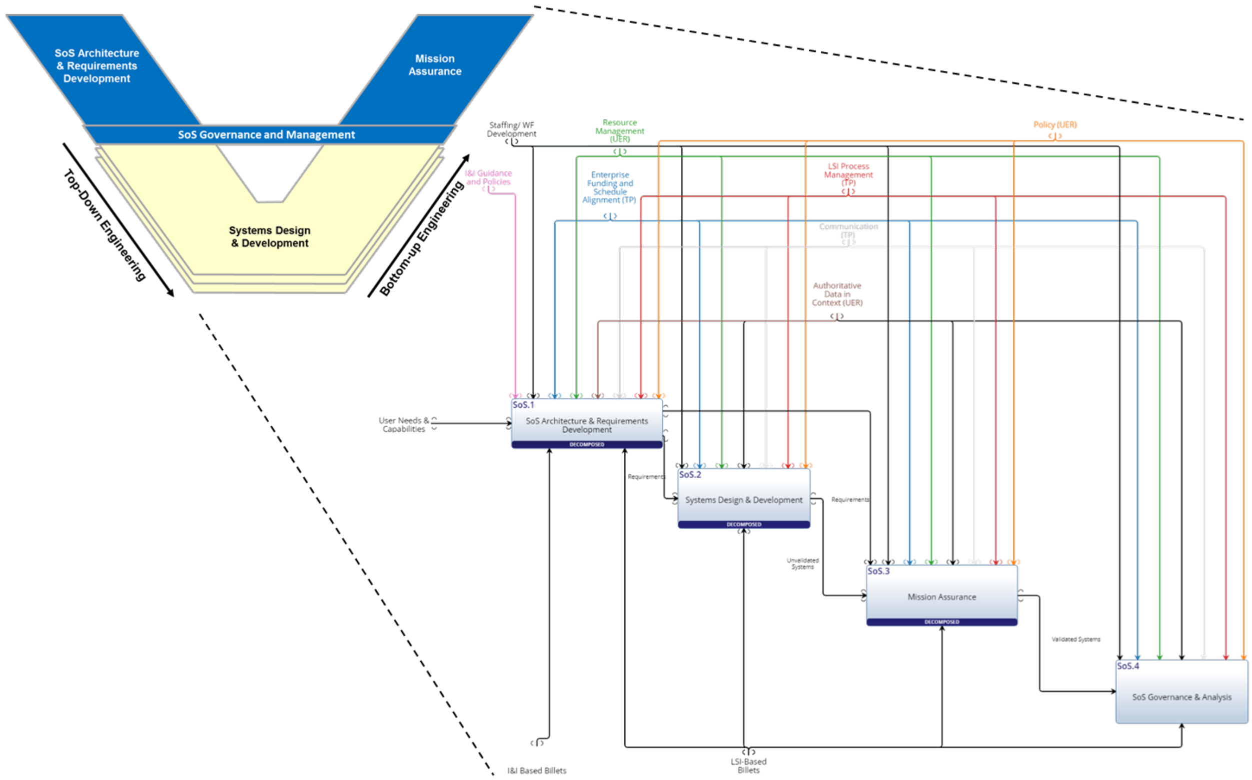

Figure 12. SoSE&I "Vee" Viewed as an IDEF0 (Level 1) Model

As discussed in Chapter II, 12 high-payoff LSI Touchpoints were identified as a part of the LSI Framework. Through the process of this research, it was discovered that some of these LSI Touchpoints could be modified or combined to create a more generalized definition to be used in this current research. One of these touchpoints was Resource Allocation/Re-Allocation. It was determined that the LSI Touchpoint Resource Allocation/Re-Allocation could be combined with the Enterprise Funding and Schedule Alignment Touchpoint. As stated in the LSI Cohort #2 (2015) report, "LSI Touchpoints do not necessarily define new processes—but they do identify how existing processes can be enhanced and used most efficiently by the LSI." Throughout the model, instead of using both the Resource Allocation/Re-Allocation and Enterprise Funding and Schedule Alignment Touchpoints, only the Enterprise Funding and Schedule Alignment Touchpoint will be used as depicted in Table 2.

Table 2. LSI Enterprise Funding and Schedule Alignment Touchpoint Combination

LSI Touchpoints	SoSE&I Control
Resource Allocation/Re-Allocation	Enterprise Funding and Schedule Alignment
Enterprise Funding and Schedule Alignment	

Another change from the aforementioned documents involved the consolidation of numerous LSI Touchpoints into one overarching LSI Process Management Touchpoint, depicted as a control in Figure 13. Figure 14 details which LSI Touchpoints are considered to be subordinates of the LSI Process Management Touchpoint, which is depicted in each of the Level 2 diagrams throughout this report. This was done to simplify the higher Level 1 diagram for readability purposes.

Finally, the definition for the Operations and Sustainment Touchpoint must be slightly augmented. The definition was augmented to include the support requirements for the total SoS, as well as considerations for sustainment costs and total lifecycle management—both of which were missing from the initial definition. The remainder of the controls' definitions can be taken as-is from their respective guiding documents.

The individual functions. Inputs, outputs, and control, and positions were further decomposed to into sub-functions in the Level 2 diagrams, discussed in the following sections.

B. SoS Architecture and Requirements Development

The first phase of this SoSE&I process model is SoS Architecture and Requirements Development. The activities in this phase are related to the design and definition of the SoS. As depicted in Figure 15, these activities are defined as Technology Assessment, Capability Collection/Customer Interface, Capability Assessment and Analysis, SoS Architecture Development and Analysis, and SoS Requirements and Allocation.

The purpose of the SoS Architecture and Requirements Development phase is to provide a "comprehensive plan to align systems that are meant to work together for mission success, provides a foundation from which Resource Sponsors can prioritize user needs and budget issues, and establish an overarching requirements baseline to improve Integration and Interoperability across the SoS" (Vaneman & Carlson, 2018, p. 14).

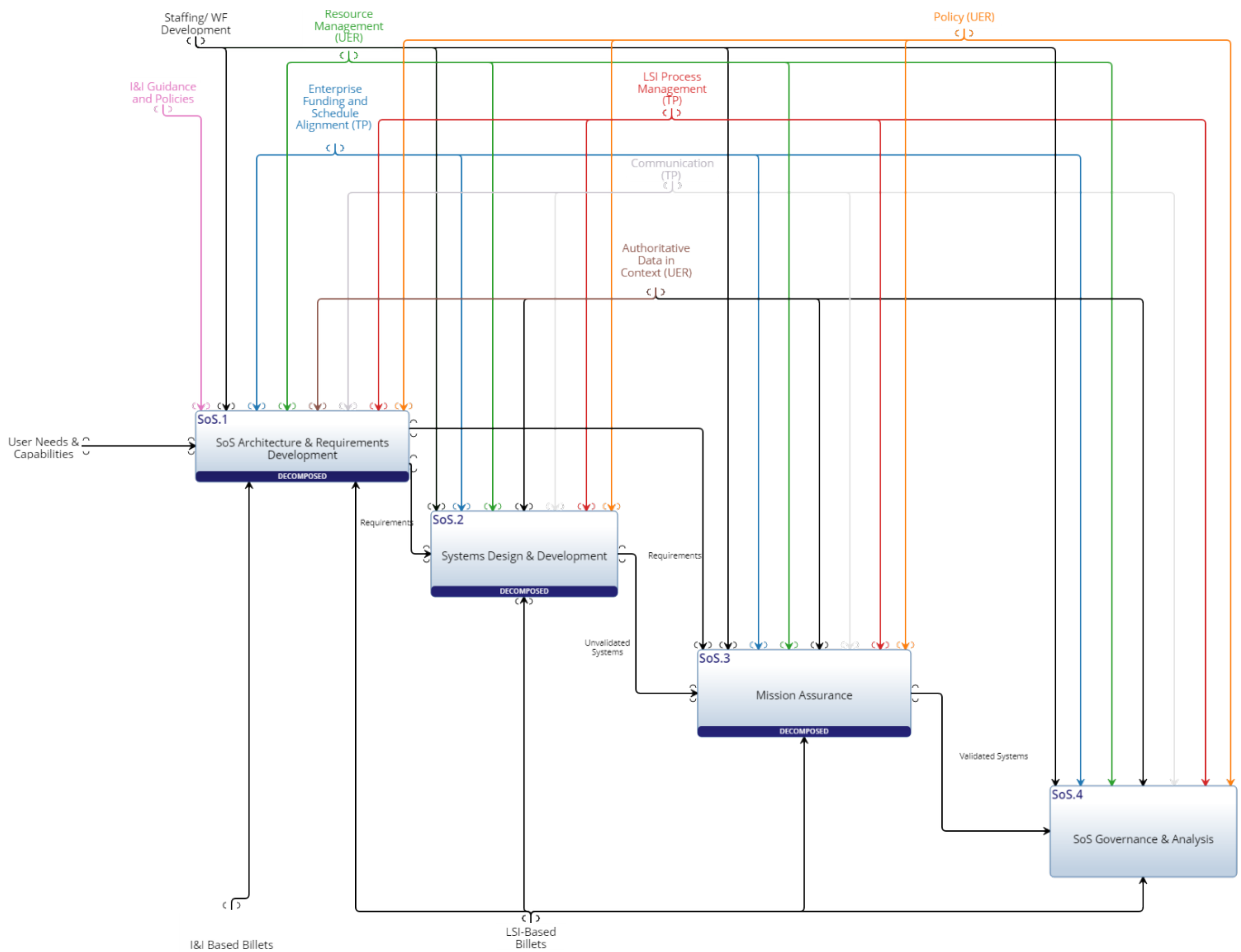

Figure 13. SoSE&I Activities (Level 1)

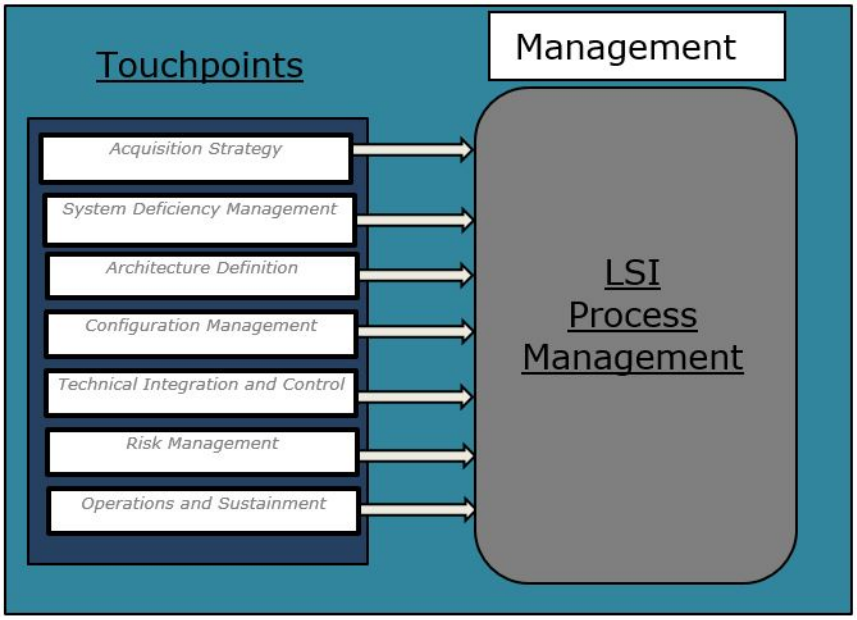

Figure 14. LSI Process Management Touchpoint Combination

The decomposition of the SoS Architecture and Requirements Development stage, as depicted in Figure 16, relies heavily on existing I&I and LSI processes to provide the guiding principles, or controls. When depicted in this fashion, it is clear that neither the existing I&I processes nor LSI Touchpoints covered the entirety of this phase. However, once combined, a more complete process begins to emerge.

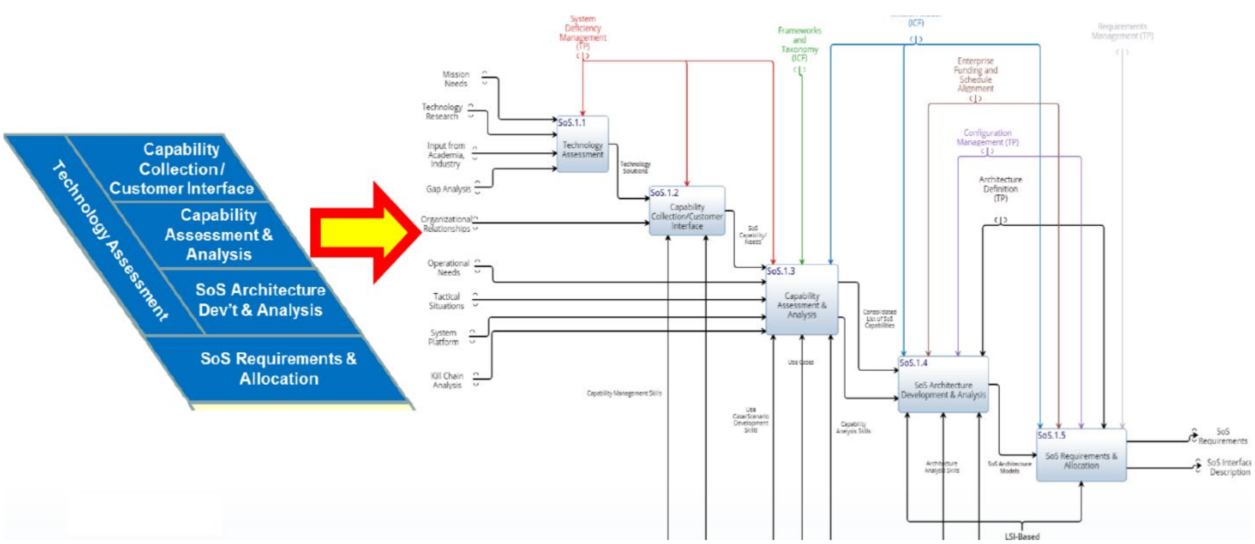

Figure 15. SoS Architecture and Requirements Development Phase Decomposed

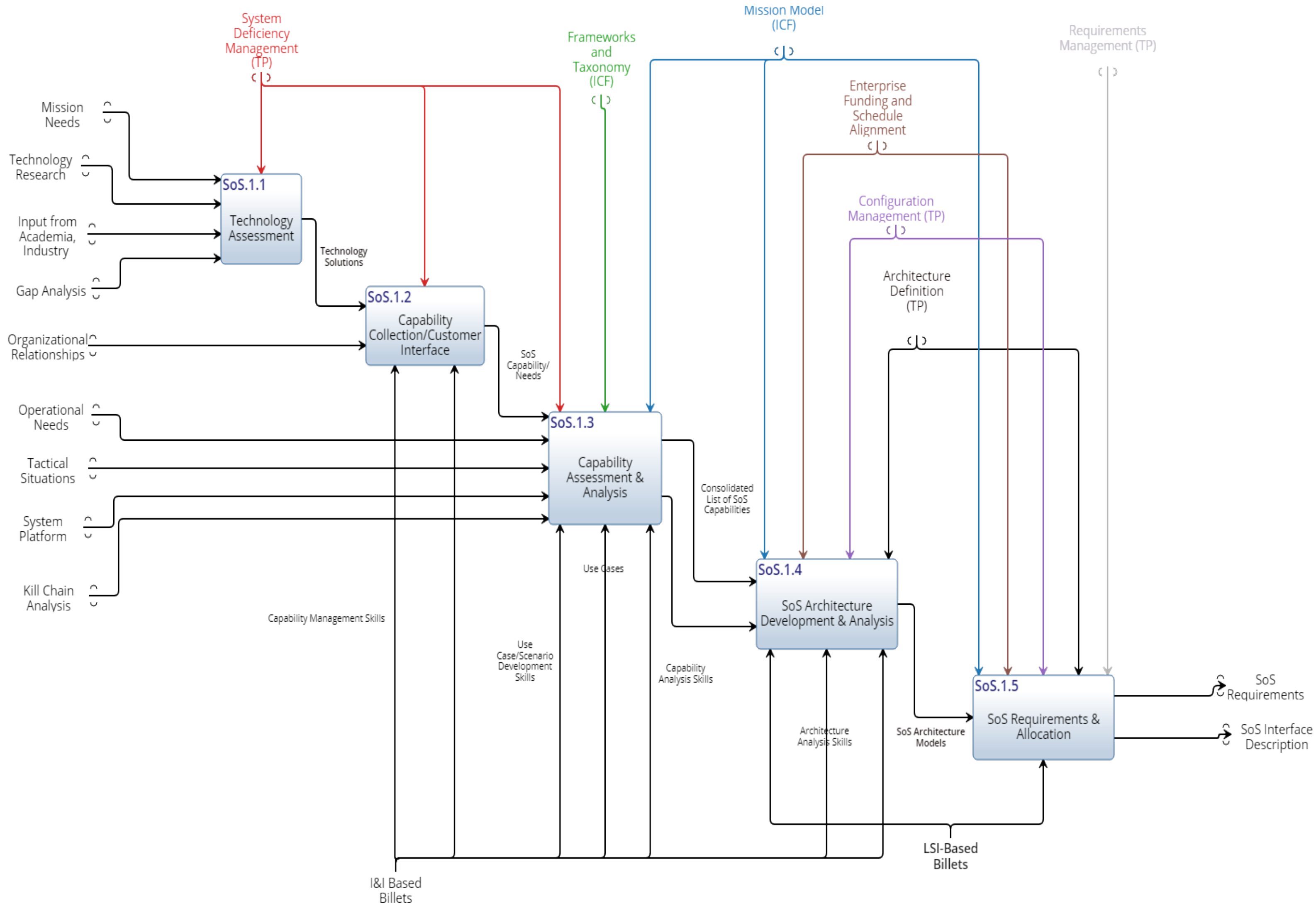

Figure 16. SoS Architecture and Requirements Development Phase (Level 2)

As with any requirements-based program designed to target a specific solution, one must first look to define what is required to meet the needs of the customer and begin with a Technology Assessment (SoS.1.1). This is no different in the case of SoSE&I, where the initial inputs to the process consist of: mission needs, technology research, industry/academia inputs and feedback, and gap analysis. Of those four inputs, the most fundamental and essential input is the mission needs, which is the primary driver for developing an approach to a solution. Combining the capabilities required to complete the mission with an effective gap analysis yields the complete set of capabilities that must be developed in order to field a complete and successful SoS. The technology research and academia/industry input provides a solution or set of possible solutions to satisfy the capabilities/requirements identified.

The next activity is Capability Collection and Customer Interface (SoS.1.2). During this activity, inputs from various stakeholders are collected, and extracted, from a wide variety of authoritative sources (e.g., Capability Description Documents [CDD], Joint Capability Documents [JCD], Concept of Operations [CONOPS], Concept of Employment [CONEMPS]), that the SoS is required to satisfy.

The output from SoS.1.2 transitions into the Capability Assessment and Analysis phase (SoS.1.3). This activity weighs the capabilities of the SoS with the tactical and operational requirements to help further validate the scope of the system(s). The capabilities are analyzed into similar capability groupings. Given that the SoS capabilities are gleaned from several authoritative sources, and perhaps from a wide-variety of stakeholder organizations, the grouping of these capabilities into thematic topics is important for capability management. The capabilities are then reviewed to determine duplication, which is highly probable given the wide-range of sources. The capabilities are then mapped to existing systems and programs. Where a mapping doesn't exist, a potential capability gap exists. Finally, the relative priority for each activity is determined and assigned.

During the first three activities, the LSI ensures that any shortfalls are addressed through system deficiency management. The I&I ICF mission model incorporates the operational requirements and required capabilities at the task/interface level, which assists in defining the system requirements to support the mission capability. ICF frameworks and taxonomy incorporate a variety of documentation to derive a baseline for identification and use of terminologies which allows the mission analysis to be effective (Department of the Navy, 2016).

Once the list of SoS capabilities and definitions are consolidated, the SoS Architecture Development and Analysis activity (SoS.1.4) is used to generate the SoS architecture models. A series of mission threads, often defined by kill chains or tactical situations (TACSIT), which correlates to the operational need(s), typically establishes the context for the architecture and analysis efforts. This activity leverages many of the concepts from the Navy I&I process and ICF document.

The architectures developed in SoS.1.4 is the basis for the SoS Requirements and Allocation phase (SoS.1.5) activities. This activity derives SoS requirements and interface specifications from the SoS architecture, thus maintaining traceability from the user capability needs, to the architecture and analysis, to the requirements. The requirements developed by this activity are those that are required for SoS to perform satisfactorily, and typically are not found in individual system requirements. Since funding is allocated at the program level, not the SoS level, the requirements are typically allocated to the appropriate program office, for inclusion in acquisition plans and program baselines. The allocated SoS requirements are managed under formal configuration control, and tracked for progress throughout the life-cycle of each individual system.

The SoS Architecture and Requirements Development Phase allows the LSI to comprehensively plan for the alignment of systems that are meant to work together for mission success. A comprehensive plan provides the LSI with the foundation from which program managers, and resource sponsors, can prioritize user needs and budget issues. Lastly, this phase allows the LSI to establish overarching requirements baseline to improve integration and interoperability across the SoS.

C. Systems Design and Development

The second phase of this SoSE&I "Vee" is System Design and Development. These activities focus on the development, sustainment, and management of individual systems. Several "Vees" are shown concurrently to illustrate that several constituent systems are developed and managed concurrently, with each system at different maturity levels within its own life-cycle (Vaneman & Budka, 2013). The activities within this phase are related to the individual constituent system's design and development. These activities are defined as System Requirements, System Design, Implementation (Development and Manufacturing), Integration and Test, and System Testing, Evaluation, and Certification.

The LSI must perform two important SoSE&I activities, during this phase, to ensure a successful SoS. First, the LSI must have sufficient insight into the system development, sustainment, and management to ensure the system is compatible with the SoS. This is an important point because as decisions are made for individual systems, it is easy for those decisions to be contrary to the stated mission of the SoS. When individual system decisions impact the interoperability of the system to be able to work with the SoS, the decision must be elevated to the SoS governance-level for resolution (Vaneman & Budka, 2013).

Second, understanding constituent system functionality and programmatic issues is critical since systems in a SoS rely on each other to achieve mission success. Issues such as system program delays are critical since other systems who depend on upstream information may not be able to fulfill their missions within an SoS. System retirements are also an area of concern because a premature decommissioning may yield gaps that inhibit the SoS (Vaneman & Budka, 2013).

Figure 17 shows the bottom of the SoSE&I "Vee," and the corresponding IDEF0 model. The IDEF0 model enables a more insightful look at the required resources and activities needed for this phase of the SE process. By approaching system design and development in this manner, the model provides a focus on SoS mission success vice system optimization. The expanded Level 2 diagram in Figure 18 demonstrates how to establish a framework for better coordination among individuals, systems, and programs.

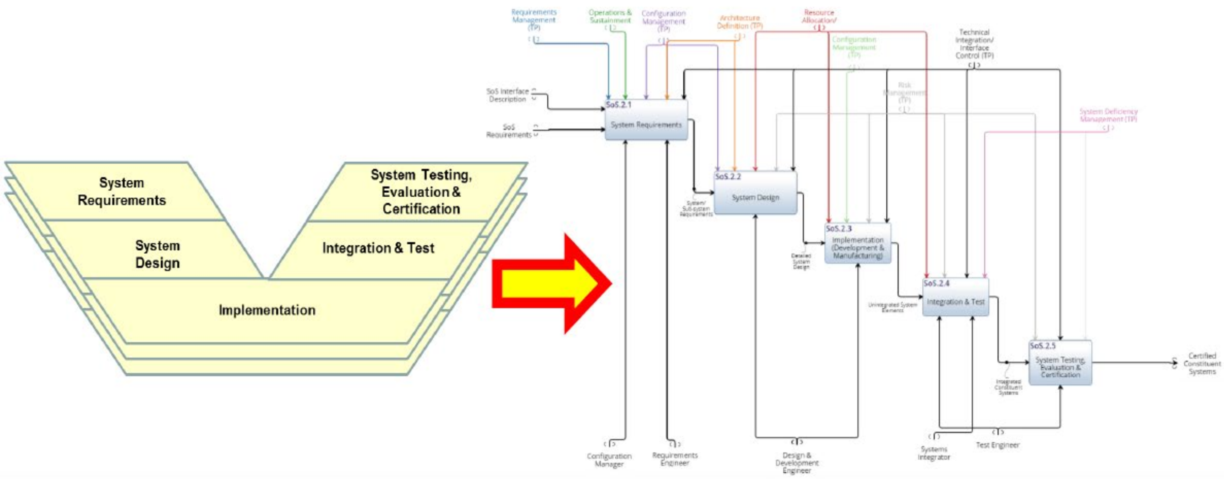

Figure 17. System Design and Development Phase Decomposed

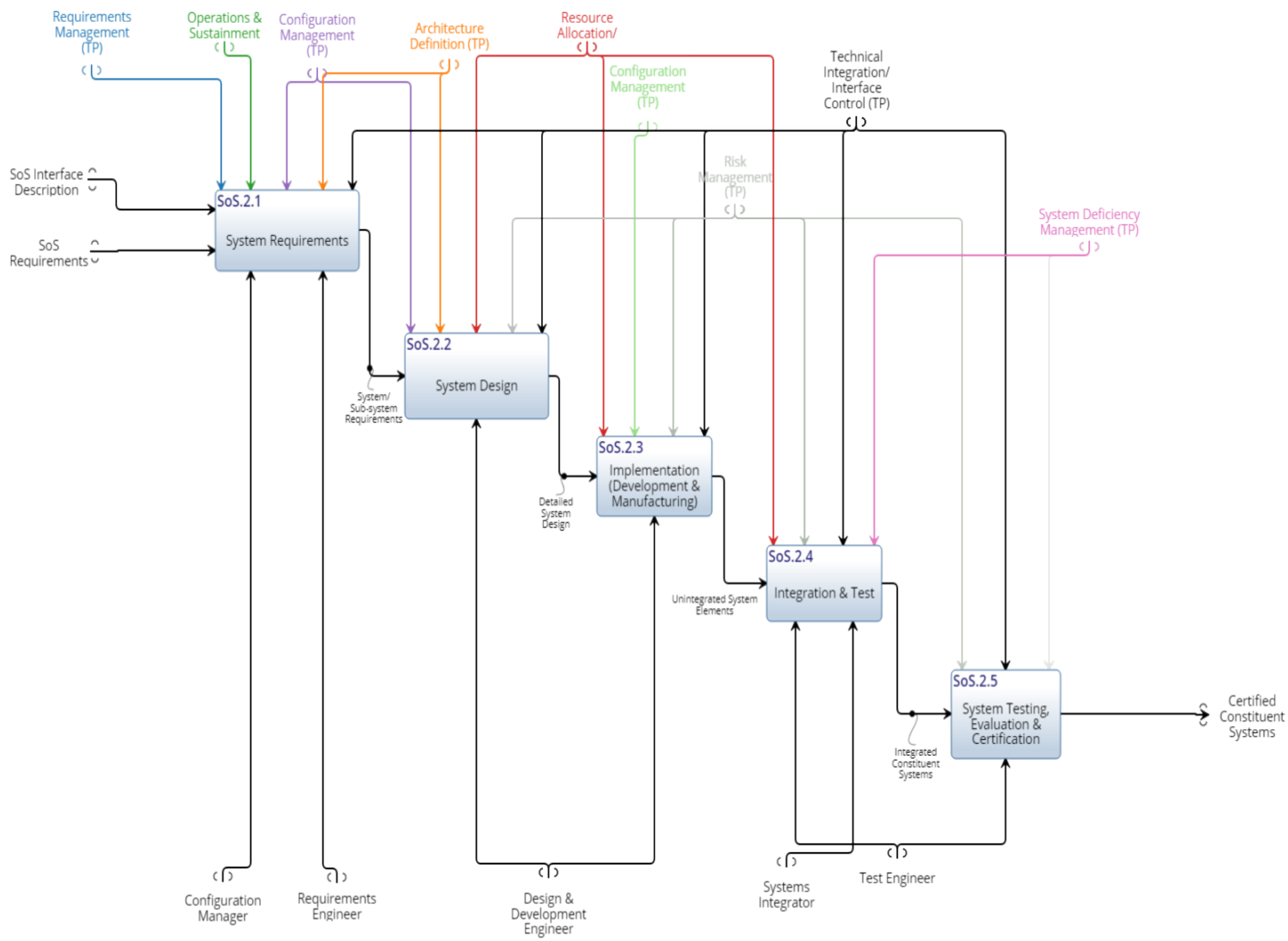

Figure 18. System Design and Development (Level 2)

The output of the SoS Requirements and Allocation process are the SoS Requirements and SoS Interface Description. Operating in an Enterprise LSI Framework requires the downward flow of requirements via higher level capabilities that are met by constituent systems. As such, the natural inputs to the individual systems' requirements are, in fact, the overall SoS Interface Description and Requirements. These serve as the stakeholder needs in traditional SE. These inputs are then transformed to System and Subsystem Requirements.

In the System Requirements functional block (SoS.2.1), the configuration manager and requirements engineer are identified. The LSI's configuration manager should address "Asynchronous CM" across interdependent stakeholders and constituent systems in the LSI's lane, which may be maturing or changing at different rates. This Asynchronous CM is especially complex for an LSI that must establish and maintain the overall SoS CM baseline throughout the product and systems' lifecycle for all baselines (e.g., Capability, Performance, Functional, Allocated, and Product baselines). Since multiple SoS program CM baselines supporting the LSI's overall CM baseline may change dynamically, and may be beyond the LSI's control, the LSI should constantly monitor all baselines and communicate their statuses to ensure the SoS capability is still maintained (LSI Cohort #2, 2015). The LSI's requirements engineer serves a critical role for performing requirement decomposition and communicating them in a manner that can be contracted and verified/validated.

System Design (SoS.2.2) is the next activity in this phase. In this activity, the input from SoS.2.1 are converted into a detailed system design, and are developed into a physical systems element. The design and development efforts are performed by the program offices. However, the LSI must understand the systems to a sufficient level of detail to evaluate system issues that may arise, and be able to derive the impacts to the SoS. The LSI must also maintain a strong governance process to communicate and manage changes during the development cycle while maximizing SoS and Mission Effectiveness.

The next activity is Implementation (Development and Manufacturing) (SoS.2.3). The output of SoS.2.2 is a collection of subsystems that have been developed independently. This activity is primarily the role of the design and development engineer. This engineer translates requirements into detailed system design and then into actual products (unintegrated system elements). These engineers must consider sustainment costs and total lifecycle management. The requirements that were input from the overall SoS must detail the length of time the respective constituent system is expected to be used in order to properly account for all applicable sustainment costs.

The next activity, integration and test (SoS 2.4), takes the unintegrated systems elements from the previous step as an input. This activity combines and tests the interoperability of the independently developed subsystems. The LSI is the individual responsible for linking constituent systems/subsystems/elements together into a usable system. It is also during this phase that the test engineer enables accurate and thorough testing through their specific skill set and training. The output of this process step is the Integrated Constituent Systems.

The last activity in the System Design and Development Phase is System Design and Development is System Testing, Evaluation, and Certification (SoS.2.5). This is a critical activity in the sequence because the constituent's subsystems/components will be tested, evaluated, and certified to ensure compliance with system requirements under the program's purview, and is presented to the SoS as a fully operational system. This process involves a thorough System Operational Verification Test for validation of these system requirements, where system strengths and weaknesses will be highlighted. System Testing, Evaluation, and Certification is the second phase specifically referencing the need for a test engineer to enable success. The test engineer determines the impact of deficiencies at the system level from constituent systems and stakeholders' deficiency management systems. Although there are defined processes in place for deficiency management at the boundary layers, the test engineer should determine how to communicate and resolve these deficiencies as they arise across multiple constituent systems and stakeholders—especially if there is an impact at the interface level (LSI Cohort #2, 2015).

The LSI test engineer has an expanded role from a typical test engineer, to include the use of extensive Live, Virtual, and Constructive (LVC) tools and modeling to capture holistic system test objectives and results (LSI Cohort #2, 2015). Ultimately, the primary control for this activity is the need to provide data to certify that the constituent system(s) will meet the SoS's need or fill the required capability gap. Additionally, when there is a requirement for certification of a constituent system, one or more policies must be in place.

The key benefit of the Systems Design and Development Phase is that the LSI is able to establish a framework for better coordination among the individual systems and programs. The LSI communicates the plans, architectures, and requirements developed for the SoS to provide the context for the system. The LSI within the program office provides the SoS LSI with insights into the status of systems functionality and limitations.

D. Mission Assurance

The upper right-hand side of the SoSE&I "Vee" is Mission Assurance. The phases in this stage bring together the individual constituent systems from the System Design and Development stage to form the SoS. These phases are defined as SoS Interoperability and Certification, Deployment, and Operations and Maintenance. Figure 19 depicts the decomposed Mission Assurance phase.

The Mission Assurance phase certifies that the SoS performance is based on mission success criteria. The understanding of SoS performance in context of mission success based on an architecture definition can help to shape acquisition planning throughout the SoSE&I "Vee."

This also includes "developing a comprehensive operations and maintenance plan to better align constituent system operations within the SoS" so that systems are ready to join or replace systems throughout the lifecycle of the SoS (Carlson & Vaneman, 2018). The Mission Assurance phases decomposed into Level 2 functions are depicted in Figure 20.

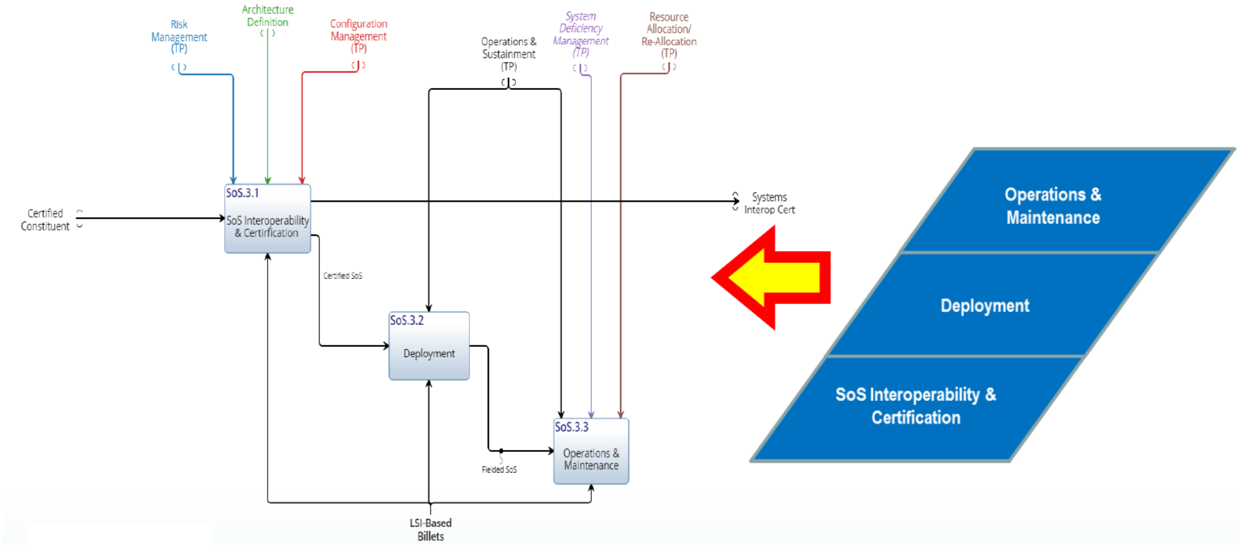

Figure 19. SoS Mission Assurance Decomposed

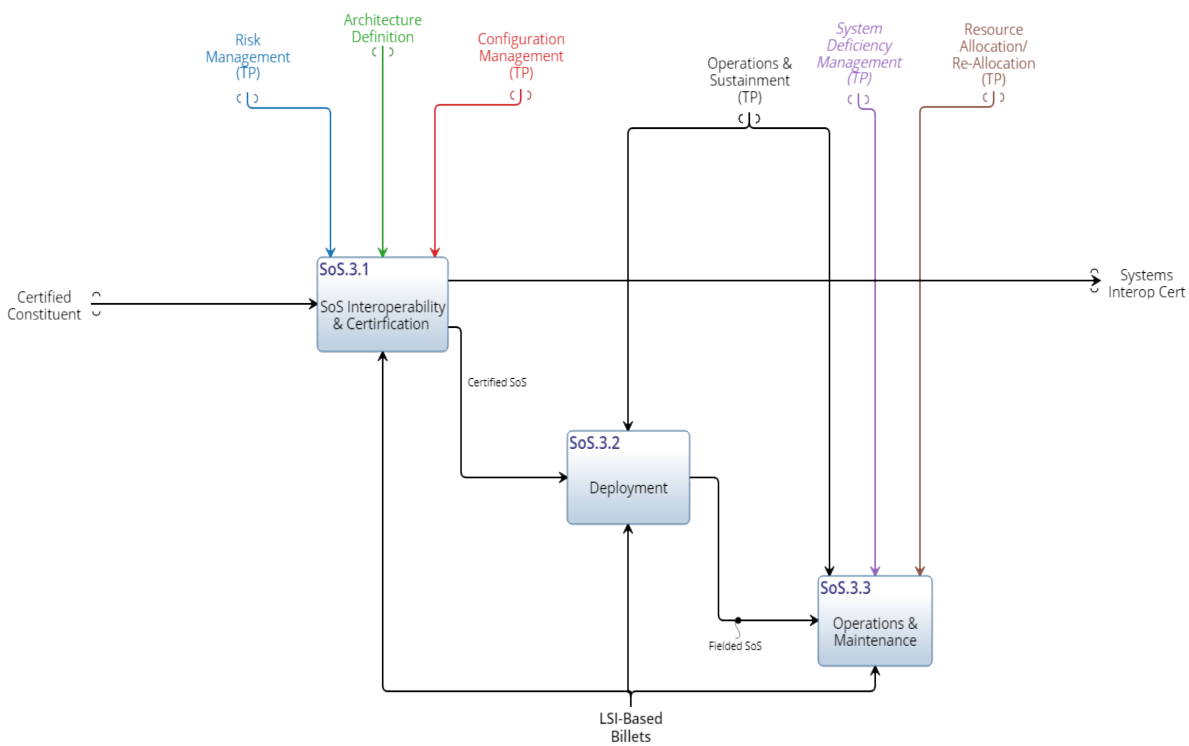

Figure 20. 1Mission Assurance (Level 2)

In 2012 the Deputy Secretary of Defense issued the Mission Assurance Strategy for the DoD. This document outlined the DoD's guidance for implementing a mission assurance framework. The strategy defines mission assurance as "a process to protect or ensure the continued function and resilience of capabilities and assets—including personnel, equipment, facilities, networks, information and information systems, infrastructure, and supply chains—critical to the performance of DoD Mission-Essential Functions (MEFs) in any operating environment or condition" (Department of Defense, 2012). This is explicitly different than the actual execution of an operational mission, and instead focuses on supporting the factors that directly impact the execution of an operational mission.

In the Mission Assurance stage, the individually verified and validated constituent systems from the System Design and Development phase come together to form the SoS. For some SoS, this phase may be the first time the constituent systems are integrated into the larger SoS to evaluate the required capability. A constituent system (i.e., a subsystem or component system) of an SoS is an individual component or part of a component. It can be composed of an organization, human, or technological unit (e.g., a division in an enterprise or an information system). A constituent system is therefore "certified" if it meets the stated requirements in the design and performance documents necessary to be incorporated into the SoS.

The larger SoS undergoes interoperability evaluation and certification during SoS Interoperability and Certification phase (SoS.3.1). The SoS interoperability and certification takes a different form than traditional testing because the SoS (especially a Navy SoS) is more difficult to test because of their sheer size and complexity (Vaneman and Budka 2013). The purpose of SoS.3.1 is to ensure that the desired mission capability is attained. This evaluation uses the previously identified SoS architecture from the SoS Architecture and Requirements Development phase as the basis for determining certification. One of the primary roles of the LSI is to ensure that the SoS level organization has sufficient insight into the individual programs within the SoS to understand the functionality and interoperability (Vaneman & Carlson, 2017).

A major issue facing SoSE&I is how to technically address issues which arise when systems identified for the SoS are limited on how much they can support the SoS. These limitations may affect initial efforts to incorporate a system into an SoS, and a system's commitments to other users may result in incompatibility or a lack of interoperability with the SoS over time. Additionally, because the systems were developed to operate in varying situations, there is risk in misunderstanding the services or data provided by one system to the entire SoS if the particular system's context differs from that of the overall SoS. These are all areas the LSI must monitor during the early stages of the SoSE&I process. Modeling and Simulation (M&S) and Live Virtual and Constructive (LVC) testing can assist in obtaining early looks at potential integration issues for the SoS and are essential tools for offsetting the cost of using real systems and hardware for total SoS evaluation. The SoS risk management plan that is developed and maintained by the LSI will contain the known risks of the constituent systems and their relationship in the SoS. This SoS risk management plan may be used by the LSI to predict an outcome for the future certification of a constituent system or the SoS as a whole, and to manage those risks accordingly (Department of Defense, 2012).

The LSI tracks the changing constituent systems CM as the systems progress through the Design and Development phase and the SoS baseline configuration is established. The larger SoS is certified using the correct CM according to the policies of the SYSCOM issuing the certification. The CM of the certified SoS is documented and controlled through the use of designated personnel. Should any issues or deficiencies within the SoS be identified, risk management controls would be instituted (Department of Defense, 2012).

The Deployment activity (SoS.3.2) of the SoSE&I "Vee" integrates the constituent systems into a SoS in accordance with established operational procedures. This integration is first conceived during the CONOPS development in the SoS Architecture and Requirements Development Phase (Vaneman & Budka, 2013). During SoS.3.2, the LSI develops a deployment and integration strategy that aligns the constituent system schedules, and uses the trade space to transition those systems into the SoS.

The Operations and Maintenance activity (SoS.3.3) considers the "health and status" of the SoS, given the "health and status" of the constituent systems (Vaneman & Budka, 2013). The Operations and Maintenance activity develops a comprehensive plan to better align constituent systems' operations and ensures a constant level of SoS functionality is provided (Vaneman, 2016). Each of the constituent systems that make up the SoS will have their own individual operations and maintenance plan. The LSI may provide input to these individual system plans for the SoS or develop a comprehensive operations and maintenance plan. Throughout the lifecycle of the SoS, the constituent systems may be upgraded and/or replaced. The operations and maintenance plan will ensure that as long as the SoS capability is required, the pieces and parts will be in place to support the SoS in order to deliver the required capability. The LSI will suggest alternative systems that are available that could take a constituent system's place in the SoS if needed. How, and when, to introduce a new or upgraded system into the larger SoS must also be included in this plan, which should also account for future growth or development if the acquisition timeline is significant. This will help ensure that subsystems or constituent systems within the SoS are not obsolete before the SoS is fielded.

The activities performed in the Mission Assurance phase are complementary to the activities performed in the upper-left side of the SoSE&I "Vee." While the SoSE&I "Vee" does not show interaction between the activities, the interaction does occur throughout the process. The strength of constant collaboration is the coordination of major activities for the successful development and integration of the SoS. The activities include: SoS interoperability and certification; SoS deployment; and SoS operation and maintenance (Vaneman & Budka, 2013).

E. Governance and Management

The fourth tenet of the SoSE&I "Vee" is Governance and Management. Governance is "the set of rules, policies, and decision-making criteria that will guide the SoS to achieving its goals and objectives" (Vaneman & Jaskot, 2013, p. 1). Governance and Management reaches across the entire SoSE&I process, as depicted in Figure 21.

This research did not decompose the Governance and Management phase into more detailed activities. However, this section provides background information that can serve as a point of departure for future research. The attributes of a multi-organizational systems of systems enterprise makes governing difficult. A government LSI's key governance challenge is pivoting from a "program/platform" focus to an SoS mission/capability focus across independent, collaborative stakeholders—generally without revolutionary organizational change. Since governance derives from the agreements between key stakeholders (at all levels of LSI) on how to achieve a common goal, a government LSI should charter decision bodies to alter the actions of individuals and organizations in support of the LSI effort (LSI Cohort #2, 2015).

LSI governance objectives describe five key governance tenets and their application in the LSI Enterprise Framework (LSI Cohort #2, 2015):

1. Distribution of authority, focused on acquisition of capabilities;

2. Conflict resolution, arbitrated by key stakeholders most capable to address enterprise goals;

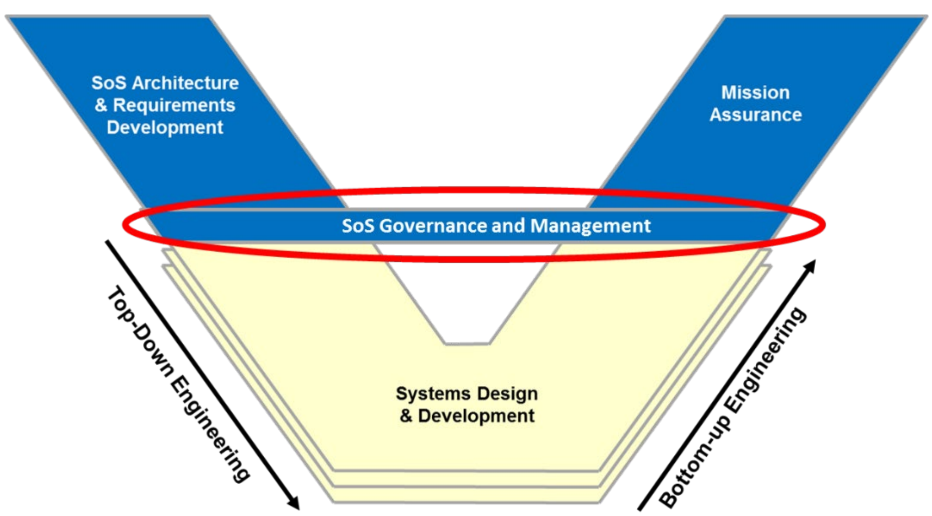

Figure 21. SoS Governance and Management

1. Maintaining atakeholder “Architecture,” since governance flows directly from stakeholder relationships;
2. Communication—LSI as the conduit of authoritative data, to maintain a “shared common understanding”; and
3. Use of an LSI Governance Charter to document roles, responsibilities, authority, conflict resolution plans, and agreements—including empowered resource management authority—to incentivize stakeholders to think and act differently.

An LSI must manage the scale and complexity of the SoS, the supply and demand division between providers and stakeholders, and the dynamics of a diverse stakeholder community to affordably deliver an integrated warfighting capability that spans multiple programs and systems. Since existing acquisition organizational structures, policies, and processes are aligned to procurement of individual constituent systems vice capabilities, an LSI’s primary governance challenge is to pivot from a system or program focus to an SoS mission and capability acquisition focus. Recognizing that sweeping “revolutionary” reorganization and budgetary realignment to a mission/capability focus is impractical, the LSI should find a way to insert LSI governance policies and processes into this existing system or program-focused acquisition environment (LSI Cohort #2, 2015).

Previous LSI proposals have met limited success because they were unable to alter the likely behavior of individuals and organizations (Space and Naval Warfare Systems Command [SPAWAR], 2012). Attempts to simply rework organizational wiring diagrams or create new and seemingly nimbler processes may fail unless they are also supported by changes in the underlying incentives that motivate individual and organizational actions. These underlying incentives can be translated into four key LSI governance objectives (LSI Cohort #2, 2015):

1. Provide the set of decision-making criteria, policies, processes, and actions that guide the responsible organizations to achieve SoS goals and objectives;
2. Define communication paths and decision authority within the various levels of the LSI Enterprise framework for conflict resolution;
3. Charter decision bodies to alter the actions of individuals and organizations in support of the LSI effort; and

4. Maintain the currency and relevance of the SoS architecture across the enterprise since governance derives from the agreements between key stakeholders, at all levels of LSI, on how to achieve a common goal.

Ultimately, LSI governance derives from the key stakeholders within the multi-organizational systems of systems enterprise who agree on the policies and principles that will form the charters and specifics of LSI governance (LSI Cohort #2, 2015). Table 3 (SPAWAR, 2012) summarizes the components for successful SoSE&I Governance. This information can be used to create or enhance an instruction document that implements LSI processes into a program and could serve as standing business rules or be used as a validation of processes.

Table 3. Components of Successful SoSE&I Governance

Components of Successful SoSE&I Governance	
Clear Regulations and Policies	Good governance requires clear guidance, fair policies and tailorable regulations that are enforced impartially through a responsive decision board. Responsive governance promotes and accommodates a streamlined, less bureaucratic acquisition strategy process by serving stakeholders in a reasonable timeframe.
Transparency	Transparency means that unambiguous information is freely available and directly accessible to those who will be affected by such decisions and their implementation.
Effectiveness and Efficiency	Effectiveness and efficiency are especially important in SoSE&I governance because participating processes and organizations produce results required to meet the needs of mission capability threads while making the best use of resources at their disposal.
Directed Responsibility	Responsibility is a collaborative endeavor shared between all stakeholders. In general an organization is responsible to those who will be affected by its decisions or actions. Formalizing the governance processes and TA lines of responsibility helps maximize planning, efficiencies, and accountability.
Interoperability	Assurance of interoperability between the constituent systems at all levels to allow the necessary communication and connectivity across the system of systems. Interoperability includes both the technical exchange of information and the end-to-end operational effectiveness of that exchanged information as required for mission accomplishment.
Governance Organization	Authoritative structure to provide guidance on the allocation of resources, coordinate and control mission area capability and promote development activity. A governance organization is critical to the synchronized, effective management and integration of multiple, independent programs and systems into a system of systems.

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IV. Applying LSI Enterprise Framework to Develop the Live Virtual Constructive Training Environment (LVC-TE) Architecture

> We need … to seek creative solutions to today's and tomorrow's complex problems. … We need to change where it makes sense, adapt as quickly as possible, and constantly innovate to stay ahead of our adversaries. Our ability to adapt more quickly that our enemies will be vital to our future success.
>
> —Neller (2016)

Following the enhanced development of the LSI Enterprise Framework, discussed in Chapter III, an assessment was performed with a focus on the development of the SoS architecture. As discussed in Chapter II, the SoS architecture provides a technical blueprint of the SoS, showing the traceability of functional and derived relationships among all constituent systems. The architectural viewpoints enable stakeholders to visualize, define, and bound the component systems and SoS and identify integration points both inside and outside the systems. From these views, system interoperability issues can be identified. The architecture serves as the foundation of the LSI Enterprise Framework depicted in Figure 7.

The SoS architecture is used throughout all levels of the LSI Enterprise Framework, and all phases of the SoSE&I lifecycle. This assessment focuses on the Mission Wholeness Level (see Figure 4), and because of the SoS focus, the ensuing discussion concentrates on the SoS Architecture and Requirements Development and Mission Assurance phases of the SoSE&I "Vee."

The Marine Corps Live Virtual Constructive-Training Environment (LVC-TE) program was selected as the subject of this assessment. LVC-TE was ripe for this assessment since it is a SoS, and was in the formative stage. While a comprehensive review was not possible due to the lack of maturity of the program, it does offer the opportunity to define how an architectural approach, using the LSI Enterprise Framework, could benefit the program.

Section A provides an overview of LVC-TE. Additional details about the constituent systems that will comprise LVC-TE are included in Appendix A. Section B discusses the architectural model that will be developed, and used, by the LSI. The architectural views in this report are generic to illustrate the benefits of this approach rather than highlight the LVC-TE details. However, potential architectural benefits for LVC-TE will be highlighted.

A. LVC-TE Overview

LVC-TE is an emerging Marine Corps Program of Record. The objective of LVC-TE is to provide greater combat readiness and enhanced operational execution. The Marine Corps requires the capability for individual Marines, units, commanders, and their staff up to the Marine Expeditionary Force (MEF) level to train like they fight—as a Marine Air Ground Task Force (MAGTF). For immersive and realistic training, the MAGTF must be seamlessly integrated horizontally across the four elements of the MAGTF—the Air Combat Element (ACE), Ground Combat Element (GCE), Logistics Combat Element (LCE), and Command Element (CE)—and vertically across all echelons of command from individual Marine rifleman to the MEF commander. The LVC-TE must provide a persistent, easy to use, and affordable distributed collective training and mission rehearsal capability to fulfill Combatant Commander (COCOM) and Service training requirements. The LVC-TE must enable individuals, staff, and units to interact and collaborate within and across LVC training domains to attain the “reps and sets” necessary to ensure every Marine encounters their initial tactical and ethical dilemmas in a simulated battlefield vice actual combat.

Required Capabilities

The LVC-TE Capability must possess the following capabilities:

- Facilitates distributed collective training of all warfighting functions across the contemporary operating environment for the range of military operations (ROMO)
- Provides access from home-station, deployed locations, or while embarked aboard naval vessels

- Provides the ability to conduct distributed collective training from geographically separated locations
- Provides a means to conduct comprehensive assessment/after-action review (AAR) of training objectives

The end-state is a transformational training and mission rehearsal capability that provides accurate, timely, relevant, and affordable training and mission rehearsal capability in support of specific operational needs and commander's priorities. The LVC-TE Operational View–1 (OV-1) is provided in Figure 22 (Marine Corps Systems Command [MARCOR], 2018).

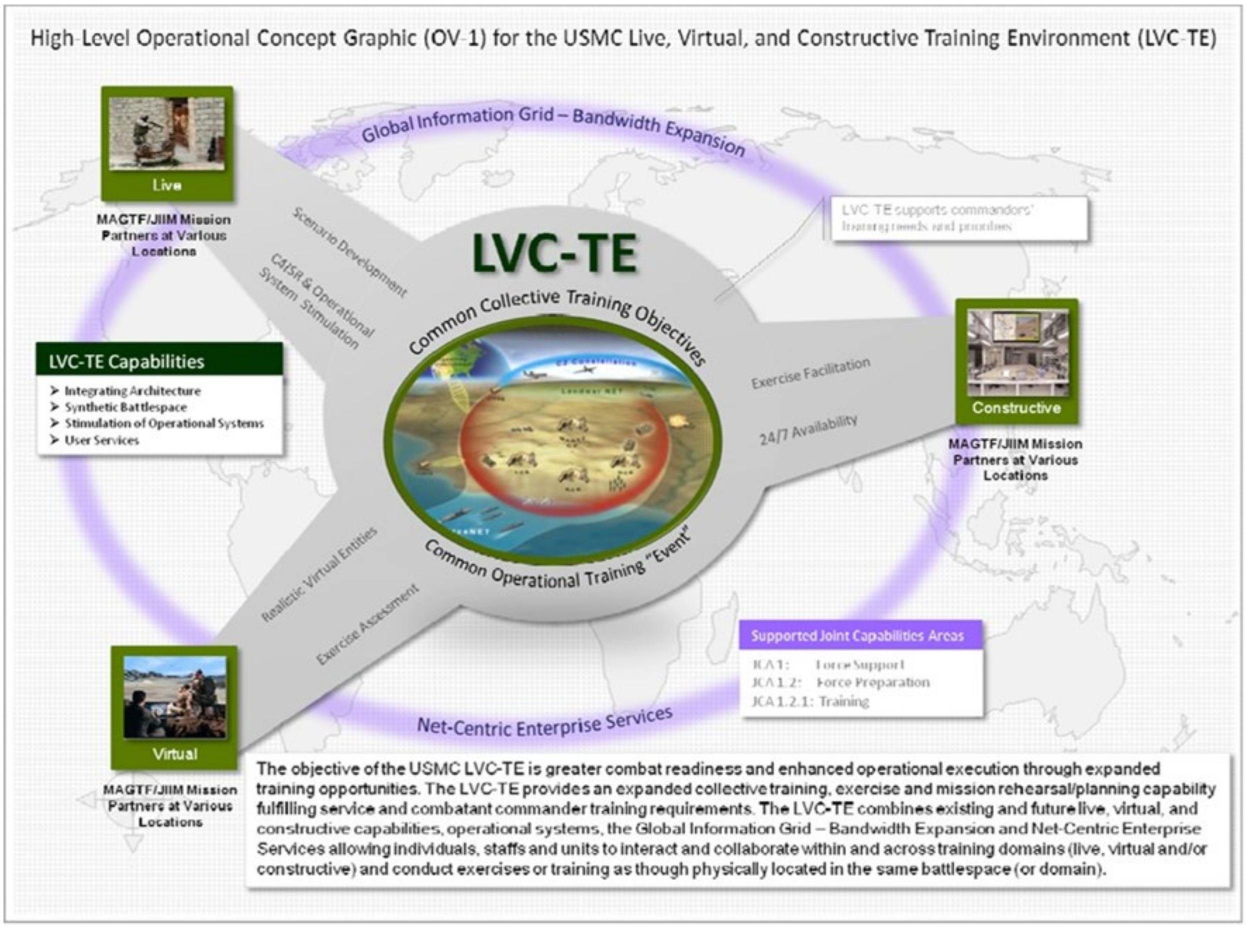

Figure 22. LVC-TE Operational View–1 (OV-1) (MARCOR, 2018)

System of Systems (SoS)

The required LVC-TE capability, by its distributed collective nature, is a true SoS. The LVC-TE will establish I&I between a number of existing, evolving, and emerging constituent systems at Marine Corps home stations, deployed locations, and while afloat throughout the world. In some cases, LVC-TE will need to develop new constituent systems. The ground training systems that are constituents of the LVC-TE SoS will retain their individual program requirements and resources. However, the combat developer recognizes these ground training system constituents must now play a role in meeting the LVC-TE distributed collective training and mission rehearsal requirements in addition to meeting their standalone training requirements. Since the LVC-TE concept will be an SoS, an acquisition strategy, wherein the government will perform LSI functions, has been planned (MARCOR, 2018).

Reference Design Concept

The LVC-TE SoS is envisioned as an evolving baseline. Constituent systems will be brought into, or retired from, the SoS as LVC-TE requirements develop. Constituent systems include: tactical Command and Control (C2) systems; training and readiness reporting systems; training facilities and ranges; Marine Corps ground training systems; other models, simulations, and training systems, joint training systems; and, the Marine Corps Enterprise Network (MCEN; MARCOR, 2018). An overview for each of these constituent categories is provided in Appendix A. This reference design concept is illustrated in Figure 23 (MARCOR, 2018).

B. Architecture Development

The architecture is the foundation of the LSI Enterprise Framework. As such, the LSI should devote a significant amount of effort and resources to develop and maintain the architecture throughout the SoS lifecycle. An architecture is defined as the fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution. Architectures describe the overall system (i.e., processes, tools,

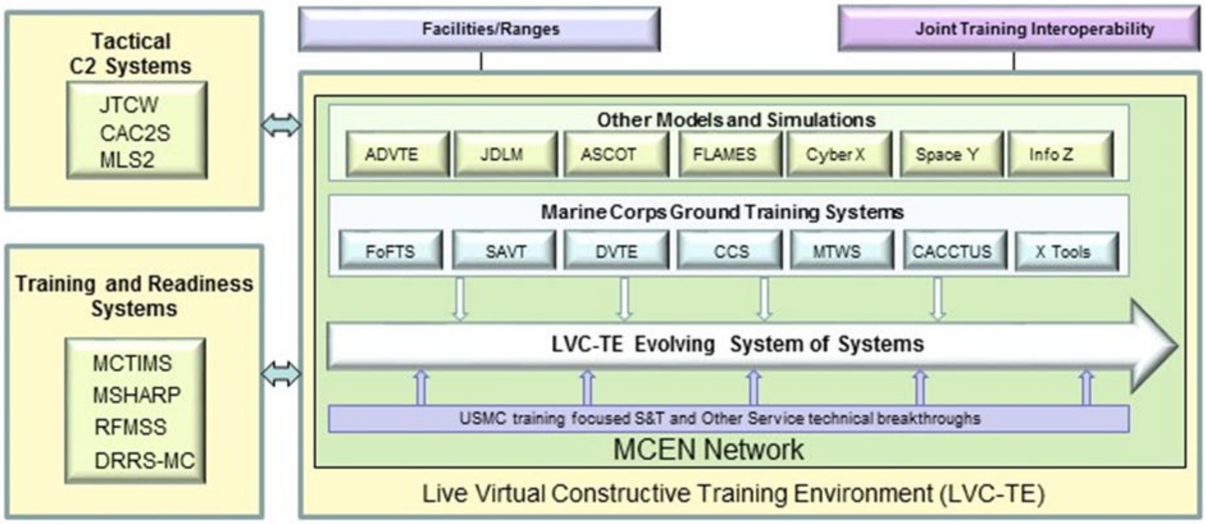

Figure 23. LVC-TE Reference Design Concept

people, organizations, etc.), in various states (i.e., "as-is," "as-planned," "as-desired"). This expands the architectural views from the traditional functional and system views, to include other system engineering views (or products) found throughout the lifecycle (e.g., requirements, risk matrices). Architectures prescribe how to transform the system from the "as-is" to the "as-desired" state and can be static or dynamic (e.g., simulation) representations of a system (Vaneman, 2012).

For the architecture to be efficiently developed and managed throughout the SoS lifecycle, the LSI should consider adopting an MBSE approach to conduct all architecture decisions. Model-Based Systems Engineering is defined as the formalized application of modeling (both static and dynamic) to support systems design and analysis, throughout all phases of the system lifecycle, through the collection of modeling languages, structure, model-based processes, and presentation frameworks used to support the discipline of systems engineering in a "model-based" or "model-driven" context (Vaneman, 2016).

Many organizations who seek an MBSE approach, to address their systems engineering needs, immediately want to select an MBSE tool to create their environment. Notice that the above definition of MBSE does not include tools, but instead discusses four tenets. The LSI should focus on these tenets as the basis of a tool study, because maximum effectiveness occurs at the convergence of the four MBSE tenets. The four tenets of MBSE are (Vaneman, 2017):

- Modeling Languages. Serves as the basis of tools, and enable the development of system models. Modeling languages are based on a logical construct (visual representation) and/or an ontology.
- Structure. Uses the ontology, and defined relationships between the systems entities, to establish concordance[1], thus allowing for the emergence of system behaviors and performance characterizations within the model.
- Model-Based Processes. Provides the analytical framework to conduct the analysis of the system virtually defined in the model. The model-based processes may be traditional systems engineering processes such as requirements management, risk management, or analytical methods such as discrete event simulation, systems dynamics modeling, and dynamic programming.
- Presentation Frameworks. Provides the framework for the logical constructs of the system data in visualization models that are appropriate for the given stakeholders. These visualization models take the form of traditional systems engineering models. These individual models are often grouped into frameworks that provide the standard views and descriptions of the models, and the standard data structure of architecture models.

An MBSE approach is also recommend because it provides the LSI with the ability to understand and manage complexity through prediction of emergent behavior within the SoS. Emergence is defined as the appearance of new properties in the course of development, evaluation, and operations. This is important because as constituent systems are assembled into an SoS, emergent behavior, both intended and unintended, is the result. In the absence of an MBSE environment, the LSI would have to rely on subjective analysis to glean concordance, from a potentially wide range of architectural views, to derive emergence.

[1] *Concordance* is the ability to represent a single entity, such that data in one view, or level of abstraction, matches the data in another view, or level of abstraction, when talking about the exact same thing (Vaneman, 2018).

The architecture serves as the foundation for LSI activities throughout the SoSE&I "Vee." From the LSI perspective, SoS Architecture and Requirements Development and Mission Assurance phases are the most important part for LVC-TE. Figure 24 provides an overview of the architecture. The remainder of this chapter discusses the architecture, and its uses for these phases.

Architecting During the SoS Architecture and Requirements Development Phase

The architecture process begins with the Capability Collection/Customer Interface (SoS.1.2) activity discussed in Chapter III, and shown as a partial functional model in **Error! Reference source not found.** During this activity, the LSI assesses the stakeholder capability inputs.

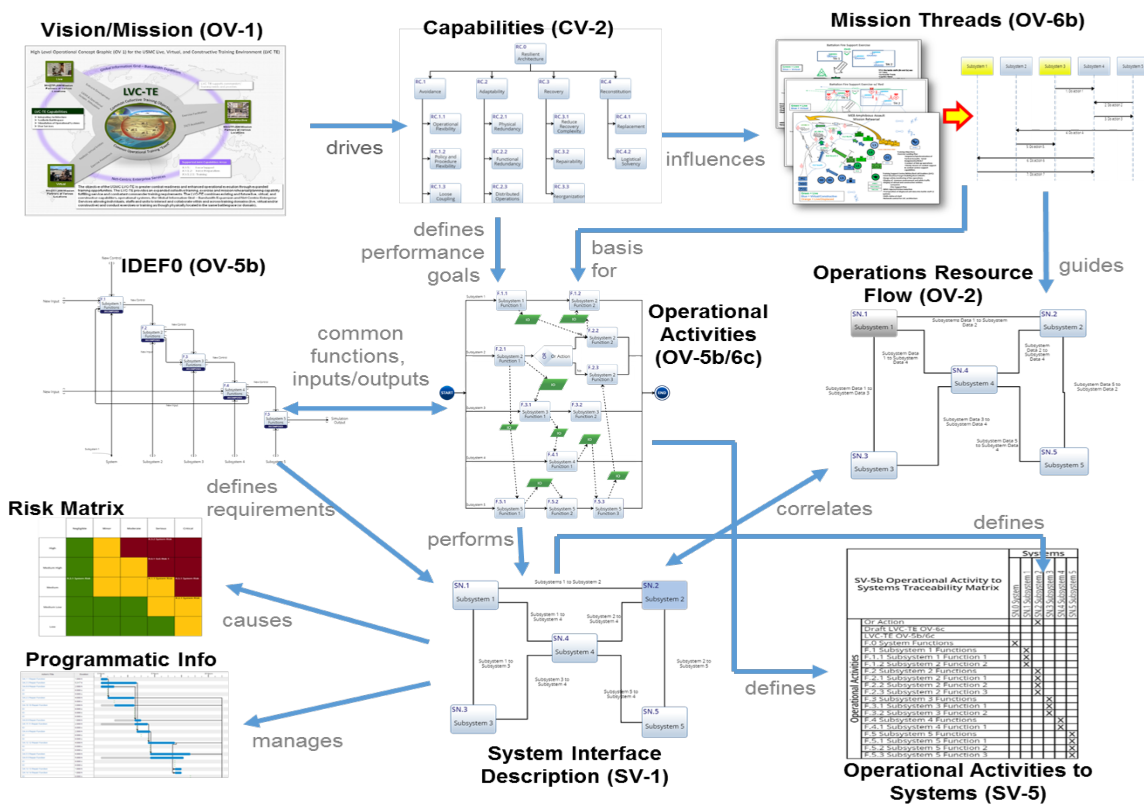

Figure 24. SoS Architecture Overview

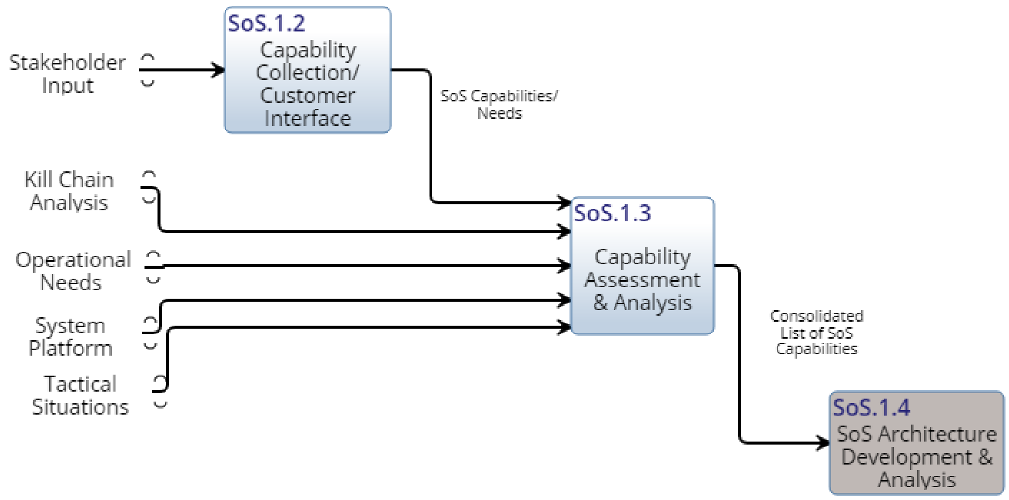

Figure 25. Partial Functional Model of Capability Collection, Assessment, and Analysis

A capability is the ability to achieve a desired effect under specified standards, and conditions, through combinations or ways and means to perform a set of tasks. The capability statements provided by the stakeholders should be solution-neutral. In this era of capability-based acquisition, capabilities are key to defining the needs to be satisfied by systems. In the SoS environment, capabilities have an added importance because the lifecycle of the SoS is defined from the definition of needed capability until there is no longer a need for that capability.

For example, the Marine Corps Requirements Oversight Council LVC-TE Initial Capabilities Document (ICD) (2010) provides the following capability statement: "LVC-TE combines any of the three training domains (live, virtual, and constructive) to create a common battlefield or environment, by which units can seamlessly interact across live, virtual, and constructive domains as though they are physically located together in the same battlespace. The LVC-TE will provide the means to conduct realistic, collaborative training and exercise of warfighting functions across the full range of military operations."

The architectural views developed to capture the capabilities includes: the High-Level Operational Concept Graphic (OV-1; Figure 22), which provides a pictorial representation, and textual description of the operational concept; the Vision (CV-1) which provides the strategic context for capabilities described in the high-level operational concept; and the Capability Taxonomy (CV-2) which depicts the hierarchy of capabilities that must be satisfied by the SoS. Combined, these architectural views provide SoS capabilities and needs to the Capability Assessment and Analysis (SoS.1.3) activity.

The Capability Assessment and Analysis (SoS.1.3) activity uses the input from SoS.1.2. as well as others, to perform a detailed analysis of capabilities required for operations. The other inputs include CONOPS, TACSITS, kill chain analysis, and representative systems that may be able to address the need.

During this activity, the LSI uses scenarios, or mission threads[2], to capture the operational activities that occur within the SoS. The CONOPS, TACSITS, and kill chain analysis are usually described in stakeholder terms. The LSI transforms these narratives into a sequence of events. A Sequence Diagram (OV-6c) is typically used for this transformation. Figure 26 illustrates scenario modeling, to include the scenarios and the Sequence Diagrams.

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[2] A *mission thread* is an end-to-end set of steps that illustrate a system's expected behavior under a set of conditions, and provides a basis for identifying and analyzing potential system gaps, and performance issues.

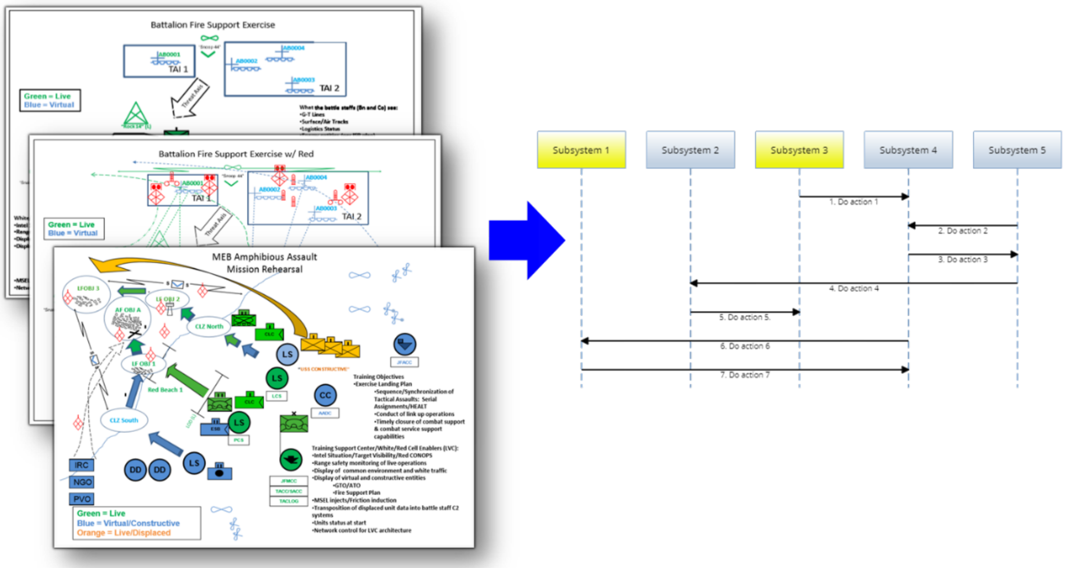

Figure 26. Scenario Modeling

During the SoS Architecture Development and Analysis (SoS.1.4) activity, the LSI uses the consolidated stakeholder capabilities that were captured, assessed, and analyzed during SoS.1.2 and SoS.1.3 to develop the functional and system architectures. Figure 27 shows a partial functional model of the SoS.1.4 and the SoS Requirements and Allocation (SoS.1.5) activities.

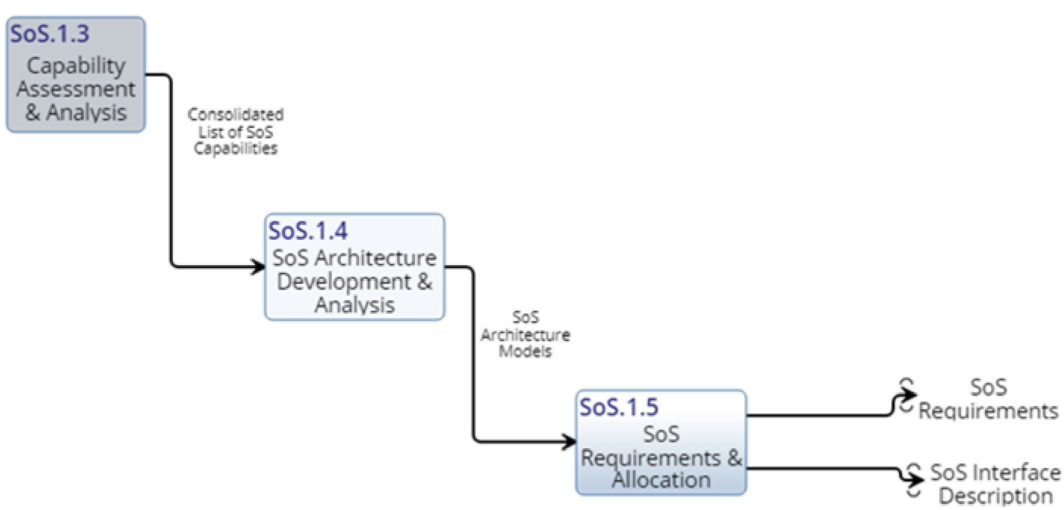

Figure 27. Partial Functional Model of SoS Architecture Development, Analysis, and Requirements

There is a wide variety of views that can be generated for both functional and system architectures that the LSI can choose from. Defining which views should be developed is dependent on the scope of the SoS, and the decisions that are required. The following is a discussion of some of the recommended views needed to address a wide swath of engineering issues.

The first logical step in SoS.1.4 is functional analysis. Functional analysis is logically structured as a top-down hierarchical decomposition of the system functions and serves several important roles in the systems engineering process. Functional analysis

- Describes what the system will do, not how the system will do it
- Derives all of the system functions and requirements the system must satisfy
- Identifies measures for systems effectiveness and its underlying performance or technical attributes at all levels
- Eliminates from further consideration in trade-off analysis those alternatives that cannot meet the system's goals and objectives
- Provides insight to the system level model builders, whose mathematical models will be used in trade studies to evaluate design alternatives

Coupled closely with the Sequence Diagram developed in SoS.1.3, the Action Diagram (OV-5b/6c) is a fit for purpose view that models the functions (operations) of the SoS to determine dependencies and system closure.[3] Functional analysis portrays how the various SoS, and constituent systems, alternatives will be used, and will highlight areas where standard operating procedures need to be changed. If operational procedures are not flexible, the model will show areas where the system needs to change. Figure 28 shows an example of an Action Diagram.

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[3] System closure is the ability of the system, or SoS, to progress from end-to-end without gaps in the process. Often system closure also has a time component that also considers if the end-to-end process meets the timeliness requirements.

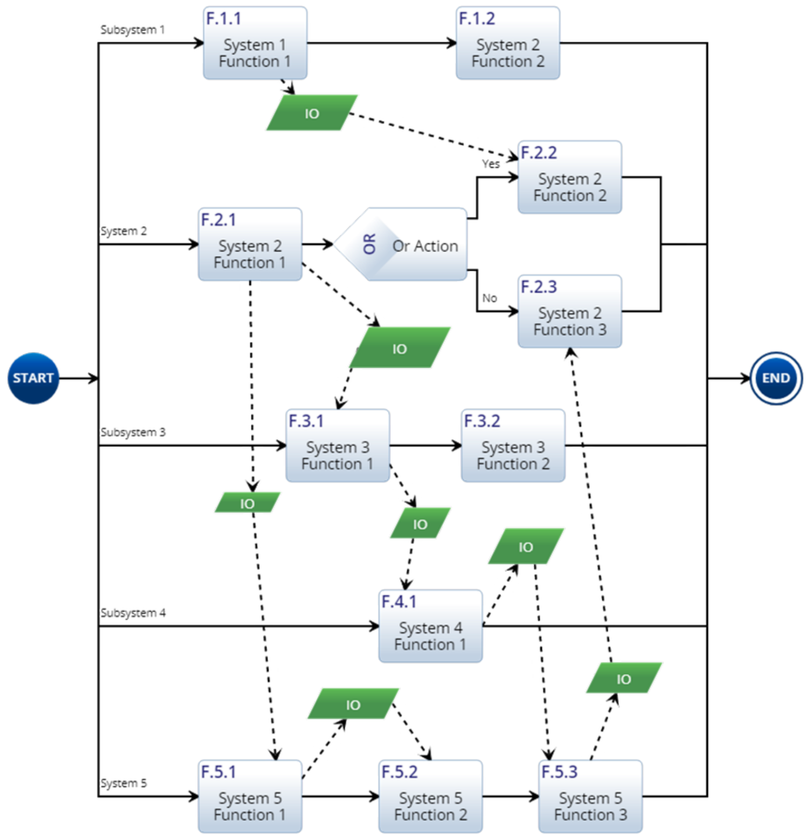

Figure 28. Example Action Diagram (OV-5b/6c)

The Action Diagram is important to LVC-TE because as constituent systems are assembled, the order of functions will need to be determined to best simulate the MAGTF. The Action Diagram also illustrates the inputs and outputs for each function within the constituent systems. In the LVC-TE, outputs from one constituent system will serve as inputs to another constituent system. Heretofore, the constituent systems operated independently, only being concerned with its own inputs and outputs.

In addition to showing the order of the functions and the interfaces between the functions, the Action Diagram may also serve as the basis for dynamic modeling of the architecture. Action diagrams can be simulated via discrete event or Monte Carlo simulation to analyze system performance. The discrete event simulation model will help identify the order in which functions occur, and highlights dependencies between functions. This is important to LVC-TE because as engineers bring the constituent systems together, regardless of whether the numerical results of the discrete event simulation are used, this simulation has tremendous value for the LSI.

The Action Diagram can also be used for Monte Carlo simulation. Given that most system functions are best represented by stochastic processes,[4] each function in the Action Diagram can be represented by a different probability distribution. Monte Carlo simulations are simulated a sufficient number of iterations, and then statistical processes are used to determine the mean time and standard deviation for each function, and identify bottlenecks within the SoS. This is important for LVC-TE because it will provide insights into the length of time required, and the numerical range of time, to simulate a certain action within the MAGTF. Currently, the timeliness of each constituent system is known, but the emergent behavior of combining those constituent systems into a SoS is unknown. Figure 29 shows the Action Diagram, with an offset showing the probability distribution of a function, and an example of Monte Carlo simulation output.

Another functional analysis view is the IDEF0, which was discussed at the beginning of Chapter III, where it was used to further define the LSI Framework. For systems, and SoS architecting, the IDEF0 is used traditionally with the inputs, outputs, and controlling elements of each function, and provides the mechanisms (systems) that perform each function. Additionally, the structure of IDEF0 makes the relationships within the model which is foundational for concordance.

[4] A stochastic process is represented by random probability distributions, that are analyzed statistically, and may not be predicted precisely.

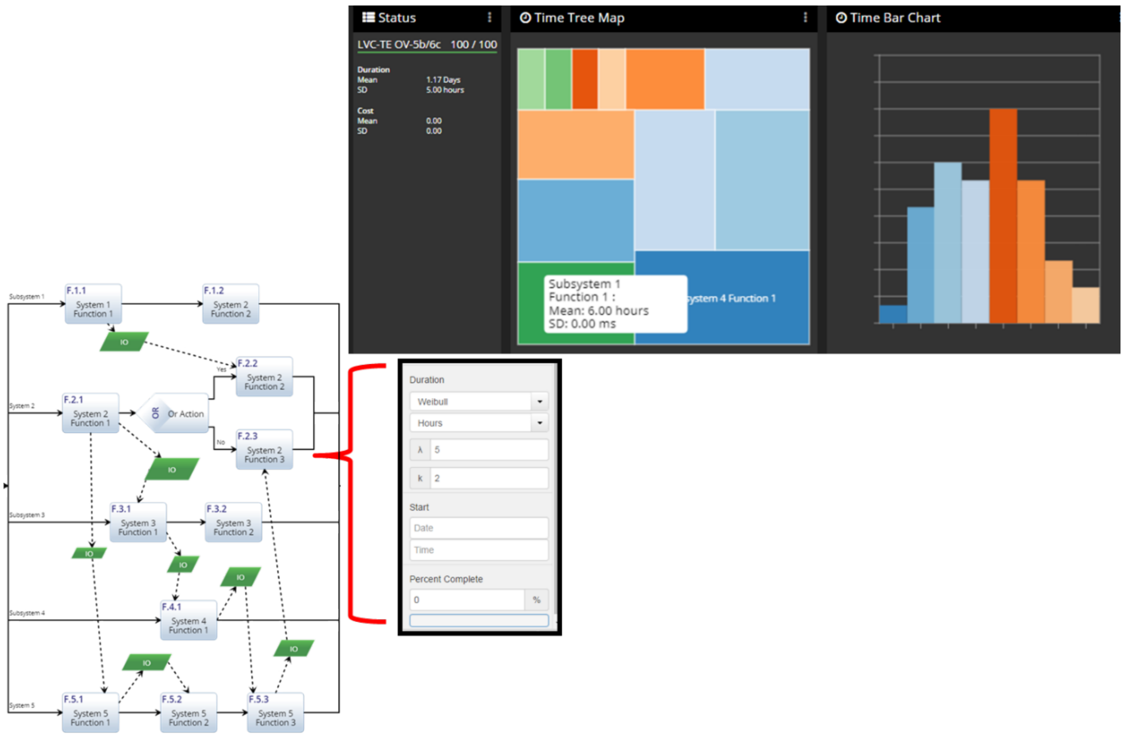

Figure 29. Example Action Diagram with Monte Carlo Simulation

Due to the broad relationships made between elements, the IDEF0 also can serve as the basis to generate architecture derived requirements. When deriving requirements in the SoS Requirements and Allocation (SoS.1.5) activity, the LSI should use the IDEF0 as the primary, but not exclusive, view. Currently, one MBSE tool will automatically generate requirements from the architecture. However, the quality of the requirements depends on the quality of the architecture model.

While these requirements may not be suitable for development, they can serve to validate existing requirements for completeness. This is an important issue for LVC-TE which seeks to combine various constituent system into an SoS that simulates the MAGTF. Given the complexity of real-world MAGTF operations, and the complexity of the constituent systems, it would be easy to omit a key relationship needed to accurately simulate the MAGTF. Figure 30 shows an example IDEF0 view and the associated derived requirements.

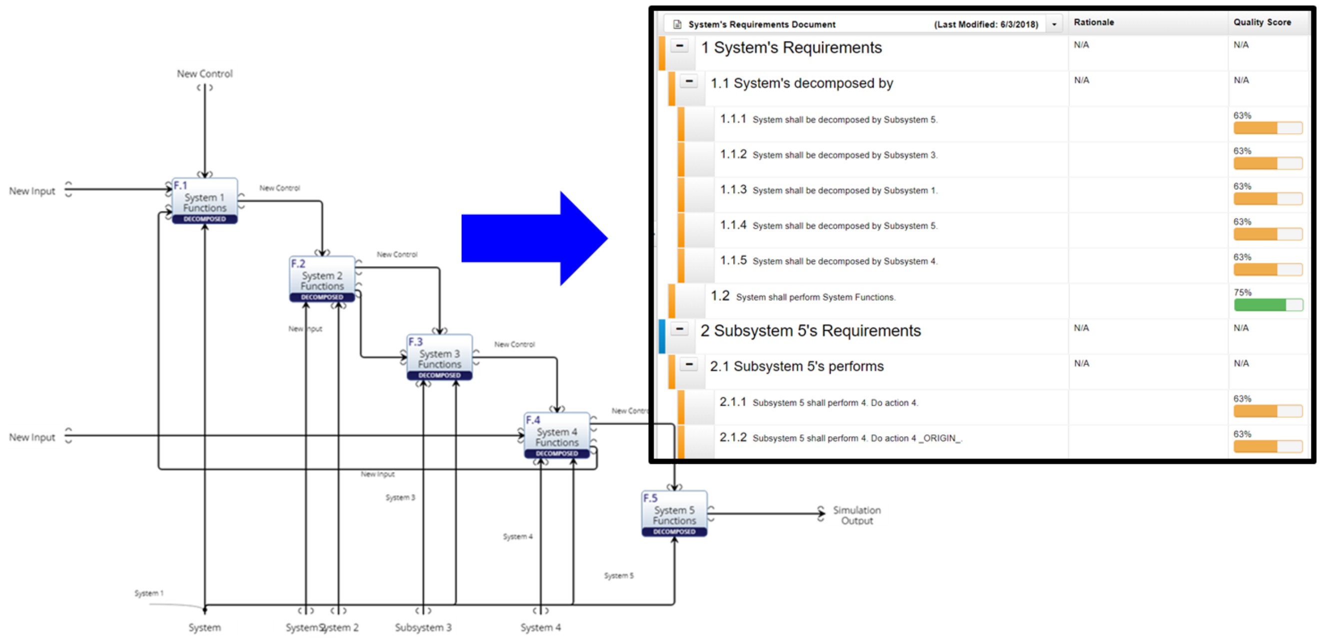

Figure 30. Example IDEF0 and Associated Derived Requirements

The next logical step in SoS Architecture Development and Analysis (SoS.1.4) is architecting the system views. The system views are essential to architecture because they allow the LSI to understand and manage the baseline, prioritize SoS issues to support investment planning and decisions, and evaluate interoperability issues.

A good place to start the system modeling is with the System Interface View (SV-1), which describes the SoS and the decomposed constituent systems. Figure 31 depicts an example of an SV-1. At the top level, the SoS is represented by a single block. The more interesting portrayal is at the first level of decomposition where the constituent systems and their interface are shown. The constituent systems can be further decomposed into a second level of decomposition which will expose the sub-systems for each constituent system. The LSI working at the SoS level will not typically be concerned with decomposing the system architecture beyond the first level of decomposition. However, the LSI working the system/program level will want to decompose the architecture to the second level of decomposition and beyond. It is at the first level of decomposition where the LVC-TE constituent systems are represented.

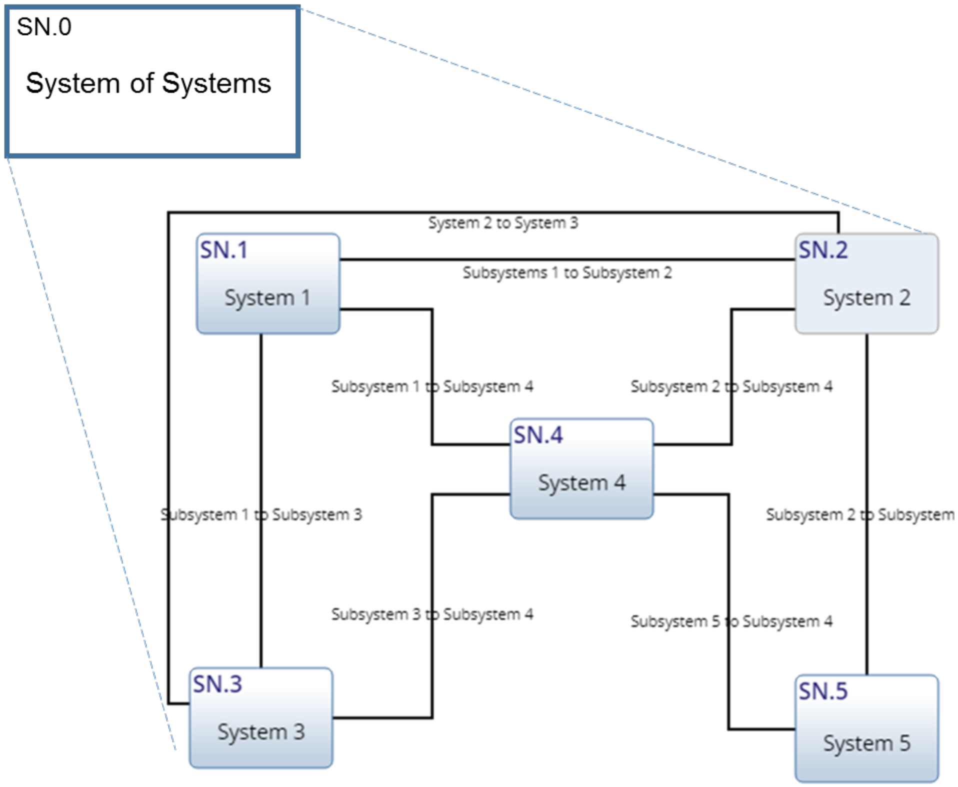

Figure 31. Example SoS Interface View with Decomposed Constitution Systems

Another aspect of the SV-1 that is of interest to the LSI are the interfaces. This view depicts the interfaces between the constituent systems and the attributes of the interfaces. These attributes highlight the physical interface type, the size of the interface, and the direction of the flow between the constituent systems.

Closely related to the SV-1 is the Operations Resource Flow View (OV-2). Like the SV-1, the OV-2 shows the constituent systems and interfaces between them. However, the interfaces in the OV-2 represent the data type, size, frequency, and direction of the transfer between system nodes. Using the OV-2 in conjunction with the SV-1, the LSI can understand the data being transferred and ensure that the physical interfaces are properly sized. This is an important point for LVC-TE since the constituent systems were developed for stand-alone operations, therefore data transfer between those systems is one of the most significant unknowns.

Interface management within the SoS is one of the primary responsibilities of the LSI because interfaces between constituent systems are critical to SoS success.

Another view that is appropriate for assisting the LSI in managing the interfaces is the Systems-Systems Matrix (SV-3). This matrix can be designed to manage a wide variety of interface attributes (e.g., interface type, planned and existing interfaces). An example is shown in Figure 32 (Dam, 2014).

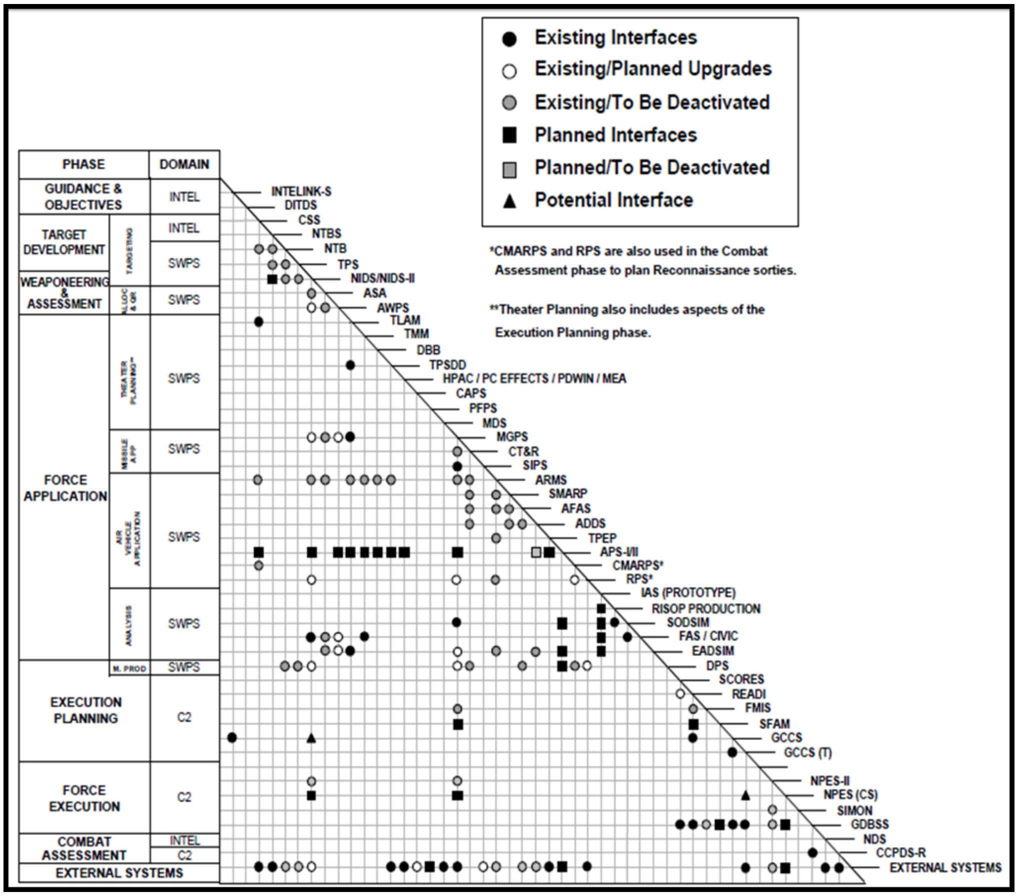

Figure 32. Example Systems-Systems Matrix (SV-3)

Another model that is critical to the LSI is the Operational Activity to System Traceability Matrix (SV-5b), shown in Figure 33. This matrix allows the LSI to ensure that the operational functions identified during the functional architecture development are assigned to a system that will perform those functions. Conversely, the matrix allows the LSI to see that every system is assigned a function. Often when assembling an SoS, legacy constituent systems are included even when they do not support an SoS operation.

SV-5b Operational Activity to Systems Traceability Matrix		Systems					
		SN.0 System	SN.1 System 1	SN.2 System 2	SN.3 System 3	SN.4 System 4	SN.5 System 5
Operational Activities	Draft LVC-TE OV-6c						
	LVC-TE OV-5b/6c						
	Or Action			X			
	F.0 System Functions	X					
	F.1 System 1 Functions		X				
	F.1.1 System 1 Function 1		X				
	F.1.2 System 2 Function 2		X				
	F.2 System 2 Functions			X			
	F.2.1 System 2 Function 1			X			
	F.2.2 System 2 Function 2			X			
	F.2.3 System 2 Function 3			X			
	F.3 System 3 Functions				X		
	F.3.1 System 3 Function 1				X		
	F.3.2 System 3 Function 2				X		
	F.4 System 4 Functions					X	
	F.4.1 System 4 Function 1					X	
	F.5 System 5 Functions						X
	F.5.1 System 5 Function 1						X
	F.5.2 System 5 Function 2						X
	F.5.3 System 5 Function 3						X

Figure 33. Example Operational Activities to Systems Matrix (SV-5b)

As mentioned earlier, architecture development is one of the most critical LSI functions. The architecture serves as the basis from which the SoS can be effectively managed, and is an essential enabler to decision making. The SoS Architecture Overview (Figure 24) illustrates the traceability (i.e., vision to capabilities to operations [functions] to systems) that can be achieved by an architecture that exhibits concordance.

Architecture Uses During the Mission Assurance Phase

The architectures initially developed during the SoS Architecture Development Phase are continually updated, and serve as a primary means to make decisions, throughout the System Design and Development and Mission Assurance Phases of the SoSE&I lifecycle. During mission assurance, the LSI can use the architecture to plan for constituent system certification and integration and to manage SoS risks.

Perhaps the most powerful application of the architecture is guiding the SoS assembly, integration, and certification (Sellers, Dam, & Vaneman, 2018). The term *certification* is used for SoS instead of testing or verification and validation. When a constituent system is available for integration into an SoS, system comprehensive verification and validation have already occurred. SoS certification seeks to determine if the SoS is going to behave as envisioned, and identifies interoperability before deployment. SoS certification is often performed by analysis, often leveraging exercises and experiments.

The SoS Integration and Certification (SoS.3.1) activity (Figure 20) is one of the most important activities performed by the LSI because this is where the strategy for integrating new constituent systems occurs. Various integration strategies exist, but the two most prevalent are integrating the constituent systems as soon as it becomes available, or integrating them during planned schedules.

The strategy for implementing constituent systems as they become available allows new capabilities to be fielded quickly. Given the scope of an SoS, this strategy does not allow for real-world certification. As such, the LSI must rely heavily on the SoS architecture to discover potential integration and performance issues in lieu of comprehensive certification. However, SoSs incur a significant risk that emergent behavior resulting from unforeseen interactions, and influences, introduced by the constituent system. Given the scope of an SoS, this strategy does not allow for real-world certification.

Integrating new constituent systems into the SoS may also occur during a planned schedule for integration and certification. While using this disciplined approach, the LSI can use the architecture to identify critical systems and processes that require extra attention to ensure compliance with the SoS capabilities. The costs, and scheduling, of conducting an SoS-wide test can be prohibitive when it includes assembling all participating systems, developing scenarios, and data collections and analysis.

For the LVC-TE, it is recommended that the strategy of planned integration and certification be used. SoS certification is essential because as a “system of simulators,” LVC-TE may potentially be used to do initial analysis on future Marine Corps Systems.

Risk analysis and management is one of the most important elements to model in any SoS as it touches on nearly every part of the SoS. Risks are assessed and mitigated throughout the “development” lifecycle of each constituent system. Figure 34 shows the risk matrices for System 1 (SN.1), System 2 (SN.2), and System 3 (SN.3) shown in Figure 31. These risk matrices contain only the risks identified by each individual system or program.

When considering SoS risks, the LSI analyzes the risks associated with each constituent system through an SoS prism. An architecture, that possess strong concordance through establishing entity relationships, allows for causally tracing constituent system risks through the architecture to identify areas where those risks may potentially impact other constituent systems, thereby causing SoS risks. A consolidated risk analysis of the three constituent risks matrices is shown in Figure 35. Upon evaluation of the risks associated with System 1, the LSI discovered that Risks 2, 3, and 4 only impact that system and therefore should be mitigated within that program. However, it was determined that Risk 1 impacts not only the system itself, but adds a risk at the SoS level. Casually tracing this risk through the SoS

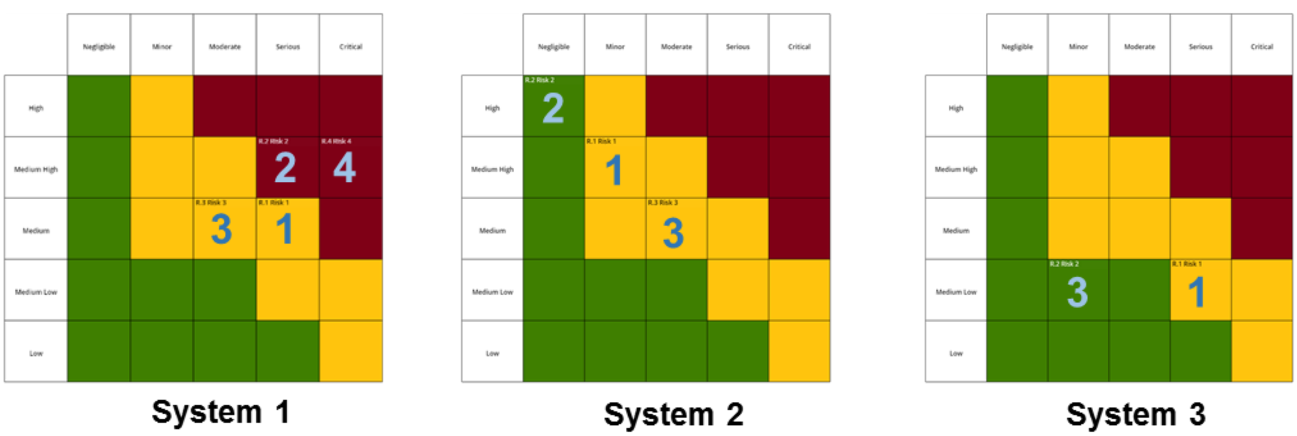

Figure 34. Risk Matrices for Three Constituent Systems

architecture, it was determined that an additional risk, Risk 4, had to be added to System 2 as a result of the SoS risk that we established because of Risk 1, System 1. Furthermore, System 3, Risk 3 was also added because of the dependence of System 3 to System 2.

The additional risks added to Systems 2 and 3 would not be visible from the system, or program, alone. It is important that the LSI conduct risk analysis at the SoS level, and convey the results across the entire SoS. It is equally important that the LSI at the system level understand the role of the constituent system in the larger capability, and consideration of the SoS role. Most constituent systems were/are designed to meet mission needs independent of an SoS. Constituent systems with a strong sense of belonging are more likely to identify ways they can support SoS objectives and accommodate need for changes within their lifecycle.

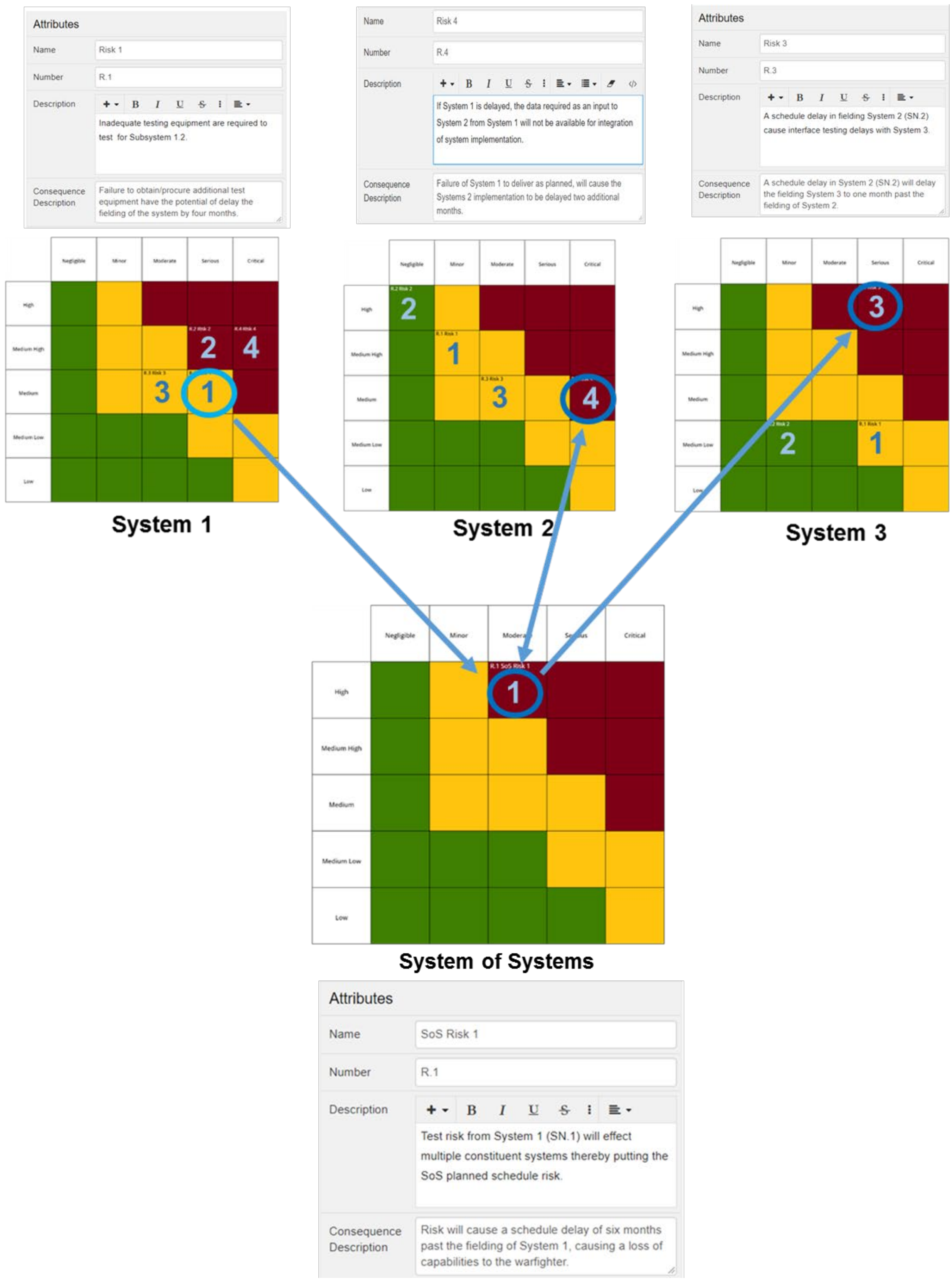

Figure 35. Risk Matrices for SoS and Constituent Systems

V. Conclusions and Opportunities for Future Research

> Almost all systems today operate as part of a large system of systems (SoS). Systems Engineers need to consider the SoS implications on the system at each stage of the system lifecycle.
>
> —International Standards Organization (2018)

A. Conclusions

This research developed an operational process for SoSE&I that flows efficiently through SoS development, deployment, and disposal. The questions for this research were as follows:

1. What is the correlation between Navy I&I, IT/TA, and LSI?
2. How can correlating the various development and acquisition processes for SoS and complex systems facilitate acquisition strategies that improve their belonging, connectivity, and integration to better satisfy mission objectives?

This research presented a new model and guidance for LSI and SoS development by combining strengths from two existing strategic documents:

- The Enterprise Lead Systems Integration (LSI) Framework
- The Navy Integration and Interoperability (I&I) Integrated Capability Framework (ICF) Operational Concept Document

Chapter II provided an overview of the I&I and LSI concepts and/or directives with respect to the SoSE&I "Vee." It was determined that neither LSI nor I&I defined a process that could "stand on its own." Moving forward, the I&I and LSI functions and processes were considered together and incorporated into a SoSE&I model as described in Chapter III. The model illustrates the interdependencies throughout the entire process flow from initial requirements through support of the fielded systems. This model can be used as a starting point and guidance for future SoS development. Chapter IV provided an application of the revised framework with respect to an existing DoD program (LVC-TE) that could benefit from implementing this new model during the early phases of the program.

This research sought to provide a more executable set of guidelines and processes for LSI professionals and SoS lifecycle development to use in conjunction with the LSI Enterprise Framework and the mission-based SoS guidance from the Navy I&I ICF document. The correlation between the LSI and I&I processes provides the blueprint for a more complete SoS governance approach. With some adjustments to the LSI Touchpoints and the additional gaps addressed in Chapters II and III, improved mission-based SoS development and LSI management can be achieved.

The enhanced LSI Enterprise Framework, used in current and future government LSI efforts, seeks to reduce risk in the affordable optimization of integrated warfighting capability acquisition efforts across the SoS lifecycle, and to increase the speed of capability delivery to the warfighter. LSI can be executed by the government within existing organizations via enhancements to legacy processes, methods, and practices if the workforce is trained and motivated to think and act differently. The LSI Enterprise Framework provides an effective set of tools, resources, and concepts to help incrementally incentivize this cultural evolution.

To achieve this goal, the Navy should increase SE, and SoSE&I, technical and management depth and breadth across the workforce by hiring professionals trained in advanced SE concepts. Candidates for LSI positions should be provided with a variety of experiences through workforce development, innovation, and cooperative exchanges/forums with both industry and government.

Additionally, a directed universal approach to SoS management, such as that presented in this report, should be implemented and enforced across the Navy Enterprise in order for LSI to be truly successful. Not only are well-trained personnel required to ensure success, but top-down directed guidance that is common to all Naval SYSCOMs for LSI in SoS will enable this approach.

B. Opportunities for Future Research

The engineering and management of an SoS will continue to evolve for the foreseeable future. The next steps in research of SoSE&I and LSI fall into three categories: continued definition and decomposition of the SoSE&I "Vee" and LSI

Enterprise Framework; defining SoS concept reviews as a means for assessing the heath and progress of the SoS; and, defining an MBSE approach for milestone and concept reviews.

Continued Exploration of SoSE&I "Vee" and the LSI Enterprise Framework

The following are additional questions that were not within the scope of this research and which are recommended for further exploitation:

- Further define the LSI processes during System Design and Development and Mission Assurance Phases of the SoSE&I lifecycle.
- Further expand on governance principles and concepts for LSI.
- Define billet descriptions and skill sets that are needed to perform LSI functions.
- Correlate the LSI model to apply across non-Navy development and acquisition and within other DoD organizations.

Defining the System of Systems Concept Review

One of the most pressing issues is how to assess the health of an SoS, since the constituent systems are developed independently and asynchronously. Figure 3 (in Chapter II) depicts the SoS concept review environment. In this example, the four partial lifecycles of the constituent systems that comprise the SoS are shown. These constituent systems need to be considered for their ability to contribute to the SoS during the concept review. Currently, the questions addressed by this SoS review go unanswered, thereby leaving decision-makers to rely on "best guesses" or "engineering intuition" to derive what the combination of constituent systems yield.

Some of the questions that should be addressed by SoS Concept Review are the following:

- Will the SoS be able to satisfy its defined capabilities throughout its lifecycle given that the SoS lifecycle is defined from the time when a capability is defined until a point in time when that capability is no longer required?
- What is the "health" of the SoS given the asynchronous lifecycles of the constituent systems?
- What is the predicted performance of the SoS throughout its lifecycle?

- Will the constituent systems successfully integrate into the SoS?
- How shall resources be prioritized to support the development and operations of the SoS and constituent systems?

Defining an MBSE Approach for Milestone Reviews

Milestone reviews are discrete points in time, within a system's lifecycle, where the system is evaluated against a set of program specific accomplishments (exit criteria). Exit criteria are used to track the technical progress, schedule, and program risks. The milestone reviews serve as gates, that when successfully evaluated, demonstrate that the program is on track to achieve its final program goals, and should be allowed to proceed to the next acquisition phase. Figure 36 shows the Systems Acquisition Lifecycle Model (Defense Acquisition University, 2018).

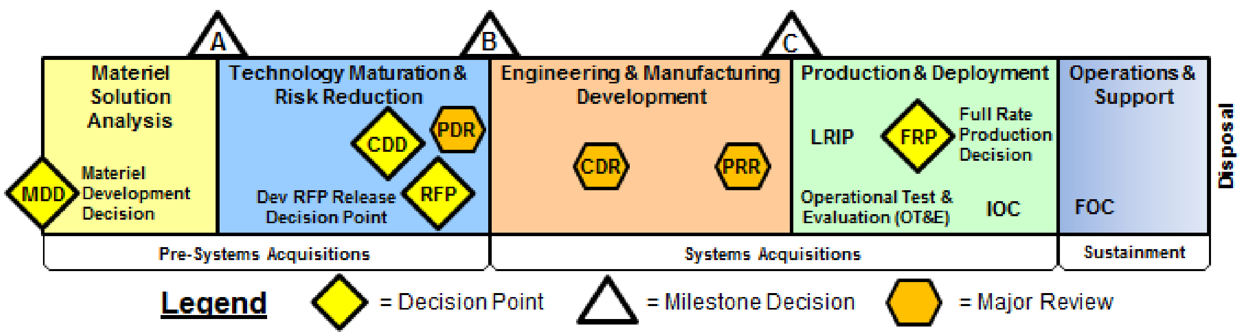

Figure 36. System Acquisition Lifecycle Model

Current milestone reviews are based around lengthy reviews of static, contractually obligated documents that are used to demonstrate successful completion of the exit criteria. Participants typically "freeze" these documents many days prior to reviews in order to provide baselines from which to synchronize various products used during the review. This baselining and eventual loss of concordance between products are the primary drawbacks when conducting reviews using document based methods.

As DoD organizations migrate to the MBSE environment, efficiencies will be gained by transitioning from the traditional paper-based reviews to model-based reviews. Model-based reviews allow for complexity to be managed more efficiently because data, in lieu of "systems engineering products," is the commodity that will be used to evaluate the exit criteria. The MBSE milestone reviews will provide greater insight with faster comprehension for the details across a program's lifecycle. This will not only provide efficiencies for the review, but will improve the program's cost and schedule efficiency.

The objective of this additional research is to define, and demonstrate, how DoD organizations can conduct milestone reviews in an MBSE environment. This effort requires an examination of current milestone review processes; a derivation of new MBSE processes that will provide the requisite system and programmatic information to satisfy the review criteria; and a demonstrated model-based milestone review environment. The following are the fundamental questions that will be answered by this research:

- What are the best practices for a traditional milestone reviews?
- How will the milestone review exit criteria change to the represent the MBSE environment?
- What are the potential benefits of utilizing an MBSE environment, and data, to develop and represent the data and information during milestone review?
- How will an MBSE milestone review be conducted?

This research is important to the LSI because to efficiently manage an SoS, a cohesive implemented MBSE strategy is required. This MBSE strategy is central to an SoS concept review. This strategy assumes the constituent systems are being represented with an MBSE approach.

C. Final Words

The Navy recognizes the need for early SoS development in a way that makes the overall fielding of Information Dominance capabilities less reliant on late integration efforts. This is instrumental in producing standardized solutions while preventing system failures in the long-term. Given the current fiscally-constrained environment, moving in this direction is a prudent course of action. However, many unaddressed questions (and possible obstacles) remain for the successful implementation of SoSE&I processes.

Over the coming years, the results of LVC-TE's implementation of LSI and the SoSE&I "Vee" will be demonstrated. It will become evident how LSI is used for the LVC-TE SoS throughout its lifecycle, and insights into a variety of concerns such as "How long do these processes take?"; "How many people do these processes require?"; and "What results have come from this approach?" will be understood. It is expected that the execution of these activities and the insights gained will advance the fields of SoSE&I and LSI.

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Appendix A Live Virtual Constructive Training Environment (LVC-TE)

A. LVC-TE Constituents

Marine Corps Enterprise Network (MCEN)

The SoS constituents that form the MCEN are depicted in the green box in Figure 23 (Chapter IV). Most instantiations of LVC-TE in support of a given training event will extend beyond the bounds of a single building or local area network (LAN). To move simulation and tactical data traffic around to these different geographical points, LVC-TE will use the MCEN. The two interesting exceptions to MCEN occur when Marines are training within a Joint training event (other network pathways are also used) and when traffic is exchanged via radio frequency (RF) means, such as with commercial or tactical radios (MARCOR, 2018).

Marine Corps Ground Training Systems Constituents

The following Marine Corps ground training systems constituents are managed by MARCORSYSCOM Program Manager Training Systems (PM TRASYS):

- Combined Arms Command and Control Trainer Upgrade System (CACCTUS)
- Combat Convoy Simulator (CCS)
- Deployable Virtual Training Environment (DVTE)
- Force on Force Training System (FoFTS)
- MAGTF Tactical Warfare Simulation (MTWS)
- Supporting Arms Virtual Trainer (SAVT)

These constituents have been fielded as standalone capabilities and must now be configured to integrate and interoperate with each other and other constituents, as shown in Figure 23, to meet the LVC-TE mission training and rehearsal requirements. An overview of each of these ground training system constituents is provided in the following paragraphs.

Command and Control Trainer Upgrade System (CACCTUS)

The CACCTUS is a combined arms staff training system that enables comprehensive Marine Corps staff, unit, and team training at home station Combined Arms Staff Training (CAST) facility. A typical CACCTUS training exercise is illustrated in Figure 37 (MARCOR, 2017b).

Figure 37. Typical CACCTUS Training Exercise

Distributed training involving CAST facilities is now available across the Marine Corps. CACCTUS is an upgrade to the Marine Corps' CAST that provides fire support training for MAGTF elements up to and including the Marine Expeditionary Brigade (MEB) level. CACCTUS immerses trainees in a realistic, scenario-driven environment using system components and simulation capabilities, 2D and 3D visuals, interfaced Command, Control, Communications, Computers, and Intelligence (C4I), synthetic terrain, and an AAR. The simulated scenarios enable commanders and their battle staffs to train or rehearse combined arms tactics, techniques, procedures, and decision-making processes prior to any physical engagement.

The CACCTUS will provide critical combined arms command and control integration and fire support coordination training to units prior to participating in live fire exercises and deployment.

Combat Convoy Simulator (CCS)

The CCS is an immersive training environment for convoy operations to include basic procedures for driver, gunner, and passengers in tactical scenarios related to combat operations. A typical CCS training exercise is illustrated in Figure 38 (MARCOR, 2017b). The simulator provides instruction in convoy operations to include resupply, patrol, logistics support, high-value target extraction, medical evacuation (MED-EVAC), calls for close air support, calls for fire, training in convoy tactics, techniques, procedures, and use of weapons in compliance with the rules of engagement (ROE) in realistic simulated combat conditions that account for terrain, weather, visibility, vehicle operating conditions, and opposing forces. The CCS also provides training for both vehicle operators and individuals in vehicle-mounted and small arms weapon utilization, C2, and improvised explosive device (IED) attacks, response, and countermeasures. CCS provides guidance for Marines to respond to ambush attacks and evolving enemy tactics in Military Operations on Urbanized Terrain (MOUT) settings.

Figure 38. Typical CCS Training Exercise

Deployable Virtual Training Environment (DVTE)

The Deployable Virtual Training Environment (DVTE) is a laptop-based simulation system developed to sustain the individual, team, and unit level critical warfighting cognitive skills associated with the application of combined arms, squad, and platoon level tactics, various recognition of combatants (ROC) packages, and language/cultural training. A typical DVTE training exercise is illustrated in Figure 39 (MARCOR, 2017b). DVTE is capable of emulating organic and supporting Infantry Battalion weapons systems and training scenarios to facilitate Training and Readiness (T&R)–based events while aboard ship, forward deployed, and in garrison or school house environments. DVTE software applications are divided into two groups: the Combined Arms Network (CAN) and the Infantry Tool Kit (ITK). The simulation programs range from individual skill sustainment to battalion-level operation.

Figure 39. Typical DVTE Training Exercise

The CAN uses GenSim software to provide combined arms training for Forward Observers (FOs), Forward Air Controllers (FACs), Fire Support Team (FiST) leaders, and various weapon systems (Assault Amphibious Vehicle [AAV], M1A1 Tank, Light Armored Vehicle [LAV], MV-22 Osprey, AV-8B Harrier and AH-1 Cobra). When connected to the Joint Semi-Automated Forces (JSAF), a constructive mission building platoon, DVTE can support combined arms missions up to the battalion level. In addition, DVTE can interface with Marine Corps Green Gear in order to facilitate training for a variety of fire support missions. Combined arms, enduring combat actions, First-aid/Casualty Evacuation (CASEVAC), fixed site security, IED defeat, motorized operations, and MOUT are among the Marine Corps Common Skills addressed by the various DVTE training games and simulations. One of the software components of the ITK is Virtual Battle Space (VBS) in which individual students or groups of students can interact to complete mission scenarios in a first-person-shooter format. Instructors can create scenarios to meet unique mission objectives and make real-time modifications to the scenario environment as students complete the mission. Instructors have the ability to control all scenario environment features to include terrain, the position and presence of structures and obstacles, the presence and behavior of constructive entities, weather, vehicles, and weapon capabilities. VBS also has a playback capability that supports student debriefs after scenario completion.

DVTE trains and reinforces MAGTF/combined arms coordination warfighting skills, maintaining individual and unit readiness during periods of training while deployed or embarked. DVTE is employed by commanders as a T&R tool to assist in evaluating individual and unit proficiency, as well as in the augmentation of their training programs. DVTE assists in maintaining their unit's proficiency and currency through a continual application and remediation of individual and collective combat skills.

Force on Force Training System (FoFTS)

The Instrumented Tactical Engagement Simulation System II (I-TESS II) is used to support direct force-on-force tactical engagement training as part of the Force on Force Training System (FoFTS). A typical FoFTS trainee is shown in Figure 40 (MARCOR, 2017b). This system consists of the following components: Small Arms Transmitter (SAT), Man-worn Detection System (MDS), C2 (mobile and portable versions), MOUT building instrumentation, and simulated battlefield weapons. The SAT is used on multiple rifle types and machine guns. The MDS and range equipment provides the individual Marine direct force-on-force engagement adjudication and includes the ability to support instrumentation functions such as Position Location Information (PLI) reporting.

The I-TESS II system is used in MOUT Facilities and Non-Live Fire Maneuver Ranges located at various Marine Corps bases and installations, providing the appropriate setting for the Marine Corps Pre-deployment Training Program (PTP) and other individual and company level training support. The Marine Corps has expressed a need to acquire and deliver training systems that provide real-time situation awareness, exercise control capabilities, and adjudicate indirect fire engagements to help facilitate training exercise objectives. I-TESS II collects the training actions/interactions of the Marines during the training exercise and has the ability to provide immediate access of collected data for AAR. I-TESS II will provide 2,400 MDS devices to instrument Marines at Marine Corps Base (MCB) Quantico, VA (MCBQ), Camp Lejeune, NC (CLNC), Camp Pendleton, CA (CPCA), MCB Hawaii (MCBH), MAGTF Training Center (MAGTFTC) Twentynine Palms, CA (Twentynine Palms), and Marine Corps Mountain Warfare Training Center (MCMWTC) Bridgeport, CA, with expected future deliveries to Camp Hansen, Okinawa, and MCB Guam.

Figure 40. Typical FoFTS Trainee

MAGTF Tactical Warfare Simulation (MTWS)

The MTWS is the Marine Corps' only constructive, aggregate-level simulation system used to support the training of Marine commanders and their battle staffs in MAGTF war-fighting principles/concepts and associated command and control procedures. A typical MTWS training exercise is illustrated in Figure 41 (MARCOR, 2017b). Using complex computer-simulation behavioral models, MTWS provides an interactive, decision-based, real-time, war game representing the six war-fighting functional areas. With interfaces to fielded Marine Corps C4I systems such as Command and Control Personal Computer (C2PC) and Intelligence Operations Server (IOS), MTWS provides the battle staff the ability to seamlessly train with and use their C4I systems during the execution of an MTWS-supported training event. Its modeling breadth and flexibility enables users to represent and exercise a wide variety of combat scenarios to prepare leaders for today's military challenges. MTWS is designed to support the training of commanders and their staffs in exercises involving LVC land, air, and Naval forces at all operational command levels. The system supports all levels of command throughout the MEF and Joint Task Force (JTF).

Figure 41. Typical MTWS Training Exercise: Supporting Arms Virtual Trainer (SAVT)

MTWS is also an automated exercise scenario driver with stop/backup and replay capabilities that can interface with tactical C2 combat systems. Weapons characteristics and parametric data are held in a dynamic data repository, allowing simulation of real or constructive forces to include all four elements of the MAGTF. The central operational objectives of MTWS include preparing Marines for the integrated and automated battlefield, synthesis of combat information and graphical (digital) control/display of the battlefield in all phases, and all warfighting functions. With the capabilities provided by MTWS, Marine units will gain significant combat training advantages.

The SAVT enhances operational readiness and tactical proficiency of Marine Corps Joint Terminal Attack Controllers (JTACs), FOs, and FACs. A typical SAVT training exercise is depicted in Figure 42 (MARCOR, 2017b). The simulator provides Marines with a virtual environment for training to scenarios that require the placement of tactical ordnance on selected targets using Joint Close Air Support (JCAS) and observed fire procedures. These scenarios allow for practical application of Naval Surface Fire Support (NSFS), artillery and mortar fire, neutralization, suppression, illumination, interdiction, and harassment fire missions.

With recent Marine Corps doctrinal changes, a JTAC memorandum of agreement and certification by Joint Forces Command (JFCOM) of the Navy's Multipurpose Supporting Arms Trainer (MSAT) and the Marine Corps SAVT, simulation events can replace certain Marine Corps live fire controls and Joint Service currency training requirements. Future system upgrades will increase the number of events/controls that can be conducted using a SAVT, thereby reducing the need for costly live fire controls.

Figure 42. Typical SAVT Training Exercise

Other Models and Simulations as Constituents

This category of systems is one that Program Manager Training Systems (PM TRASYS) can assert less than direct influence and control in its direction and evolution. One example is when a commercial tool or system is used. LVC-TE may include the tool or system in the SoS, or it could take the system as-is or have a limited ability to modify the system. Another example includes the adoption of a system completely owned and controlled by another service or government organization. The Aviation Distributed Virtual Training Environment (ADVTE) and Joint Deployable Logistics Module (JDLM) are prominent examples. In both cases there may be limits on the ability for the LVC-TE program to influence and direct the evolution of the tool. Approaches to mitigating such circumstances include participating in external Configuration Control Boards (CCBs) and redirecting funding to ensure funding alignment through resource re-allocation when LVC-TE unique requirements exist. Other systems within this category (e.g., Cyber, Space, and Information) represent systems that could be identified as required by LVC-TE, though it may not be prudent to own within a Marine Corps portfolio. The LVC-TE Analysis of Alternatives (AoA) is currently considering such tools for inclusion within LVC-TE (LVC-TE Acquisition Strategy, 2018).

Tactical C2 Systems

This category of systems includes both C2 and mission planning tools used by the training audience within an LVC-TE supported training event. Joint Tactical Common Operational Picture (COP) Workstation (JTCW), Common Aviation Command and Control System (CAC2S), and MAGTF Logistics Support Systems (MLS2) are specifically identified. Aside from the above tactical C2 systems and their constituent systems, many other tactical C2/planning tools have been discussed within the LVC-TE AoA. The Marine Corps Combat Operations Center (CoC), MAGTF Deployment Support System II (MDSS II), and Joint Operation Planning and Execution System (JOPES) are but a few of these additional C2/Planning systems. The outcome of the LVC-TE AoA will aid in creating a prioritized baseline of such systems. As previously discussed, accurate ICDs and MOAs will be critically important in managing the LVC-TE interfaces for these systems (LVC-TE Acquisition Strategy, 2018).

Training and Readiness Systems

A significant requirement of LVC-TE includes the exchange of individual Marine and unit level training data between LVC-TE and various training and readiness systems. In addition to training records, both Marine Corps Tasks (MCTs) and T&R event data are exchanged between LVC-TE and these external systems. Specific systems identified in the Design Reference Mission (DRM) include the Marine Corps Training Information Management System (MCTIMS), Marine-Sierra Hotel Aviation Readiness Program (M-SHARP), Range Facility Management Support System (RFMSS), and the Defense Readiness Reporting System-Marine Corps (DRRS-MC; LVC-TE Acquisition Strategy, 2018).

Facilities and Ranges

LVC-TE supported training events require spaces, places, logistics support, technical support, administrative support, and network access to conduct their training. The Battle Simulation Centers, Operations Centers, battalion and squadron classrooms, conference rooms, training areas, numbered ranges (e.g., Range 220 at Twentynine Palms), and other facilities must be available and sufficient to support LVC-TE events. Whether these capabilities are locally MEF/MCB owned/managed or centrally managed through Marine Corps Installations Command (MCICOM) drives the coordination and planning that needs to occur between LVC-TE program management and others. Factors such as the last tactical mile of the network and sufficient space for the training audience can become critical to the success of LVC-TE supported training events (LVC-TE Acquisition Strategy, 2018).

Joint Training Interoperability

Marines train in both Marine-only training events, as well as training events that can be Joint, Interagency, Intergovernmental, and Multinational (JIIM). In the latter case, the context is critically important. External to the Marine Corps, operating forces encounter training events using tools such as the Joint Live Virtual Constructive (JLVC) federation and Joint Land Component Constructive Training Capability (JLCCTC) federation. The LVC-TE capability must be interoperable with these external federations. Each of these federations are SoS in their own right and evolve over time. When Marines participate in a Joint or multi-service event, there is a need for LVC-TE integration and interoperability. To ensure this happens effectively, appropriate interfaces must be proactively managed over time to ensure interoperability. It is worth noting that some of the LVC-TE constituent systems already have a level of interoperability with these Joint federations, though most others do not. The LVC-TE AoA's specific material solution decisions will require a dedicated effort during the development phase to ensure LVC-TE maintains an appropriate level of Joint Training Interoperability (LVC-TE Acquisition Strategy, 2018).

B. LVC-TE Applied to the SoS Architecture and Requirements Development Phase

LVC-TE will drive requirements associated with new integration, interoperability, and functionality for constituent LVC-TE systems. In such cases, existing LVC-TE constituent systems must be modified and a disciplined engineering process provided through an LSI. This will be essential to the SoS's success and will ensure LVC-TE requirements are properly allocated and traced as they flow down to its constituent systems.

LSI, by definition, is an acquisition strategy that employs a series of methods, practices, and principles to increase the span of both management and engineering acquisition authority and control to acquire highly complex systems (NPS LSI Cohort #1, 2014). LVC-TE will be acquired through a government team functioning as the LSI, and software development will occur through the implementation of a software product line (MARCOR, 2018).

The result of effective LSI is effectively a "marriage" of program management and multiple functional disciplines that must work together cooperatively to assert and execute trade space in complex SoS acquisitions. Affordability is a key objective that requires a balancing (or optimization) of multiple factors to deliver an integrated warfighting capability.

As previously stated, the LVC-TE is currently in the MSA phase of the Department of Defense Architecture Framework (DoDAF). It is imperative that its AoA is well informed, timely in its analysis of technology alternatives, and accurate in its findings. Otherwise, the MSA phase risks making an incorrect or inaccurate recommendation to the Milestone Decision Authority (MDA). When correctly used, the LSI function coupled with the disciplined approach of the SoS Architecture & Requirements Development model can help reduce risk during the MSA phase and ensure a successful AoA.

The AoA Study Plan, developed in accordance with Chapter 3.3.3 of the *Defense Acquisition Guidebook*, requires the identification of and subsequent participation by all pertinent stakeholders (Defense Acquisition University, 2018). The senior members of the AoA effort will then form a study advisory group (SAG) that will function as an overarching integrated product team (IPT) to ensure the study director and study team are properly guided, staffed, and resourced for success. The formation of the working level study team, however, is a more complex undertaking. The AoA study team consists of four working groups that must collaborate with one another in order to achieve a successful outcome. The Operational Concepts and Scenarios Working Group (OCSWG), Effectiveness Working Group (EWG), Technology and Alternatives Working Group (TAWG), and the Cost Working Group (CWG) must also be empowered by the appropriate stakeholders. The Stakeholder "Architecture" depicted in Figure 24 and **Error! Reference source not found.** provides a robust and disciplined approach for determining the stakeholders that should be assigned to the SAG and each of the AoA study team working groups. In this manner, the Stakeholder "Architecture" influences each of the Level 2 functions in the SoS Architecture & Requirements Development model.

Figure 43 represents the upper left-hand portion of the SoSE&I "Vee," specifically functions SoS 1.1 through 1.4, and coincides with the MSA phase. Using this disciplined approach from the beginning of the AoA would have ensured the LVC-TE emerging program had the required AoA stakeholders in place more quickly. Instead of adhering to such an approach, an ad hoc process was used in the LVC-TE's MSA phase to identify its stakeholders. These results are summarized in Table 4 (MARCOR, 2017a).

This table was subsequently used to begin the process of assigning stakeholder representatives to the AoA SAG and study team. Table 4 illustrates the complexity of the Stakeholder "Architecture" for LVC-TE, but does not provide the stakeholders' dimensions (operational, acquisition, and resource sponsor), levels (enterprise, mission, system, and subsystem), or characterization (importance, influence, commitment, and engagement) that the application of the Stakeholder "Architecture" depicted in Figure 24 and Figure 32 would have provided. If this Stakeholder "Architecture" had been used, the AoA SAG and Study Team would have been more quickly established with the correct personnel and no stakeholder dimension/level gaps, thereby increasing the likelihood of a successful outcome for the AoA.

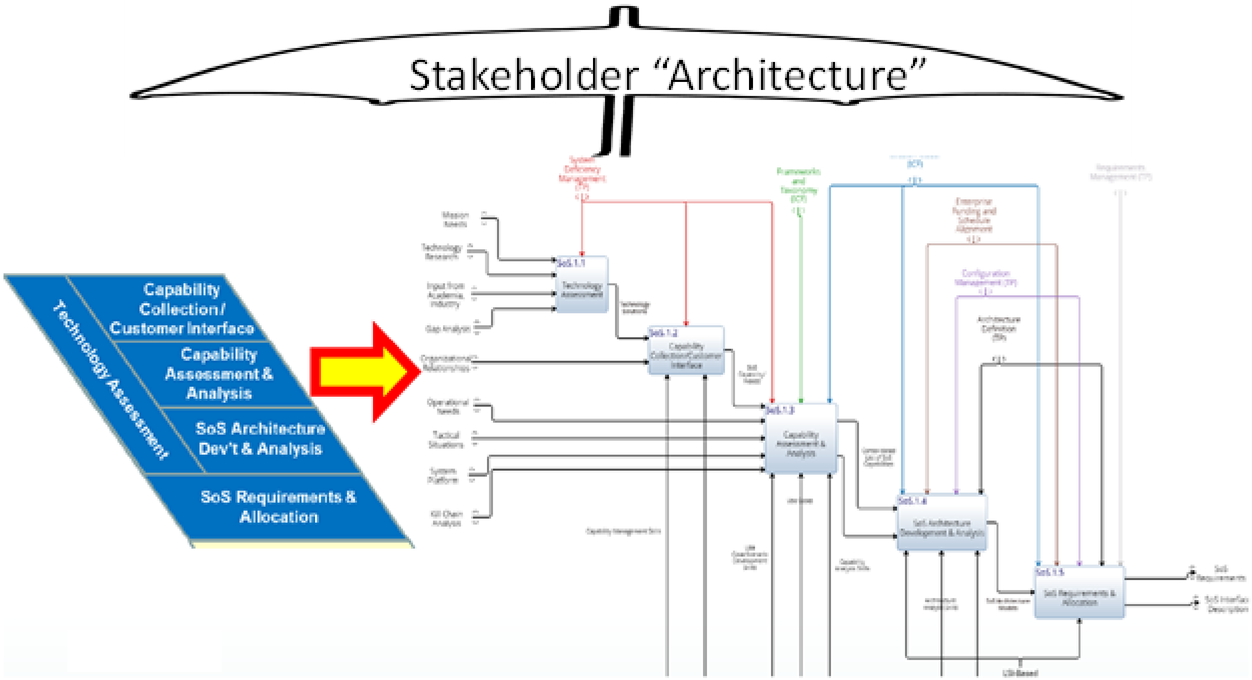

Figure 43. SoS Architecture & Requirements Development Decomposed

There are a number of technology alternatives that must be evaluated for their ability to contribute to the enterprise level LVC-TE capability. These technologies must be quickly and effectively assessed for how well they will provide the required capabilities using the prescribed.

Measures of Effectiveness (MoEs) and Measures of Performance (MoPs) for each of the required mission level scenarios while also evaluating their effect(s) on the SoS's lifecycle cost. Additionally, the current rate of technological advancement and innovation means the "cloud" of available technology alternatives is evolving at a rapid pace. In order to reduce the scope of the AoA to a manageable level while simultaneously reducing technical risk, the technology alternatives were limited to those at a Technology Readiness Level (TRL) 6 or greater. TRL 6 is defined as a system or subsystem model or prototype that has been demonstrated in a relevant environment (Office of the Deputy Under Secretary of Defense for Science and Technology, 2003).

Table 4. LVC-TE AoA Study Team Stakeholders

LVC-TE AoA Study Team						Key: M = Member M* = Membership contingent upon output of OCSWG R = Reviewer
Organization	Study Dir	CWG	EWG	OCSWG	TAWG	Stakeholder Interest
MCSC, Director Ops and Programs	TBD	Lead	Lead			RTP; MOEs/MOPs (EWG)
TECOM, TECD		M	M	Lead		G-6, TCOM, EDCOM, TESD, MCIS
TECOM, MSTP			M	M		MSTP MEFEX Training Events, C2 Training (C2TECOE)
TECOM, MAGTF-TC,			M	M		MCLOG, MCTOG, MAWTS, MWTC Training Events
MCSC, PM TRASYS		M	M		M	Ground Training Systems
MCSC, PfM CES		M			M	Ground C2 Systems
MCSC, PfM SES		M			M	Supporting Establishment Systems
MCSC, PfM LCES		M			M	Logistics Combat Element Systems
MCSC, SIAT			M		M	RAM (EWG), Technology Readiness Assessment (TAWG)
HQMC, C4					M	Cybersecurity, MCEN RMF Accreditation, Circuit Provisioning
HQMC, DC, AVN		M	M		M	Aviation C2 Systems
HQMC, DC, I&L			M		M	Regional Networks, Facilities (TAWG)
HQMC, DC, P&R, PA&E		M				Lead for Affordability Analysis within CWG
PEO LS, PM AC2SN		M*			M	Aviation C2 Systems
PEO EIS, PM GCSS-MC		M*			M	Logistics C2 Systems
MCCDC, OAD, MCMS MO			M			Operational Analysis
DC CD&I, Futures Directorate				M		Future Concepts and Technology
MARFORCYBER					M	MCEN Operations, MCCOG
MCOTEA			R	R		Operational Test Requirements
Marine Forces, G7, G3			M	M		Homestation Training
Independent Technical Expert		M	M	M	Lead	AoA Data Collection and Analysis

However, if a lower TRL was initially considered for later implementation it would have allowed a plan to be developed further out. For example, if an application is TRL 4 today we can project when it will be TRL 6 or higher and can track the progress of the application as it progresses towards TRL 6. The disciplined approach of the SoS Architecture & Requirements Development model (Level 2), as seen in Figure 16 beginning with the Technology Assessment function, will allow the Technology & Alternatives Working Group (TAWG) to have a consistent, repeatable process for evaluating the large number of candidate technologies. Once a technology solution has gone from the Technology Assessment phase through the SoS Architecture Development & Analysis phase to become a SoS Architecture Model, the stakeholders can evaluate the planned allocation of requirements and determine if the demonstrated technology meets the mission capability requirements. Furthermore, there are cases where the introduction of new capabilities by one constituent creates additional gaps for the SoS which require further refinement through this iterative/recursive process. The model helps to identify processes and inputs that will be repeated to achieve the desired end state. In this manner, the TAWG can efficiently evaluate a number of candidate technologies and provide the SoS Requirements and Interface Description for the Systems Design and Development phase.

In addition, the SoS Architecture and Requirements Development processes first established and used in the MSA phase will continue to be useful throughout the LVC-TE SoS lifecycle. The capability to quickly and efficiently evaluate new technologies and alternatives will pay dividends by accelerating “Speed to the Fleet” as new SoS requirements emerge.

In summary, LVC-TE, through a disciplined application of the Stakeholder “Architecture” and the LSI acquisition strategy, will have a greater probability of achieving the desired SoS distributed collective training and mission rehearsal capability that is persistent, easy to use, and affordable. LVC-TE will provide enhanced service-level and home station training and mission rehearsal capability that will feature the integration of live participants, virtual simulators, and constructive scenarios. This shared synthetic training environment will be immersive and capable of providing the “reps and sets” for warfighters to increase their combat readiness. LVC-TE will support both large and small exercises/training events within the Marine Corps and other services (to include joint, interagency, and coalition partners) to meet operational needs and commanders’ priorities. Without the processes outlined by the SoSE&I “Vee” and the effective use of government LSIs, there would be considerable risk that this important enterprise-level capability would not be achieved.

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