SYM-AM-15-110

PROCEEDINGS
OF THE
TWELFTH ANNUAL ACQUISITION RESEARCH SYMPOSIUM

THURSDAY SESSIONS
VOLUME II

Orchestrating the Development of a Complex System of Systems: Systems Engineering Tools and Methodologies

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Published April 30, 2015

ACQUISITION RESEARCH PROGRAM
GRADUATE SCHOOL OF BUSINESS & PUBLIC POLICY
NAVAL POSTGRADUATE SCHOOL

The research presented in this report was supported by the Acquisition Research Program of the Graduate School of Business & Public Policy at the Naval Postgraduate School.

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Orchestrating the Development of a Complex System of Systems: Systems Engineering Tools and Methodologies

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Introduction

Acquisition efforts are under increasing pressure to deliver systems rapidly and at lower cost while providing enhanced performance capability. This is happening in an environment where research and development budgets are decreasing across the Department of Defense (DoD), the acquisition workforce is rebuilding, and the DoD is looking to rebalance warfighting portfolios. This has been compounded by an extremely dynamic environment of fiscal change and uncertainty imposed by significant budget cuts and sequestration impacts in the recent past.

The overall trend of DoD budgets has been declining. The president's fiscal year (FY) 2015 budget recognizes the fiscal imperative of deficit reduction, reducing projected defense budgets by about $113 billion over five years compared to levels requested in the FY2014 budget (DoD, 2014). As a percentage of Gross Domestic Product (GDP), the DoD budget has been declining from approximately 15% in the mid-1950s to around 3% today. The growth in the DoD's costs under the Congressional Budget Office (CBO) projection of the base budget is somewhat less than the CBO's (2014) projection of the growth of the U.S. economy, decreasing slowly from 2.8% of GDP in 2015 to 2.5% in 2025, and 2.3% in 2030.

One outcome of the fiscal pressures has been an increase in defense acquisition efforts that are focused on the rapid development and fielding of an integrated system of systems (SoS) capability. Many of these SoS leverage mature systems and sub-systems as "constituent" systems but do not contract directly with industry to deliver the integrated capability. Elements of the DoD acquisition workforce are therefore taking on increasingly technical roles and responsibilities as the lead integrators for complex SoS. It should also be noted that the acquisition workforce (AWF) has declined by more than 50% since the 1990s, while the value of Department of the Navy (DoN) contracting has increased by more than 50%. With these significant AWF losses and attendant workload increases, the DoN recognized the loss in ability to manage the technical-cost tradespace it is responsible to execute, including major weapons systems acquisition (DoN, 2010). While the DoN AWF has grown by more than 20% (DoN, 2015) since 2010, some program managers are still challenged with staffing and resourcing an acquisition workforce with the technical depth to assume the increasingly technical roles associated with the development and fielding of an inherently government SoS capability. In many cases, the Naval Warfare Center and Systems Center's engineering workforce is tasked to supplement the acquisition workforce with technical subject matter expertise in systems engineering, rapid prototyping, development and integration, test and evaluation, operations analysis, and other inherently government roles.

Several novel systems engineering tools and methodologies have been developed to support the lead SoS engineer (LSoSE) with assessing system performance, system readiness, and risk through incremental development of a complex SoS. This paper will review the systems engineering processes and required level of technical rigor to manage the development and integration of a complex SoS in a distributed environment. A specific implementation of a Kill Chain framework that was designed to provide the PM and LSoSEs with comprehensive insight into the technical status and major risks for a complex SoS across specific mission threads will be presented. This paper will also review some of the systems engineering tools and methodologies developed and implemented by the Littoral Combat Ships (LCS) Mission Modules (MM) Program Office (PMS 420) that support the LCS MM Kill Chain framework.

LCS Program Overview and Background

Acquisition Strategy

The Flight Zero Capability Development Document (CDD) for the Littoral Combat Ship (LCS) was approved in April 2004 and established the requirements of the LCS and three "focused" missions. Each Mission Package (MP) provides warfighting capability for one of three focused mission areas:

- Mine Countermeasures (MCM)—Detection and neutralization of mine threats
- Surface Warfare (SUW)—Maritime security missions and fleet protection from small boats and other asymmetric threats
- Anti-Submarine Warfare (ASW)—Countering shallow water diesel submarine threats

The CDD was updated in 2008 to the current Flight 0+ version which included several requirement updates, which were used to drive the design for the full "production" versions of the seaframe and MPs. MP specific requirement updates included the Net Ready Key Performance Parameter (KPP), Material Availability KPP, and others.

In 2003, the LCS MM Program Office (PMS 420) was established as part of the Program Executive Officer (PEO) for Littoral and Mine Warfare (LMW). PMS 420's responsibilities originally involved end-to-end LCS MP development and lifecycle support. In 2011, PEO LCS was established to align several program offices into one consolidated PEO focused entirely on delivering the LCS Program. This included the establishment of PMS 505 to assume the responsibility for Fleet Introduction and Sustainment of Mission Modules and the seaframes. PMS 420 continues to rely heavily on Participating Acquisition Resource Managers (PARMs) to deliver mission systems to meet LCS MP specific requirements and is effectively the lead SoS integrator of this complex system of manned and unmanned systems. Examples of PARM systems include manned helicopters, sensor systems, weapons systems, and unmanned aerial, surface, and sub-surface vehicles. In some cases where commercial or government technology solutions cannot be identified, PMS 420 works with the naval science and technology (S&T) community to conduct accelerated development of non-POR technologies.

The LCS MMs are being developed and delivered using a rapid fielding approach where initial increments are fielded as the PARM technology matures and is integrated into useful elements of capability. Key to enabling this incremental development has been the definition and configuration management of standard interfaces between the seaframe and the MPs, as defined in the Interface Control Document (ICD) for the LCS. This approach allows the seaframes and MMs to mature independent of each other's development and facilitates reconfiguration of the LCS seaframe and incremental upgrade of the modular MPs over their life cycle. This independence of interfaces, which are managed by the common ICD, allows both programs to develop and test against their unique KPPs, key system attributes (KSAs), and milestones. This effectively enables the MP incremental fielding approach. Useful increments of capability are fielded, which build upon the initial capabilities, ultimately satisfying the full KPP requirements with the final increment. The incremental approach to delivering fleet capability also allows continued capability insertion throughout the life of the program. Capability Production Documents (CPDs) are developed to describe the capabilities required to meet the production baseline for a specific increment and also provide a testable requirement for the test community.

The LCS MM acquisition strategy leverages an organic Navy workforce, which provided flexibility to accommodate requirements refinement as the initial MP capability matured. This effectively reduced the Navy's exposure to cost and contract risk with industry throughout the early prototyping phases. The various lead SoSEs are aligned to their respective chartered mission areas as shown in Figure 1 (i.e., Naval Surface Naval Surface Warfare Center [NSWC] Panama City Division is the LSoSE for the MCM MP, NSWC Dahlgren Division is the LSoSE for the SUW MP, Naval Undersea Warfare Center [NUWC] Newport Division is the LSoSE for the ASW MP, while SPAWAR Systems Center [SSC] Pacific provides overarching SoSE support for cross-package requirements and architecture activities).

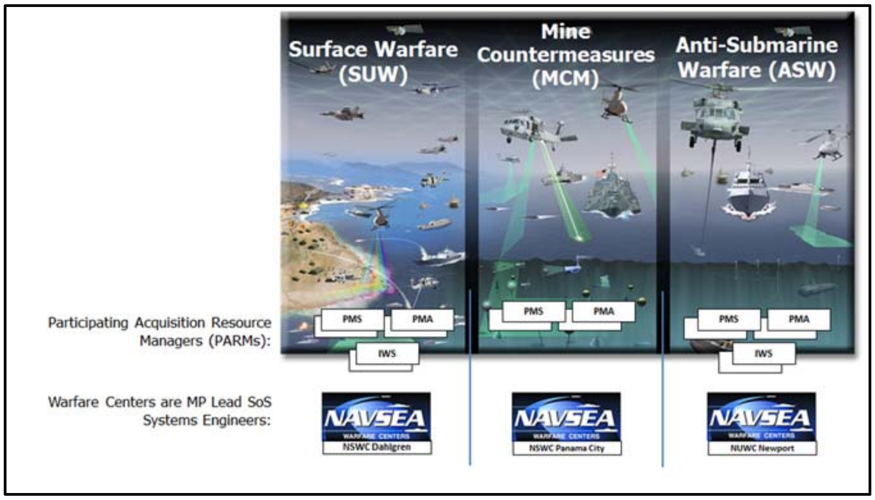

Figure 1. LCS MM Lead SoS Systems Engineers by Mission Area

In a departure from the traditional prime integrator role, industry supports the LCS MM program as the Mission Package Integrator (MPI) to perform production, packaging, and assembly (PP&A) functions. The MPI role is limited and focuses on productionizing systems and equipment once a useful capability has been demonstrated. The various Naval Warfare and Systems Centers continue to assume primary responsibility of developing and integrating the initial MP increments through initial testing, fieldings, and early deployments as the LSoSE. The LCS MM acquisition workforce has also been supplemented significantly with functional area subject matter expertise as available from the various Navy Warfare and Systems Centers to provide cross MP support in areas which include, but are not limited to the following: System Safety, Environmental Safety and Occupational Health, Information Assurance/Cybersecurity, Configuration Management, Human Systems Integration, Corrosion Control, and so forth.

LCS Mission Package and Open Architecture

The LCS MMs program was founded on the principles of incremental acquisition, open system architecture, and an open business model. As previously discussed, incremental acquisition promotes fielding of needed capabilities as they become available. Standard interfaces and an open business model enable more rapid integration of PARM and other systems as they mature. The LCS MM reference architecture is shown in Figure 2. It is a high-level, system-agnostic block diagram that articulates functional as well as business dimensions. It is not intended to be the primary design tool, but is used by the lead SoSE and Program Manager (PM) to easily communicate SoS boundaries and interfaces with internal and external stakeholders, the S&T community, and other stakeholders. Additionally, it is used as the basis to establish boundaries for configuration management and certification events.

“Focused” warfare MPs are designed to be installed on an LCS one mission at a time with the LCS Combat System providing the MPs with access to the seaframe hosted information technology (IT) infrastructure, sensors, weapons, countermeasures, and communications reachback through Exterior Communications (EXCOMMS). Functionality provided by the MP Combat System includes, but is not limited to computing, communications, mission planning, execution, and post-mission analysis. MP manned and unmanned vehicles may be augmented with specific weapons, and/or sensors, and/or countermeasures to execute a focused mission. The level of detail of the reference architecture does not allow for the arrows to depict the specific data path, but implies connectivity at the end points.

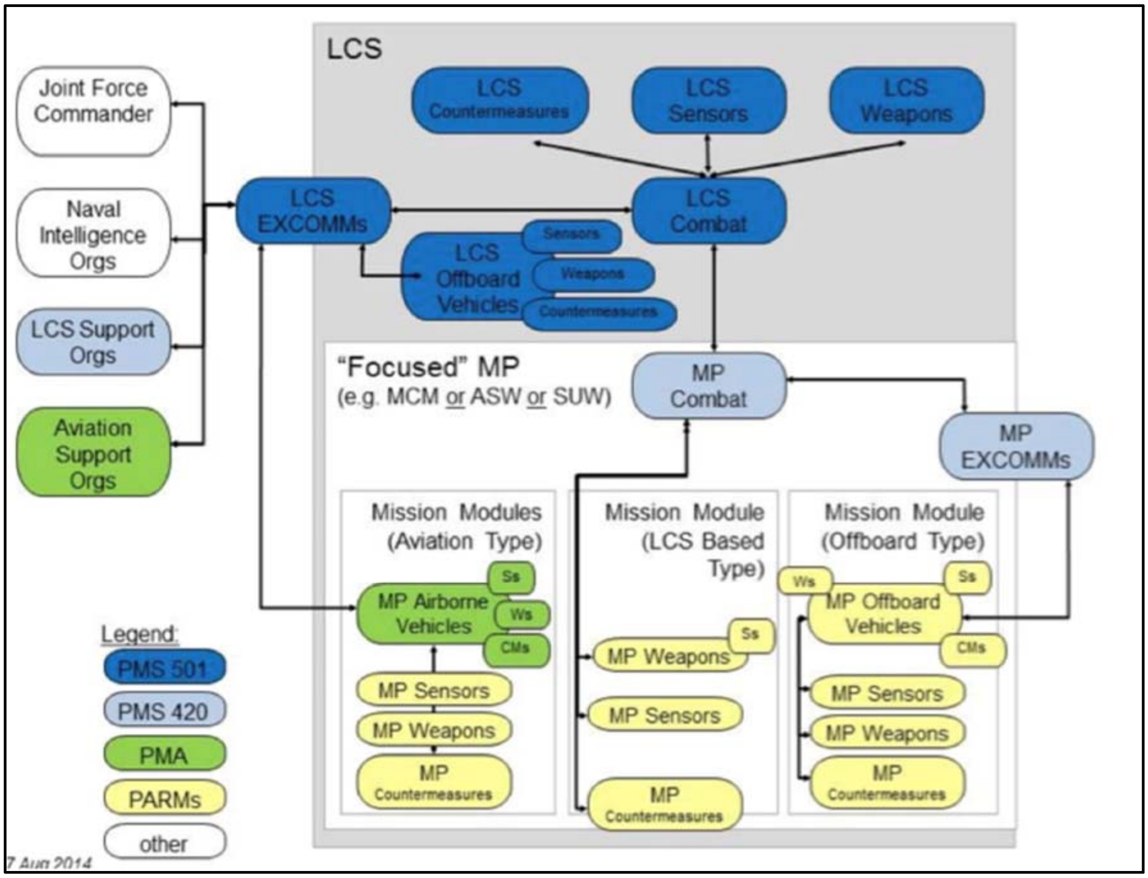

Figure 2. LCS MMs Reference Architecture

Requirements, Architecture, and Interface Models

Orchestrating the development of a complex SoS requires clear communication and organization of requirements in ways that clearly derive and allocate requirements as well as define boundaries between where responsibility lies and where negotiation may be required between program offices, Systems Commands, or other stakeholders. The LCS MM specific example is further challenged by the need to manage multiple increments at varying levels of maturity and cost targets which drove concerted efforts to identify common services, hardware, and systems.

This requires a robust and disciplined SoSE activity to first decompose the high-level requirements communicated in the CDD and CPDs, and to then perform the detailed analysis required to support the technical and cost trades needed to ensure that the architecture, requirements, and interfaces are developed and maintained at a sufficient level of detail to ensure the development of a capable and cost effective SoS capability. A cross-MP Systems Engineering Integrated Product Team (SEIPT) was established at the working level responsible for developing requirements, architectures, and the associated SE tools and processes required to support the development of complete, verifiable, and cost effective functional and allocated baselines for the MPs which dictate the development of the LCS MM SoS. As various increments proceed through the development, PARMs and other external stakeholders are engaged as required to ensure that requirements and interfaces are understood and managed effectively. A series of Technical Interchange Meetings (TIMs) are typically held as a specific increment proceeds toward a formal Systems Engineering Technical Review (SETR; i.e., Preliminary Design Review [PDR], Critical Design Review [CDR], etc.). The LCS MM requirements framework was developed by the SEIPT and provides a hierarchical framework used to derive and allocate top-level requirements, prescribed by the CDD, down to the Mission Module and Mission System levels.

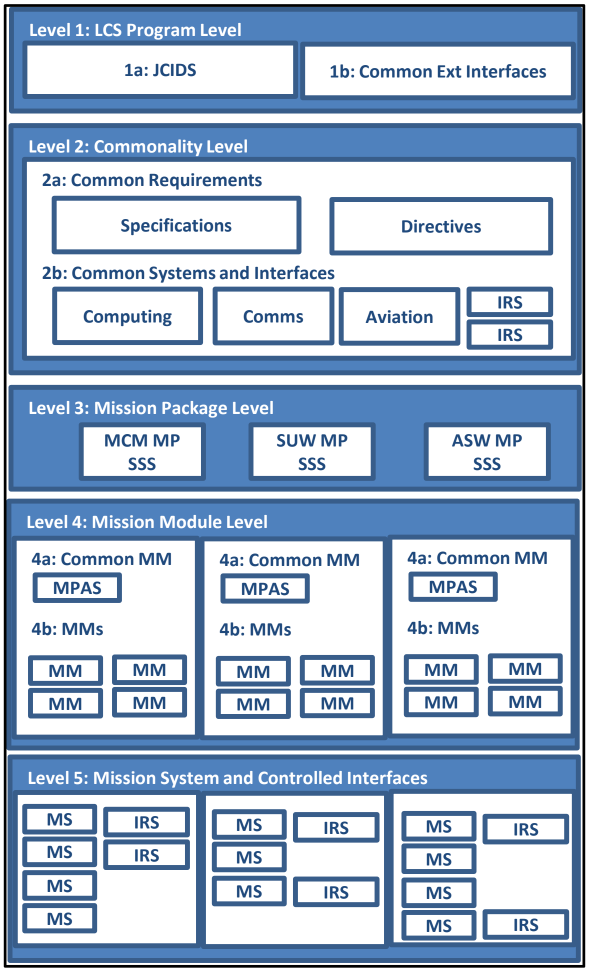

Figure 3. LCS MMs Requirements Framework

Level 1 requirements are defined as program level requirements provided by external sources. Level 1a requirements are developed by the user through the Joint Capabilities Integration Development System (JCIDS) process. For example, the LCS Flight 0+ CDD provides the required performance attributes for the initial MP Increments, and the Incremental CPDs provide the specific performance attributes in support of the incremental production and fielding of the MPs. Level 1b requirements define common external interfaces which are typically outside the span of PMS 420 or the LSoSE's control. Level 2 requirements are defined as the common requirements developed by the LSoSE. These “common” or Level 2 requirements are typically driven by open architecture, cost savings, or other acquisition-type objectives. Level 2a captures sets of like functional requirements which are common to more than one Mission Package (i.e., Safety, Information Assurance/ Cybersecurity, Environmental, Logistics, etc.). Level 2b defines Systems and sub-systems which are common to more than one MP (i.e., computing infrastructure, communications, sustainment, etc.). The MP requirements are defined at Level 3 and typically include the level of detail to understand the incremental nature of the MP under development and/or test. Mission Module requirements and intra-MM interfaces are typically defined at Level 4. Capabilities common to more than one MM within a specific MP, such as the MP Application Software (MPAS), are implemented at Level 4. Mission System requirements and interfaces are defined at Level 5. Interfaces which the LSoSE must retain control over to ensure capability or modularity objectives are documented in PMS 420 controlled Interface Requirement Specifications (IRSs) or ICDs.

The respective warfare focused MP technical teams manage the interfaces within an MM or MP by defining the details of the interfaces in the requirements and architecture products. Internal MP interfaces are documented within the standard section of the System/Sub-System Specification (SSS) and flowed down to Sub-system Specification (SS) and other documents. To control parallel development among the various MPs or external stakeholders, PMS 420 defines and controls common services and interfaces via standalone an IRS or an ICD/IDD depending on the level of control required. An IRS describes the functional requirements (e.g., data communication requirements) and an IDD or ICD describes the design details of the interface.

Program offices responsible for constituent system development typically contract to a prime developer and find it sufficient to decompose the CDD into a System/Sub-System Specification (SSS) or an A-Spec, which is then put on contract. Due to the complex nature of the LCS MM SoS and the number of organizations involved in development of MMs, mission systems, sub-systems, and so forth, PMS 420 has found it necessary to manage its specification tree down to the MM level (or Level 4) with a strong understanding of how those MM requirements are allocated to individual Mission Systems. PMS 420 has historically formalized such technical agreements with its PARMs or other stakeholders through System Project Directives (SPDs), which are essentially Memorandums of Agreement between government program offices supplemented with SSS, Sub-System Specification (SS), ICDs, and architecture products as appropriate. Architecture products are typically developed through the MM and mission system Levels 4 and 5 in accordance with version 2.0 of the Defense Architecture Framework (DODAF) framework (DoN, 2011). Interfaces which require high levels of integration and/or are anticipated to be high risk are further detailed using high fidelity interface models using Systems Modeling Language (SysML). Interface requirements further derived through the use of DODAF and SysML are fed back, or synchronized, into the appropriate requirements specification documents. The SPDs appended with SSS, SS, and IRSs at Level 4 or below to inform contract actions with PARM contract actions. As most of the mission systems which are constituent to the SoS have their own ACAT designation, requirements, and funding lines, it is not until this level of analysis is performed that we can begin to understand the gaps between the prescribed SoS and mission system requirements. This synchronized requirements and architecture development process is depicted in Figure 4.

The requirements derivation and supporting architecture development process requires collaboration across several organizations. PMS 420 utilizes a collaborative engineering environment such that its distributed user base can access the LCS MM DOORS modules from government and contractor facilities. In 2014, this capability was expanded to include access to the LCS MM System Architect encyclopedias. These DOORS and system architect instantiations are used mostly by the PMS 420 core SE IPT. In 2013, the Navy Systems Engineering Resource Center (NSERC) hosted Systems Engineering Integrated Data Environment (SE IDE) was redesigned to ensure internal and external users timely access to requirements, architectures, and technical data packages in support of formal reviews (i.e., SETRs, certification events, or other events as required).

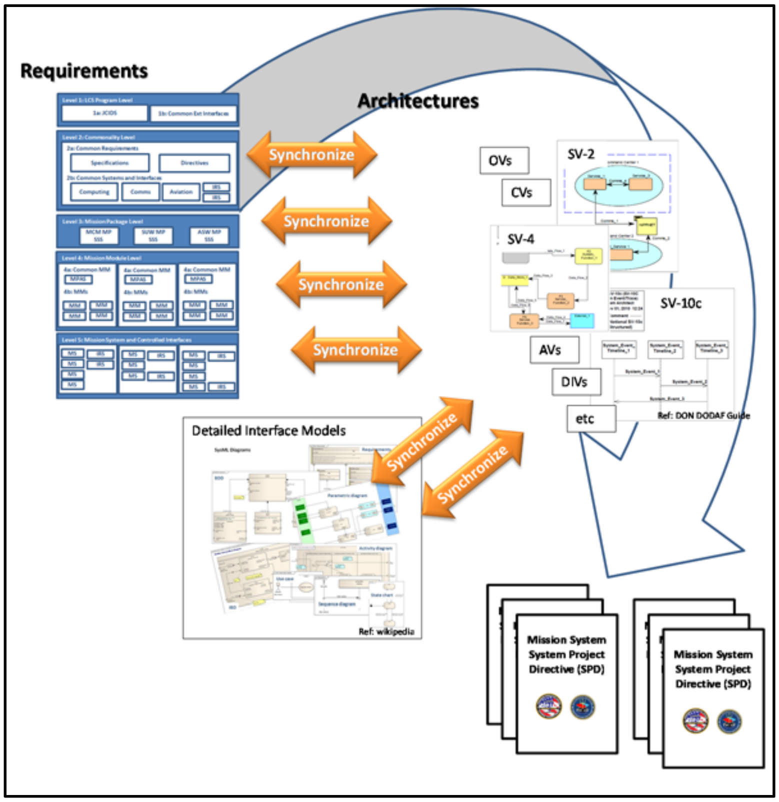

Figure 4. Requirements and Architecture Approach

Assessing Technical Performance Measures for a Complex SoS

Technical Performance Measures (TPMs) are a time-based metric used to compare actual performance to projected performance as a system advances through various developmental and test events. The specific metrics are typically implemented at the system or sub-system level. The TPMs which have the greatest impact on SoS mission performance are specified in the SPD and supporting requirements documents. The PARMs are responsible to report any scheduled test results back to the LSoSE on a quarterly basis, or sooner via the integrated risk management, or other technical management process. The LSoSE is then challenged with understanding the impact of any performance shortfalls and then assessing the impact to SoS mission performance and presenting the impacts to leadership.

The LCS MM program developed a framework to identify and track the TPMs which are critical for LCS mission success. Therefore, thoughtful selection, review, and tracking of TPMs are required to allow technical managers to make informed decisions during system design and to identify the need for corrective actions when deviations from planned technical progress occur. In cases of complex SoS with multiple variables, dependencies and/or mission execution paths, multiple TPMs inform a modeling and simulation (M&S) tool to project probable performance of the MSs and/or MMs associated with an MP. In some cases, the TPMs that PARMS are tracking for other missions are not critical to PMS 420 and therefore are not tracked by the LCS MM LSoSE.

The allocation of KPPs to TPMs for a notional ASW MP is depicted in Figure 5. High fidelity, non-linear, complex M&S tools are usually required to predict the performance of the integrated MP based on the TPMs' inputs of the constituent mission systems. For example, the Naval Mine Warfare Simulation (NMWS) tool is an object-oriented, event-driven simulation tool traditionally used by the Navy's Mine Warfare community. This SoS M&S tool is capable of reflecting the complexity of an SoS because it can accommodate multiple inputs, such as mission thread information, environmental predictions, mission system performance parameters, high-level reliability parameters, and critical task analysis inputs. PMS 420 has found the use of a Kill Chain based modeling methodology to provide benefit to program management and risk identification, and we will now discuss that process.

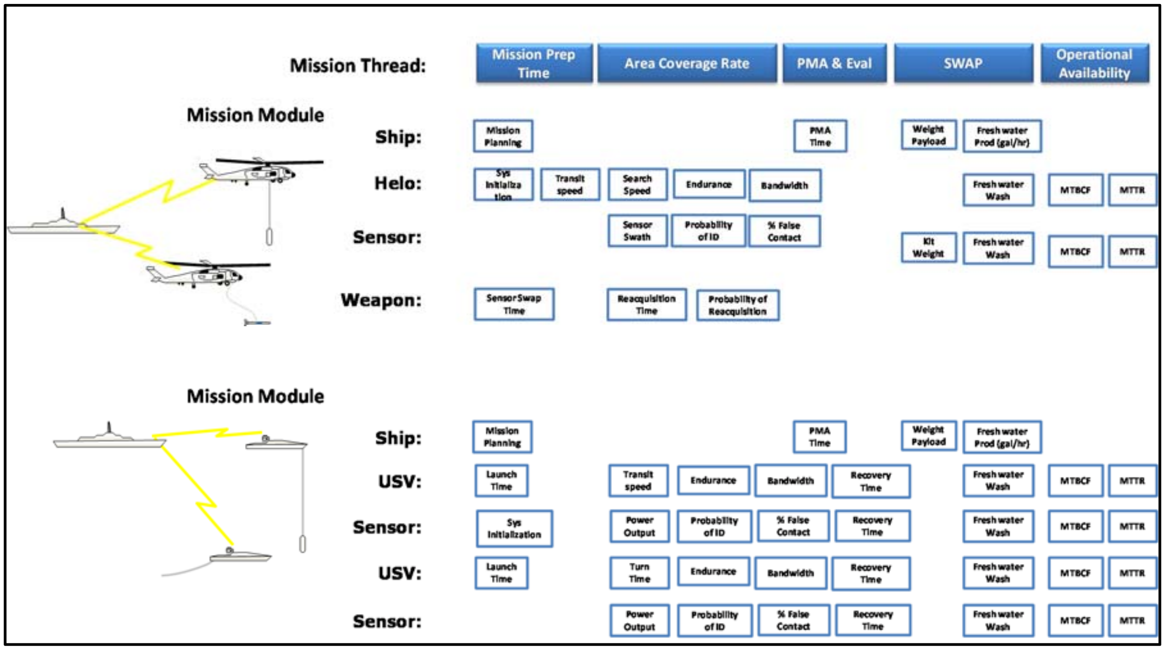

Figure 5. Notional TPM for a Notional ASW MP

Applying the Kill Chain Methodology to a Complex SoS

Given a notional SoS with 12 constituent systems, each with six to eight TPMs, over 100 TPMs can result. The LSoSE cannot always expect to present status on each TPM at TIMs, SETRs, certification events, or other decision meetings. To assist in managing this challenge, the Kill Chain methodology of a mission-based approach to assessing and visualizing how an SoS is expected to perform in the execution of a specific mission thread is used. It is intended to provide insight into any risks or issues associated for the individual systems, sub-systems, or interfaces in properly executing its allocated functionality. Several communities have developed specific implementations for various purposes. Perhaps the most pervasive are the operational test community's Warfare Capability Baseline (WCB) process and larger Navy Integration and Interoperability (I&I) implementations (Clawson et al., 2015). The WCB approach in particular was developed with a focus on test data in preparation for an operational test event. LCS MM LSoSEs have expanded upon and tailored a Kill Chain implementation to compensate for the incremental, technical, and organizational complexities that can complicate the assessment and presentation for a complex SoS.

As previously described, the LCS MM SoS is made up of various manned and unmanned vehicles, sensor systems, communication systems, weapons systems, and systems provided by the core LCS seaframe. As MPs are fielded incrementally, mission systems and/or capability upgrades are added to the MP baselines. Further, multiple submission threads, or “passes,” with various permutations of these vehicles, sensors, and systems, can be required to accomplish missions with extended timelines, such as those required to clear a minefield. An example Kill Chain for a notional ASW MP is shown in Figure 6. The overarching Kill Chain assessment process is depicted in Figure 7. The Kill Chain is presented as a matrix of systems and sub-systems, laid against mission phases (i.e., Prepare/Configure, Search/Detect/Classify/Localize, Identify, Neutralize, Assess, Post Mission Analysis). Each system, sub-system, and integration point is assessed for its individual contribution associated and risk of meeting the mission specific requirements set using the LCS MM standard risk assessment criteria. In many cases, multiple TPMs are tracked and used to quantitatively assess the respective system or sub-system against its allocated contributions. Any system which misses a major TPM milestone cues a re-evaluation of the Kill Chain for impact. If the performance degradation does not force a change to the risk rating, then the Kill Chain is not updated. The assessment method is also denoted to provide insight into the level of confidence in the assessment (i.e., S = SME estimate, M = Modeled result, T = Verified in test, F = Fielded System). A path key with varying thickness is used to assist the PM or LSoSE to understand where the specific system falls in the multi-pass sequence of events. Notes can be overlaid on the Kill Chain to reference the PM or LSoSE to specific risks or issues. In order to not lose the fidelity, Kill Chains are typically created for major test configurations, deployed configurations, or Increments.

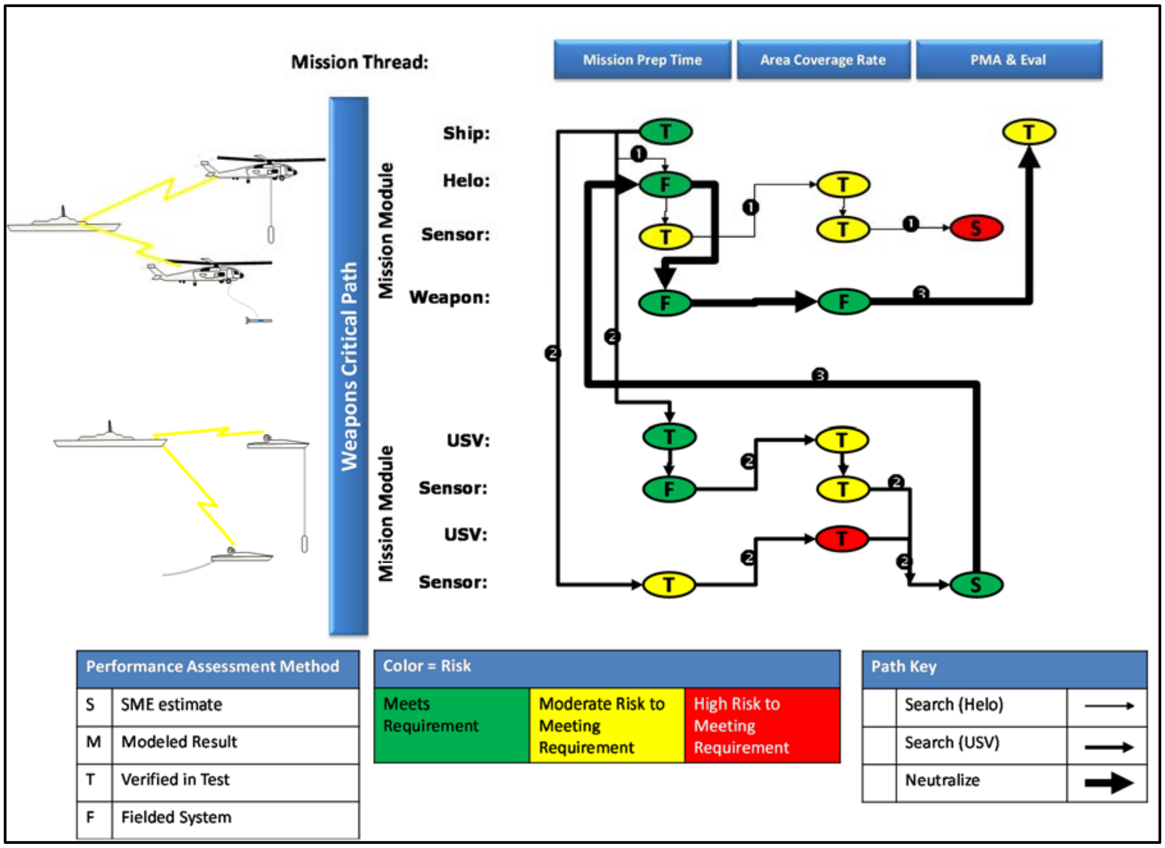

Figure 6. Example Kill Chain for a Notional ASW MP

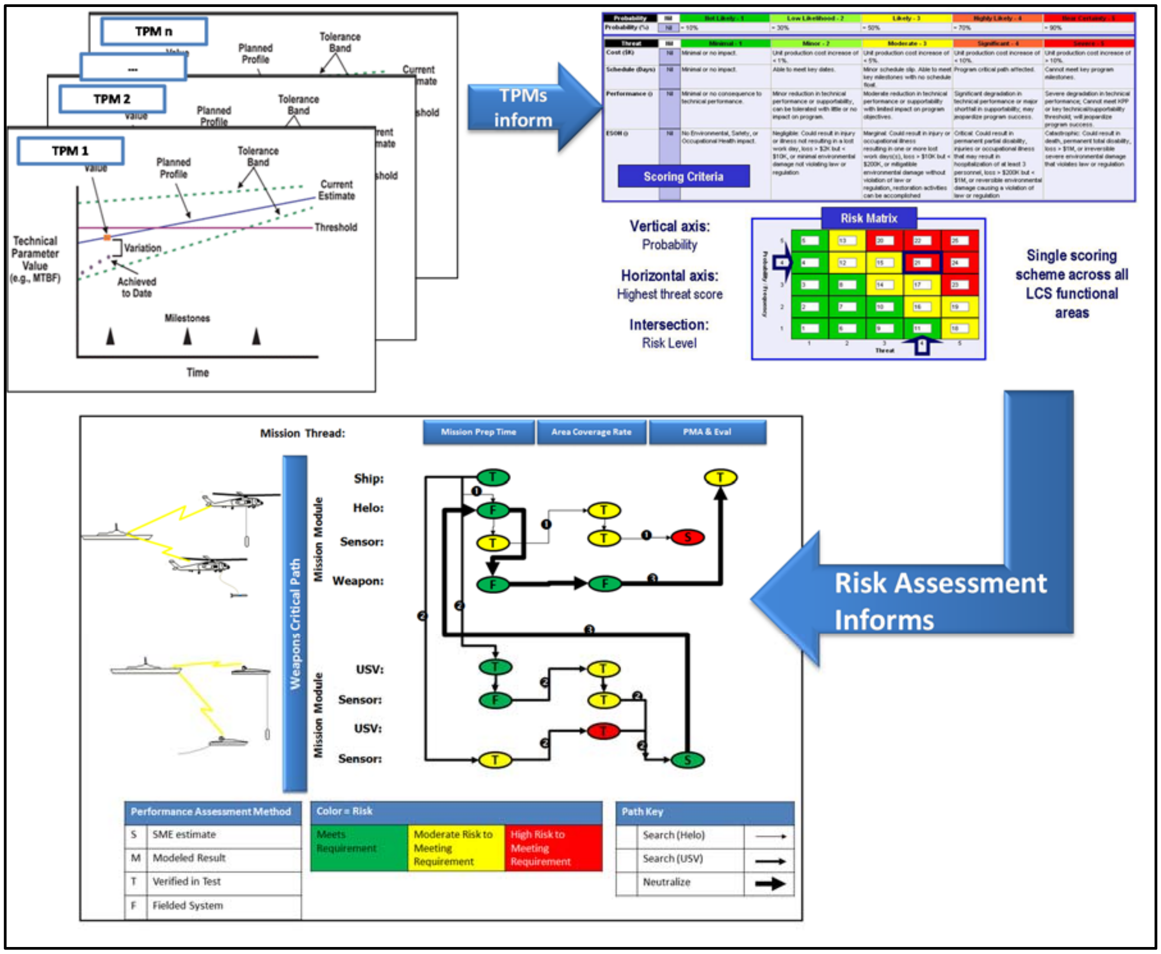

Figure 7. LCS MM Kill Chain Framework

Lessons Learned and Opportunities for Future Work

This paper presented the systems engineering processes and level of technical rigor required to manage the development and integration of a complex SoS. A specific Kill Chain framework was presented, which is currently used to assess and visualize the impact of TPMs on a complex systems of manned and unmanned systems mission threads. As currently constructed, the Kill Chains provide the PM with comprehensive insight into the technical status and major risks and issues for a complex SoS across specific mission threads. Due to the various configurations that the LCS MM PMs and LSoSEs are responsible to track, the LCS MM program office has invested significant resources into coordinating several of the basic systems engineering methodologies and tools to support the Kill Chain process, namely requirements, architectures, and risk management.

- Requirements were developed to a sufficient level of detail to articulate the specific contribution of the system, sub-system, and interface required at each phase in the mission thread.
- Architectures were developed to the sufficient level of detail to ensure that the weapons critical path covers the sequence of events critical for mission success.
- Constituent system requirements must be aligned to LCS MM requirements. In the cases when constituent systems have their own requirements sets

(CDDs, CPDs, or other), the LSoSE must work with both resource sponsors to identify and work to close significant requirements and/or interface misalignments.

- Constituent system program managers must also be responsible to, and have a mechanism to report, TPMs to the LSoSE routinely.
- Risk and issues are flagged at least to the level of detail (i.e., system, sub-system, interface) presented in the Kill Chain.
- The team responsible to develop MM requirements is distributed across at least four Naval Warfare and Systems centers. PMS 420 has developed a common access card (CAC)-enabled collaborative engineering environment where a distributed user base can access the LCS MM DOORS modules from government and contractor facilities. Change management and control processes were also developed. In 2014, this capability was expanded to include access to the LCS MM System Architect encyclopedias.

To date, the Kill Chain framework has been extremely effective as LCS MM prepares for several operational test events. Performance issues are captured, assessed, and presented in the context of their impact to the overall mission success. In order to expand this approach to provide the PM with a more predictive tool that can be used for technology insertion planning and to better support the developmental phases of the next increments, some of the other technical management and systems engineering methodologies and tools must be appropriately configured. Integrating a robust modeling and simulation capability would better support analysis of alternative and technology insertion trade-off–type analyses. Integrating cost, schedule, and the -ilities, such as reliability, sustainability, and other models, would better support understanding the capability from a performance and total ownership cost (TOC) perspective.

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