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Proposed Methodology for Performance Prediction and Monitoring for an Acknowledged Systems of Systems

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Preface & Acknowledgements

During his internship with the Graduate School of Business & Public Policy in June 2010, U.S. Air Force Academy Cadet Chase Lane surveyed the activities of the Naval Postgraduate School's Acquisition Research Program in its first seven years. The sheer volume of research products—almost 600 published papers (e.g., technical reports, journal articles, theses)—indicates the extent to which the depth and breadth of acquisition research has increased during these years. Over 300 authors contributed to these works, which means that the pool of those who have had significant intellectual engagement with acquisition issues has increased substantially. The broad range of research topics includes acquisition reform, defense industry, fielding, contracting, interoperability, organizational behavior, risk management, cost estimating, and many others. Approaches range from conceptual and exploratory studies to develop propositions about various aspects of acquisition, to applied and statistical analyses to test specific hypotheses. Methodologies include case studies, modeling, surveys, and experiments. On the whole, such findings make us both grateful for the ARP's progress to date, and hopeful that this progress in research will lead to substantive improvements in the DoD's acquisition outcomes.

As pragmatists, we of course recognize that such change can only occur to the extent that the potential knowledge wrapped up in these products is put to use and tested to determine its value. We take seriously the pernicious effects of the so-called "theory–practice" gap, which would separate the acquisition scholar from the acquisition practitioner, and relegate the scholar's work to mere academic "shelfware." Some design features of our program that we believe help avoid these effects include the following: connecting researchers with practitioners on specific projects; requiring researchers to brief sponsors on project findings as a condition of funding award; "pushing" potentially high-impact research reports (e.g., via overnight shipping) to selected practitioners and policy-makers; and most notably, sponsoring this symposium, which we craft intentionally as an opportunity for fruitful, lasting connections between scholars and practitioners.

A former Defense Acquisition Executive, responding to a comment that academic research was not generally useful in acquisition practice, opined, "That's not their [the academics'] problem—it's ours [the practitioners']. They can only perform research; it's up to us to use it." While we certainly agree with this sentiment, we also recognize that any research, however theoretical, must point to some termination in action; academics have a responsibility to make their work intelligible to practitioners. Thus we continue to seek projects that both comport with solid standards of scholarship, and address relevant acquisition issues. These years of experience have shown us the difficulty in attempting to balance these two objectives, but we are convinced that the attempt is absolutely essential if any real improvement is to be realized.

We gratefully acknowledge the ongoing support and leadership of our sponsors, whose foresight and vision have assured the continuing success of the Acquisition Research Program:

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James B. Greene, Jr.
Rear Admiral, U.S. Navy (Ret.)

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Associate Professor

Panel 9 – New Dimensions in Acquisition Management

Wednesday, May 11, 2011	
1:45 p.m. – 3:15 p.m.	**Chair: Joseph L. Yakovac Jr.,** LTG, USA, (Ret.), NPS; former Military Deputy to the Assistant Secretary of the Army (Acquisition, Logistics, & Technology) ***Ship Maintenance Processes with Collaborative Product Lifecycle Management and 3D Terrestrial Laser Scanning Tools: Reducing Costs and Increasing Productivity*** David Ford, Texas A&M, Thomas Housel and Johnathan Mun, NPS ***Analysis of Alternatives in System Capability Satisficing for Effective Acquisition*** Brian Sauser, Jose Ramirez-Marquez, and Weiping Tan, Stevens Institute of Technology ***Proposed Methodology for Performance Prediction and Monitoring for an Acknowledged Systems of Systems*** Carly Jackson and Rich Volkert, SSC Pacific

Joseph L. Yakovac Jr.—Lt. Gen. Yakovac retired from the United States Army in 2007, concluding 30 years of military service. His last assignment was as director of the Army Acquisition Corps and Military Deputy to the Assistant Secretary of Defense for Acquisition, Logistics, and Technology. In those roles, Lt. Gen. Yakovac managed a dedicated team of military and civilian acquisition experts to make sure America's soldiers received state-of-the-art critical systems and support across a full spectrum of Army operations. He also provided critical military insight to the Department of Defense senior civilian leadership on acquisition management, technological infrastructure development, and systems management.

Previously, Lt. Gen. Yakovac worked in systems acquisition, U.S. Army Tank-Automotive Command (TACOM), and in systems management and horizontal technology integration for the Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology. He has also served as executive officer and branch chief for the Bradley Fighting Vehicle and as a brigade operations officer and battalion executive officer, U.S. Army Europe and U.S. Army Tank-Automotive Command (TACOM).

Lt. Gen. Yakovac was commissioned in the infantry upon his graduation from the U.S. Military Academy at West Point. He served as a platoon leader, executive officer, and company commander in mechanized infantry units. He earned a Master of Science in Mechanical Engineering from the University of Colorado at Boulder before returning to West Point as an assistant professor.

Lt. Gen. Yakovac is a graduate of the Armor Officer Advanced Course, the Army Command and General Staff College, the Defense Systems Management College, and the Industrial College of the Armed Forces. He has earned the Expert Infantry Badge, the Ranger Tab, the Parachutist Badge, and for his service has received the Distinguished Service Medal, the Legion of Merit three times and the Army Meritorious Service Medal seven times.

Proposed Methodology for Performance Prediction and Monitoring for an Acknowledged Systems of Systems

Carly Jackson—Systems Engineer, SSC Pacific, Distributed Surveillance Systems Branch Supervisor. Ms. Jackson is currently supporting the LCS MM Program Technical Director's office, primarily tasked with the implementation of product and process commonality across complex systems of systems, systems engineering preparations for the impending Milestone B, technology transition planning, and overall management of the Mission Package Technology Development Working Group. Ms. Jackson earned simultaneous BS and MS degrees in Mechanical Engineering from UCLA in 2002 and an MBA in Business Administration from Pepperdine University in 2007. She is Level III certified by the DAU in SPRDE-Systems Engineering and Level II certified in Program Management. [carly.jackson@navy.mil]

Rich Volkert—Space and Naval Warfare (SPAWAR) Systems Center Pacific (SSC Pacific), ISR/IO Departments Lead Systems Engineer supporting SSC Pacific, and PMS 420 Deputy Technical Director. Mr. Volkert has over 28 years of service in the government, including 20 years as an active duty Naval officer with service as a engineering duty officer and in submarines. Over 19 years of that time he has been involved in the fields of research, development, acquisition, and systems engineering. He possesses degrees in Aerospace Engineering and Acoustical Engineering and is presently enrolled in a PhD program for Systems Engineering. He is Level III certified by the DAU in SPRDE-Systems Engineering, Program Systems Engineering, Test and Evaluation, and Program Management. [richard.volkert@navy.mil]

Abstract

Program managers (PMs) are expected to quantifiably justify that their program will result in the delivery of a system with the required performance through development. Traditionally, the PM has several technical management tools at their disposal, including Technical Performance Measures (TPMs), modeling and simulation, etc., that provide insight and predictive capability in system performance. When the program matures to a point where actual test data can be gathered, it is compared against expected system performance. The increasing use of the system of systems (SoS) model for the rapid fielding of warfighting capabilities poses new systems engineering challenges for the DoD. Due to the complex nature of SoS interdependencies, PMs are especially challenged when asked to quantifiably predict progress made toward full-capability SoS performance in an incremental development. To support the PM in making technical trades and tracking performance progress for an acknowledged SoS, the U.S. Navy (PMS 420 and SSC Pacific) have been collaborating on the development and verification of an SoS Performance Measure (SPM) tool set. The SPM tool applies a modified TPM-type approach to an SoS construct. However, instead of focusing on a single measurable technical value that can be monitored during development of an individual system, the SPM links the SoS Key Performance Parameters (KPPs) to individual component capabilities, their maturity, and their potential usage rates. The System Maturity Model (SMM), Concept of Operations (CONOPS), and usage rate variance analyses are all considered in the SPM calculation. The SPM tool will be reviewed and valuable lessons learned to date within the Mission Modules Program will be discussed.

The Challenges of System of Systems Management

The Department of Defense (DoD) has seen a growth in the acquisition of systems of systems (SoSs) over the last few decades. This trend is expected to continue as the DoD increases focus on capabilities without changing its system oriented acquisition methodologies. While providing significant opportunities for extending mission capabilities through the integration of existing and new capabilities into a synergistic SoS, there exists significant systems engineering challenges related to the integration and management of SoSs. These engineering challenges are discussed in the Systems Engineering Guide for Systems of Systems (ODUSD[A&T]SSE, 2008). While several types of systems of systems exist, the most challenging one from the management viewpoint is the acknowledged SoS. An acknowledged SoS is defined as one where a set or arrangement of systems results when independent and useful systems are integrated into a larger system that delivers unique capabilities. These capabilities are generally expected to exceed the capability achievable by the component systems acting independently. An acknowledged SoS has recognized objectives, a designated manager, and its constituent Mission Systems (MS) retain their independent ownership, objectives, funding, development, and sustainment approaches. The DoD Systems of Systems Engineering Guide acknowledges that the acknowledged SoS program construct poses a significant challenge to the SoS program manager (PM) in trying to determine, monitor, and predict the technical maturation status of the SoS during development and integration, and as SoSs become more tightly integrated this issue becomes even more challenging. Asynchronous development schedules, product obsolescence, program cancellations, and the planned use of technical insertions to take advantage of technology improvements further increase this management challenge for the PM.

Within this challenging environment, the role of the acknowledged PM remains to balance cost and schedule while managing risk to provide a desired level of capability/performance. In the area of predicting performance, the challenge presently facing SoS PMs is the understanding of the SoS's technical level of integration and maturity, and then relating that data, especially during development, to the predictions of performance to be achieved. Historically, the Technical Performance Measure (TPM) methodology has been used as a key gauge of the probability of an individual system meeting its performance objective when development is complete. Unfortunately, in an SoS context this methodology often fails to provide the desired insight for several reasons including the fact that TPM data at the system level may not be obtainable by the SoS PM, the metric at the system level may not be relevant to how the SoS will employ the existing system, and the end user may have a variety of options in employing the components of the SoS to achieve the desired end capability so that a single point value may be of minimal use. Aside from TPMs, modeling and simulation (M&S) have also been used to provide insights into performance. However, these methods are often costly and time consuming to conduct, thus limiting their usefulness in the fast paced world of acquisition. Additionally, this approach suffers from two additional challenges in an SoS application. The first issue is that the model or simulation developed for the system level capability may not be reflective of its operational performance or usage within the SoS. This could result in the need for costly redevelopment and validation of the model or simulation and/or the development of new interfacing software. The second issue is that today's SoSs often enable the use of their individual component systems in various combinations and in various operational methods to accomplish the top level tasking. Thus any single model run may not provide the overall insight into the range of performance the SoS may actually provide and could lead to a misunderstanding of the SoS capabilities.

This paper will review the use of metrics in acquisition and then provide a brief overview of various methodologies and metrics presently used or proposed for providing insight into the management of systems of systems, including those being developed and tested by the Littoral Combat Ship (LCS) Mission Modules Program Office (PMS 420). The paper will then seek to address what appears to be a gap within the management and oversight of SoS development. Specifically, while various methods exist for supporting the PM in the challenge of monitoring SoS development, an area that does not seem to have been extensively addressed in the literature is the challenge of predicting performance for an SoS. To address this challenge, an approach being investigated by PMS 420 will be presented. This method involves the development of a proposed metric called the SoS Performance Measure (SPM) which will be discussed and a notional case study will be presented.

Metrics and Their Limitations

When discussing metrics, perhaps the first issue to be clarified is the definition of a metric. Figure 1 shows the Merriam-Webster online dictionary definition of the term metric ("Metric," n.d.). For the DoD, the second definition, "a standard of measurement," appears to be the most relevant in terms of how the metric is used in acquisition. Selection of, and concurrence with the selection of the definition is a critical issue in the discussion to follow in part because the third definition of a metric is "a mathematical function that associates a real nonnegative number analogous to distance with each pair of elements in a set such that the number is zero only if the two elements are identical, the number is the same regardless of the order in which the two elements are taken, and the number associated with one pair of elements plus that associated with one member of the pair and a third element is equal to or greater than the number associated with the other member of the pair and the third element." Metrics, as generally used within the DoD, are normally viewed to reflect the use of ordinal or interval data vice ratio scaled data. Whereas arguments exist with respect to this classification and its mathematical implications, its primary impact is in terms of usability to a PM. In terms of operational utility for the PM, what it means is the need to understand that the metric data presented for their effort is best used for providing informational insight into the specific project being analyzed and may not have validity when compared as a measure against other efforts. In other words, we should use metrics for understanding trends within a program and not count on them for precision answers.

Does this limitation impact the utility of metrics? This paper argues no. In the world of defense acquisition, insight is often what is required, and metrics have been used successfully to provide that insight to decision-makers. For effective program execution what an SoS or system PM is often seeking is insight into their immediate status, the ability to predict whether they're on track to provide the requisite performance within cost and schedule constraints, and to understand the impacts of the various options they may have to choose between when executing their program. Many of the metrics are well known and are often expressed as readiness levels including the evaluation of Technology Readiness Level (TRL), Manufacturing Readiness Level (MRL), and Earned Value (EV). Newer metrics that are becoming of increased use within the acquisition community include those of Software Readiness Levels (SwRL), Integration Readiness Levels (IRL), and System Readiness Levels (SRL). Many of these metrics operate by comparison of a product against a known scale to determine a present value (TRL, MRL) which can then be compared against the program's status and against historical data to indicate if a program is on track against its present developmental stage. Others such as EV and SRL, while based on known status, can also be used in a manner similar to TPMs to provide indications of whether the program is on a trend to achieve desired objectives or if a potential risk exists. Let us now look at how an executing program office is using these tools within an acknowledged SoS.

The Mission Modules Program Office—Developing Tools for Understanding, Predicting, and Managing an Acknowledged SoS

The LCS Mission Modules Program Office (PMS 420) was established by the Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN RD&A) on October 1, 2003, within the Program Executive Office, Littoral and Mine Warfare (PEO LMW) for the development, acquisition, and sustainment of the modular mission packages (MPs). The initial focus of PMS 420 was to take existing independent capabilities in the fields of surface warfare (SUW), mine countermeasure (MCM), and anti-submarine warfare (ASW) and to integrate and modularize those capabilities to provide deployable and swappable warfighting capabilities for the LCS. Thus the LCS MPs meet the definition of being an SoS because they are made up of individual MSs, including: vehicle, communication, sensor, or weapon systems; support equipment, including support containers, or vehicle cradles; software; mission crew detachments; and aviation systems, which are then integrated into a larger system to deliver unique capability. Because the charter of PMS 420 is to acquire, integrate, modularize, and sustain focused warfighting capabilities from existing program lines, PMS 420 primarily serves as a Ships Acquisition Program Manager (SHAPM) with a focus on acquiring the individual mission systems from Participating Acquisition Resource Managers (PARMs), who manage existing product lines and programs of records. This lack of direct management responsibility for the individual mission systems means that the SoSs comprising the MPs are acknowledged SoSs. Since its founding, PMS 420 has recognized the challenge of leading an acknowledged SoS development and quickly began development of novel system engineering tools and methodologies, designed to ultimately reduce risk and provide enhanced management (technical, cost, schedule) insight into the SoS problem. Initial tools addressing some of the traditional programmatic concern related to determining technology readiness, understanding technology insertion options, and managing investments have been developed and are being used by PMS 420 on a daily basis. Lessons learned by PMS 420 related to these issues, the approaches used, and their benefits have been discussed previously at this symposium (Volkert, Jackson, Harper, & Van Norstrand, 2010).

One of the primary methods used by PMS 420 to gain insight and manage the development maturity of their SoS, as presented to this symposium in 2009, has been the concept known as the SRL developed by Dr. Sauser (Forbes, Volkert, Gentile, & Michaud, 2009). By pairing the traditional TRL scale with a new series of criteria known as the Integration Readiness Level (IRL), a more complete look at true system maturity can be obtained (Sauser, Ramirez-Marquez, Magnaye, & Tan, 2008). Under this methodology the readiness of each technology is still considered, but instead of being a stand-alone metric for determining readiness for incorporation, it is analyzed in concert with both its integration requirements and the maturity of other technologies with which it interfaces. The calculation of SRL is described in the above referenced papers. The SRL methodology has been highly successful on the program and has paid dividends in terms of both increasing decision-maker visibility into true system status and allowing for pre-emptive actions to be taken to mitigate potential developmental issues. Since the initial presentation of the SRL method, the program has developed and documented a comprehensive process for System Maturity Assessments (SMA) and has described its application to generic SoSs. The SMA process is iterative with a structured set of well developed tasks that are described in detail in the System Maturity Assessment Guide (PMS 420, 2009). The first three steps of this process need only be conducted during initial system architecture development. Once the system architecture, a key factor noted in many of the methodologies reviewed for defining parameters within an SoS, and subsequent system designs have been placed under configuration control, successive assessment iterations need only review the previous TRL and IRL criteria for any updates due to development progress and then recalculate the SRL with updates to reporting mechanisms conducted as needed. The fundamental basis of the SMA process is the proper creation of an assessment framework to include technologies, integrations, and their resulting architecture. It is also imperative that buy-in from all stakeholders be obtained in order to ensure common understanding among all participants with regard to both what will be evaluated and in what manner. The SMA model has been applied for the purpose of monitoring the maturity and integration status of individual technologies within the MP SoSs for PMS 420. The Mission Modules Program has used this methodology to monitor developmental status by incorporating it into a continuing quarterly evaluation of the SRL level for each of the mission packages. This consistent evaluation allows the PMS 420 PM to better understand maturation of the individual MP SoS and of each increment within the SoS. In turn, this provides him with a greater understanding of the program's technical status, enabling the PM to better maintain and manage the development risk of the MPs as they progress though design and development.

However, as viable as the above tools have been to PMS 420 in managing its SoSs, the tools still fail to provide insight into one of the most asked questions of the PM. Will the SoS obtain the performance desired and within the incremental development approach, when and with what combination of capabilities? For this issue a new approach is required.

Relationship of Performance Prediction to Technical Measurements

The International Council on Systems Engineering (INCOSE) has published a technical measurement guide that lays out the standard acquisition approach for relating operator requirements to quantifiable and measureable data that can be obtained during development (Roedler & Jones, 2005). To set the stage for the proposed methodology this present methodology is summarized as follows. Traditionally, within defense acquisition system development, performance expectations for a developmental program are established by defining a set of criteria called the Measures of Effectiveness (MOEs). MOEs are generally used within the DoD community to define the level of operational success desired of the developing capability that is related to the mission and environment for which the system is being developed. They represent the end users' desires for system capability in terms of operational value vice any specific technical approach. Critical elements of the MOE's generally get translated into the Key Performance Parameters (KPPs) of a system that are used to help drive the critical performance aspects of a proposed design. As a system design concept evolves for providing the performance required by the MOEs and the KPPs, Measures of Performance (MOP) are then developed. The MOPs for a system represent selected physical and functional characteristics related to the systems' operations that can be measured during testing/operations and used to indicate that the performance requirements of the MOEs and KPPs are being achieved by the design being evaluated. Because testing generally occurs late in the program development cycle, an indicator of the desired performance attainability prior to the gathering of MOP data is desired to justify the ongoing investment. At the single system level this is obtained through the selection of TPMs. TPMs represent an ongoing measurement of a technical requirement where the technical requirement being measured is assumed to have a direct relationship to the eventual accomplishment of a MOP, see Figure 1 (DoD, 2003). Trend monitoring of the various TPMs of a program towards their goals is then used as an indicator that the system should eventually accomplish its required performance goals.

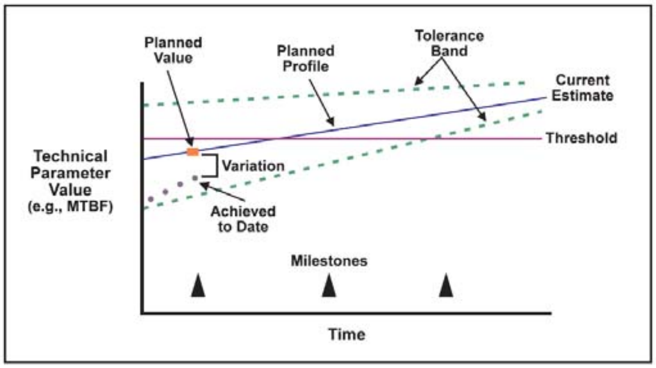

Figure 1. Technical Parameter Measure Notional Chart

Why Individual System TPM's May Fail to Provide Insight for a System in an Acknowledged SoS

While TPMs have been used successfully at a system level to provide indication of end product performance related to customer needs, this methodology presents challenges within an acknowledged SoS for several reasons. First, because the SoS PM does not have direct control over the developmental PMs gaining and maintaining status of the individual system, TPMs may not be achievable. Second, and perhaps more relevant, is that even if the data is obtainable, it may not be relevant with respect to the systems use within the SoS. One of the key aspects of an SoS is that enhanced performance is achieved by the integration of the individual, independent, and useful systems into a larger system that delivers unique capabilities. These unique capabilities are often achieved through changes to the operational use, maintenance support, operational environment, or employment methodology of the individual system. For example, a system originally developed for airborne use where weight is often a critical TPM may be reconfigured in an SoS for use off of an unmanned vehicle (UV). In this application, the weight may no longer be a critical factor for the SoS, but reliability may be. Because airborne systems are generally used on missions of relatively short durations, what was acceptable reliability before for the system may not be operationally effective for a long duration UV application. Thus, the carryover and monitoring of just the system level TPMs from the component systems could result in an erroneous view of the SoS's capabilities. Additionally, as systems are incorporated into the SoS they are often integrated with other components of the SoS. This integration may result in some of the initial capabilities of the individual system being either enhanced (such as interfacing an improved sensor with an existing detection system) or degraded (removing a data input previously provided by another interfacing system that is not included within the SoS's capability set). For these reasons, a methodology for predicting performance within the sphere of control of the SoS PM that can account for the uniqueness of the SoS approach is required.

Criteria for a Useful SoS Performance Measure (SPM) Metric

For a metric to successfully assist an SoS PM in predicting performance we must understand some of the key drivers in SoS development and fielding. As discussed previously, one key criterion is the need for the SoS PM to be able to develop a level of insight with respect to the ability of their SoS to obtain the desired performance levels without detailed insight into the detailed technical capabilities and limitations of the component systems. In addition, the methodology will need to be able to adjust known system performance data for the impacts to be expected when operating within the integrated, operational, and environmental constraints of the SoS vice those that the individual system was developed for. Because SoSs often offer greater flexibility in the assignment of tasking among the component capabilities than may have existed at the individual system level, this range of operational employment details and its impact on usage rates will need to be considered. Finally, because an SoS reflects a combination of capabilities, it is reasonable to assume that as subsets of these capabilities mature the incremental fielding of the capabilities will occur. Also, the SoS will face a greater need than a single system to be able to deal with the challenges posed by technology/capabilities both maturing at various rates than may have been initially planned and also those that go obsolete and require replacement. A metric called the SoS Performance Measure (SPM) is an attempt by PMS 420 to answer these challenges.

SoS Performance Measure (SPM)

To arrive at a useable metric for the SoS PM we must start to define the metric in terms of the criteria discussed above. Therefore we start by defining the SoS Performance Measure as follows:

$$SPM_{(SoS\ evaluated)} = f(\ SoS\ capability,\ operational\ employment) \qquad (1)$$

Where the SoS capability is defined as a combination of the impacts of the system and SoS technical maturity, SoS integration impacts, SoS support impacts, and weighted system performance. For the operational employment component of SPM we consider the planned usage options (can a system in the SoS help meet a performance goal), and potential usage rates (how much will it be used) under a range of perspective Concept of Operations. Once we have the broadly stated functions, we must then determine how to convolve the values and what constraints are imposed in the selection of the values being used to determine SPM. Basically, we must answer the question of can we define the component elements of the function in a meaningful way that provides value to the PM?

To initiate this activity some preliminary work is required by the SoS PM and their staff. Specifically, a well defined architecture for the SoS is critical. Without this baseline tool to define the systems composing the SoS and their interactions, analysis of performance, risk, or maturity is challenging. With respect to the SPM, the architecture and interaction of the systems in the SoS is needed to enable the mapping of how the individual systems contribute towards the performance metrics (KPP for this case) and to assist the operation users in developing the various operational usage concepts.

SoS Capability Components (SoS Technical Maturity, SoS Integration, SoS Support, & System Performance)

Accounting for SoS Component Technical Maturity & Integration. Seeking not to reinvent the wheel, the SPM methodology using SRL data can be used to provide insight into the status of the SoS in terms of maturity and integration. While the use of SRL is a subject of debate with respect to the validity of its mathematical methodologies, what it provides is an effective risk evaluation of a set of capabilities combined together. What the application of the SRL methodology provides, constrained against the defined architecture, is a defined and repeatable process for arriving at a single point value for representing the SoS. While not a perfect answer, and as with all metrics requiring the application of a healthy amount of skepticism to what its results really represent, it is in effect no worse than the mental integration of capabilities into a single value that we are often called upon to do daily with complex systems.

Accounting for SoS Support. As discussed previously, one of the impacting factors in SoS performance is the delta between the supportability concept that the original system was developed under and the implications of the support concept to be used by the SoS. These deltas can have either a positive or negative impact on the system and on SoS capabilities. In the early stages of SoS development, this delta may not be fully quantifiable in terms of impact, but as the SoS develops it should become clearer to the PM. Because the eventual purpose of the SPM metric is to provide insight and support sensitivity analysis and to support the ease of calculations, the use of a weighting factor will need to be applied to the existing supporting concept, which is notionally set to 1.0 to account for impact. Thus, the impact at a system level can be defined as:

$$S_{SoS}=\sum \omega_i S_i / \sum S_i \quad (2)$$

where i = 1,..n for n systems in the SoS, and where the notional level of SoS supportability reflects the sum of the weighted supportabilities of the individual systems within the SoS normalized against their existing level of supportability as a standalone system.

Accounting for System Performance. System performance varies over time generally in accordance with where the system stands in terms of its developmental maturity. Figure 2 provides a notional example of this performance maturation mapped against a curve looking at historical maturation stages reflective of developmental milestones such as Advanced Developmental Models, the Engineering Development Model, and Production Representative Models.

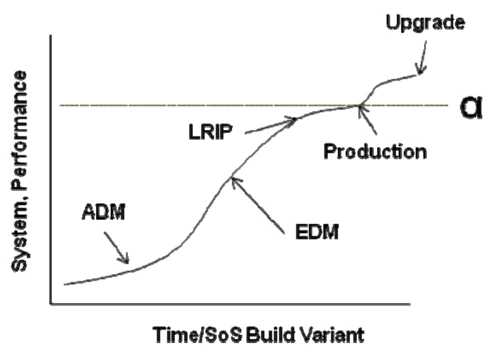

Figure 2. Notional System Performance Growth Over Developmental Timeline

Alternatively, test milestones could also be used. While the SoS PM may not have specific insight into present performance status, at a minimum performance should be expected to match those required of the system's KPP thresholds when a system enters production. The individual system capabilities can then scaled by the SoS PM in terms of their knowledge of the stage of the individual system's maturity in development, any data relevant to its performance at that stage, and how that performance is expected to be enhanced or degraded by incorporation into the SoS. This adjudication of systems is represented through the use of a weighting function to represent the individual capabilities' maturity (real or anticipated) for each level of development and could be expressed as follows:

$$P_{1n} = \omega_n * \alpha \quad (3)$$

where P=system performance in the SoS as a function of the adjustment weight (ω_n) and the systems expected performance (α) at production. Independent of how the weights are assigned, the range of the weighting factors (ω_n) will need to be set within a scale from 0 to 1.0 so that when full capability is provided, $P_1 = \alpha$.

While this method works well for systems that are not integrated with others to deliver required capability in an SoS, this issue becomes more complex when two or more systems must come together to provide a level of capability for the SoS. This is due in part to the fact that the integration of the capabilities into a single capability can result in the combined capabilities' performance being either enhanced or degraded. Where systems become integrated into a single capability that provides the performance value it can expressed as:

$$Pm_{(x,y,..)n} = \omega_n * \alpha_{(x,y,...)} \quad (4)$$

where $Pm_{(x,y,..)n}$ represents the level of capability that is comprised of systems (x,y, and ..) contributing towards the satisfaction of the stated performance requirement given the level of maturity of the system or SoS (*n*) and the anticipated maximum level of performance expected from that combined capability. The value $\alpha_{(x,y,...)}$ now represents the maximum level of performance capability the combined capability is expected to eventually satisfy.

Operational Employment Components (Usage Options and Usage Rate). The operational employment function of the SPM is to define and address the impact of various CONOPS on the SoS and its ability to satisfy the KPP requirements. Because one of the strengths of an SoS is its inherent flexibility, in that component systems can be organized to solve the capability problem, this can often be translated to where the individual capabilities may be used in varying ways to accomplish the same mission. These varying CONOPS result in increased complexity for the analyst in trying to predict what level of performance is being achieved. To address this issue the SoS PM should seek operator input in the development of a set of scenarios that represent the range of potential operational usage concepts for the individual systems within the SoS as applicable to each KPP and increment of development. This enables the derivation of a set of equations relating the KPPs to their component systems and to a specific CONOP. The set of CONOPS, each reflecting an anticipated level of performance and technical maturity/integration of a specific capability (x) at a specific point in time (n) can then be matrixed together to enable a calculation of the overall predicated performance of the SoS across a range of scenarios. For example, for a specific performance metric, several CONOPS reflecting various usage options and rates may be developed and expressed as follows:

$$CONOPS_{Xn} = \beta P_{1n} + \eta P_{2n} + \delta P_{3n} + \varepsilon P_{4n} + \gamma P_{5n} \quad (5)$$

where CONOPS X represents SoS maturity level n, P_{xn} represents the anticipated level of performance of a specific capability (x) at a specific point (for this example as represented by a specific SoS state) in time (n). The symbols γ, δ, ε, β, and η represent pre-defined and documented usage values of the system (integrated or standalone as appropriate) for each operational scenario/performance factor derived. If the notional system is not used in a specific CONOP then the associated γ, δ, ε, β, or η value equals zero.

A Notional Case Analysis of SPM for an Anti-Submarine Warfare (ASW) SoS

Having defined the contributing factors towards determining SPM and its potential use for an SoS PM, let us now explore a notional example of how it may be applied. For this analysis we look at a subset of a notional ASW SoS based loosely on the capabilities that were being developed by PMS 420; all performance values and weightings are created purely for this academic exercise. Based on the elements contributing to the definition of what constitutes the components of an SPM value, we can break it down into 10 process steps for determining the value for the SoS being analyzed. These steps are as follows:

1. Define the notional SoS composed of “n” systems (what systems are in the SoS?);
2. Develop the notional mission strings (defines the system level elements of the SoS that contribute towards the individual SoS missions/functions/mission strings);
3. Map system level contributions towards desired SoS performance attributes (answering the question of how do the individual system capabilities contribute to satisfying the SoS requirements);
4. Define the notional system maturity growth paths in terms of an expected developmental capability/ performance (reflecting typical product growth paths and the impact of the integration of systems to provide a capability component);
5. Account for where individual systems/technologies must be integrated to support the functional thread;
6. Develop a performance corollary to reflect where multiple technologies work together to provide a unified capability;
7. Define the methodology for mapping the performance factors and their associated technologies to potential CONOPS (usage options/rates);
8. Combine and normalize the outcomes from the CONOPS analysis to provide a single point metric indicating the performance expectation of the defined SoS state;
9. Use the predicted system maturation paths anticipated in the SoS to predict the probability that the production SoS will be able to satisfy its performance metrics; and then
10. Combine and normalize the calculated values to arrive at a single point prediction on whether the SoS can provide the required performance related to the specified KPP.

For this notional case, consider an ASW SoS (Step 1) comprised of n=5 components systems, as indicated in Table 1, which combine together to enable the conduct of the traditional detect to engage sequence of ASW operations. As shown in Table 1, Steps 2 and 3 have been completed by mapping the individual systems to where they are expected to contribute to fulfilling the various KPPs identified (search, detect, classify, and engage). For simplicity, only the search KPP will be evaluated, which has an arbitrarily assigned desired threshold of 400 square miles per hour. For this case, only four of the systems have application to the search KPP. The four systems are comprised of three sensors (a passive towed array [System 1], a vehicle mounted dipping sonar [System 2], and an airborne dipping sonar [System 3]) that can contribute towards fulfilling the search KPP. The passive array represents a developmental technology, and the vehicle mounted dipping sonar represents a mature capability that is repackaged for this SoS and the airborne dipper reflects a system in production.

Table 1. Notional ASW SoS

	KPP Impacted			
Capability/MS	Search	Detect	Classify	Engage
System 1 (USV-Towed Array)	X	X		
System 2 (USV-Dipper)	X	X	X	
System 3 (60R-Dipper)	X	X	X	X
System 4				X
System 5 (USV)	X	X	X	

With respect to Step 4, the maturation path is defined to reflect the growth in capabilities expected to where at production capability is normalized to a 1.0. Table 2 maps this and is used to present a notionally assigned weighting (ω) value of the individual capabilities.

Table 2. Notional ASW SoS Maturity Growth Plan

	Developmental status (n state)			
Capability (ω)	Present (n=1)	Test Event 1 (n=2)	OPEVAL (n=3)	Production (n=4)
System 1	0.7	0.8	0.9	1.0
System 2	0.8	0.9	1.0	1.0
System 3	1.0	1.0	1.0	1.0
System 5	0.5	0.7	0.9	1.0

For Step 5, note that for the first two systems (Systems 1 and 2), an integration challenge exists because they are to operate off of an Unmanned Surface Vehicle which is developmental (System 5). For Step 6, there are two system combinations (Systems 1 and 5 [USV/TA] and Systems 2 and 5 [USV/Dipper]) that have to be considered and one system that operates as a standalone capability. For simplicity in this example, in integration of capabilities, the lower weighting (ω) value of the individual capabilities has been assumed to be the driving factor and thus the value for the combined capabilities. For a more comprehensive/complete analysis, the SRL methodology, or other methodology, maybe used to develop this insight. For the performance value ($\alpha_{(x,y,\ldots)}$), sensor performance is taken as the primary parameter of interest and (for this example) it represents the maximum level of performance capability as based on the maximum capability that the sensor (TA or Dipper) is expected to eventually satisfy. Then, for performance, using the equations from the Accounting for System Performance section means that the expressions become:

$$\text{USV/TA} = Pm_{(1,5)n} = \omega_n * \alpha_{(x,y,\ldots)} = Pm_{(1,5)n} = \omega_{5n} * \alpha_{(1)} \qquad (6)$$

$$\text{USV/Dipper} = Pm_{(2,5.)n} = \omega_n * \alpha_{(x,y,\ldots)} = Pm_{(2,5)n} = \omega_{5n} * \alpha_{(2)} \qquad (7)$$

$$\text{MH60R Dipper} = P_3 = \omega_n * \alpha = \omega_{3n} * \alpha_3 \qquad (8)$$

Again to simplify the example, it is assumed that supportability is not impacted by the combination of the systems into the SoS. Therefore, there is no need to adjust the weights (ω) to account for such an impact. The next Step (7) now requires adjudication on how these systems will be potentially used in real world operations. Table 3 provides a notional mapping to address the impact of potential operational usage concepts (or CONOPS) on the functional capabilities for the search KPP.

Table 3. Mapping CONOPS to Capabilities Usage

KPP/Capability -Search	CONOP A	CONOP B	CONOP C
Integrated System 1 – USV with Towed Array	100%	50%	50%
Integrated System 2- USV with Dipping Sonar		50%	25%
System 3 –MH-60R with Dipping Sonar			25%

This data leads to the equations for the three defined CONOPS as follows:

$$CONOPS_A = 1.0(\ \omega_{5n} * \alpha_{(1)}); \quad (9)$$

$$CONOPS_B = 0.5(\omega_{5n} * \alpha_{(1)}) + 0.5(\omega_{5n} * \alpha_{(2)}) \text{ ; and} \quad (10)$$

$$CONOPS_B = 0.5(\omega_{5n} * \alpha_{(1)}) + 0.25(\omega_{5n} * \alpha_{(2)}) + 0.25(\omega_{3n} * \alpha_3) \quad (11)$$

These equations could then be brought together to provide a point indication of the performance to be expected across the range of CONOPS and systems used for executing that specific KPP as follows for the search example:

$$\mathbf{SPM}_{searchn} = \{\ \mathbf{CONOPS}_{A(n)}\ ,\ \mathbf{CONOPS}_{B(n)},\ \mathbf{CONOPS}_{C(n)}\ \} = \begin{bmatrix} \omega_{5n} & 0 & 0 \\ 0.5\ \omega_{5n} & 0.5\ \omega_{5n} & 0 \\ 0.5\ \omega_{5n} & 0.25\ \omega_{5n} & 0.25\ \omega_{5n} \end{bmatrix} \mathbf{X} \begin{bmatrix} \alpha_{(1)} \\ \alpha_{(2)} \\ \alpha_3 \end{bmatrix} \quad (12)$$

Now, assuming that the predicted performance of each of the systems as α(1) = 600 nm2/hr, α(2) = 100 nm2/hr, and α_3 = 300 nm^2/hr, it is straightforward to complete the calculation and arrive at single point values across the SoSs pre-defined evaluation spots (n= 1, 4 in Table 2) to see if the SoS is on track to develop the desired performance capability. Table 4 provides the notional results from the above analysis. This data can then be plotted, and a curve representative of the traditional TPM curve can be derived, as shown in Figure 3. Although not an exact indication of the performance that will be achieved by the SoS, the PM now has insight into the probability of whether the system will meet the KPP and at what stage of development under various operator use scenarios. For the example used, the PM could now have reasonable certainty that the SoS should be able to satisfy the designated KPP by production and could provide recommendations to the operator on more effective operational modes for enhancing the SoS's performance.

Table 4. Notional ASW SoS PML Over Time

Table 4: Notional ASW SoS PML over time

Capability (nm2/hr)	Present (n=1)	Test Event 1 (n=2)	OPEVAL (n=3)	Production (n=4)
CONOPS A	300	420	540	600
CONOPS B	175	245	315	350
CONOPS C	200	280	360	400
Normalized Average	225	315	405	450

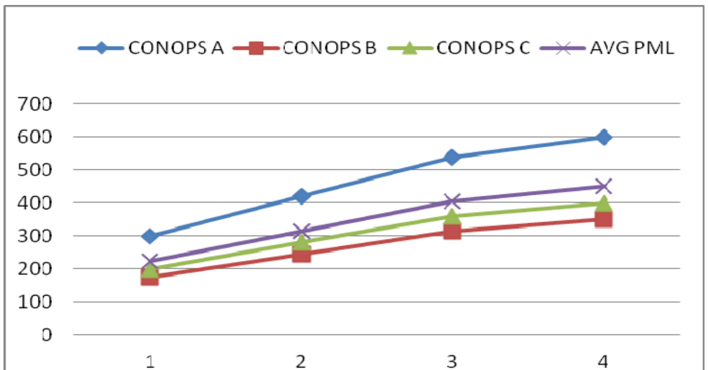

Figure 3: SPM of the Search KPP as a Function of CONOPS and SoS Maturity

Figure 3. SPM of the Search KPP as a Function of CONOPS and SoS Maturity

Conclusion

SoS use continues to expand across the DoD, providing significant advantages in increasing the acquisition community's ability to provide enhanced capability with reduced cost and developmental time. However, because most DoD SOS acquisitions are acknowledged SoSs, some significant management challenges exist for the SoS PM. Whereas tools are being developed to support the PM in management of their efforts, one area where a tool appears to be missing is in assisting the PM in understanding where they stand with respect to being able to provide the end capability desired by the SoS as expressed by the KPPs. As metrics have been shown to be beneficial tools for PMs in managing their challenges, a metric for predicting performance called the SoS Performance Measure is proposed that leverages knowledge the SoS PM should be able to obtain. Although significant up-front evaluation will be required by the SoS program office to implement the SPM methodology, the investment of time helps to establish a common baseline for monitoring. As a tool (metric), SPM appears to provide the PMs with insight into their SoS, enabling more effective management of risk and more effective prediction of when performance will be achieved. Additionally, as a tool, SPM could potentially be used to model various operational and technical options to aid in the understanding of the potential impact of the proposed changes. A graphic similar to the traditional TPM graphic can then be constructed by calculating composite KPP values for each MP increment and plotting the composite level of performance against time. It should be remembered that the intent behind SPM is to provide the SoS PM with the necessary insight into developmental performance compared with documented performance requirements. As with all predictive models, the analysis will need to be compared against measured test data as it becomes available in order to verify predictions and identify whether the program is on course to meeting its stated performance requirements. A projected further expansion of this methodology will be to allow for the evaluation of new capabilities prior to their being incorporated into a planned upgrade or replacement of an existing capability.

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