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Development and Extension of a Deterministic System of Systems Performance Prediction Methodology for an Acknowledged System of Systems

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Preface & Acknowledgements

Welcome to our Ninth Annual Acquisition Research Symposium! This event is the highlight of the year for the Acquisition Research Program (ARP) here at the Naval Postgraduate School (NPS) because it showcases the findings of recently completed research projects—and that research activity has been prolific! Since the ARP's founding in 2003, over 800 original research reports have been added to the acquisition body of knowledge. We continue to add to that library, located online at www.acquisitionresearch.net, at a rate of roughly 140 reports per year. This activity has engaged researchers at over 60 universities and other institutions, greatly enhancing the diversity of thought brought to bear on the business activities of the DoD.

We generate this level of activity in three ways. First, we solicit research topics from academia and other institutions through an annual Broad Agency Announcement, sponsored by the USD(AT&L). Second, we issue an annual internal call for proposals to seek NPS faculty research supporting the interests of our program sponsors. Finally, we serve as a "broker" to market specific research topics identified by our sponsors to NPS graduate students. This three-pronged approach provides for a rich and broad diversity of scholarly rigor mixed with a good blend of practitioner experience in the field of acquisition. We are grateful to those of you who have contributed to our research program in the past and hope this symposium will spark even more participation.

We encourage you to be active participants at the symposium. Indeed, active participation has been the hallmark of previous symposia. We purposely limit attendance to 350 people to encourage just that. In addition, this forum is unique in its effort to bring scholars and practitioners together around acquisition research that is both relevant in application and rigorous in method. Seldom will you get the opportunity to interact with so many top DoD acquisition officials and acquisition researchers. We encourage dialogue both in the formal panel sessions and in the many opportunities we make available at meals, breaks, and the day-ending socials. Many of our researchers use these occasions to establish new teaming arrangements for future research work. In the words of one senior government official, "I would not miss this symposium for the world as it is the best forum I've found for catching up on acquisition issues and learning from the great presenters."

We expect affordability to be a major focus at this year's event. It is a central tenet of the DoD's Better Buying Power initiatives, and budget projections indicate it will continue to be important as the nation works its way out of the recession. This suggests that research with a focus on affordability will be of great interest to the DoD leadership in the year to come. Whether you're a practitioner or scholar, we invite you to participate in that research.

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

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- Office of the Assistant Secretary of the Air Force (Acquisition)

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- Program Executive Officer, Littoral Combat Ships

We also thank the Naval Postgraduate School Foundation and acknowledge its generous contributions in support of this symposium.

James B. Greene Jr.	Keith F. Snider, PhD
Rear Admiral, U.S. Navy (Ret.)	Associate Professor

Panel 2. Systems Engineering for Complex Systems Acquisition

Wednesday, May 16, 2012	
11:15 a.m. – 12:45 p.m.	**Chair: Joseph L. Yakovac Jr., LTG, USA, (Ret.),** Naval Postgraduate School; former Military Deputy to the Assistant Secretary of the Army for Acquisition, Logistics and Technology ***System Definition-Enabled Acquisition (SDEA)—A Concept for Defining Requirements for Applying Model-Based Systems Engineering (MBSE) to the Acquisition of DoD Complex Systems*** Paul Montgomery, Ron Carlson, and John Quartuccio *Naval Postgraduate School* ***Development and Extension of a Deterministic System of Systems Performance Prediction Methodology for an Acknowledged System of Systems*** Richard Volkert and Carly Jackson, *SSC-Pacific* Jerrell Stracener and Junfang Yu, *Southern Methodist University* ***Multi-Objective Optimization of System Capability Satisficing in Defense Acquisition*** Brian Sauser and Jose E. Ramirez-Marquez *Stevens Institute of Technology*

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.

Development and Extension of a Deterministic System of Systems Performance Prediction Methodology for an Acknowledged System of Systems

Richard Volkert—Mr. Volkert is the lead systems engineer supporting SSC Pacific, and the PMS 420 deputy technical director. He 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]

Jerrell Stracener—Dr. Stracener plans, directs, develops, and administers Southern Methodist University's (SMU) Systems Engineering Program, which is entering its tenth year since being approved by the SMU Board of Trustees. He also develops and teaches graduate courses in systems analysis, reliability, probability and statistics, and quality control. In addition, Dr. Stracener was employed by Vought Aircraft Company/Northrop Grumman Corporation (NGC) for 31 years and led the Product Support Center of Excellence concept development effort. He has conducted research in motional aircraft reliability prediction for the Naval Air Systems Command and critical infrastructure systems engineering for the Navy Space and Warfare Command. Dr. Stracener is an elected fellow of SAE and an associate fellow of AIAA. He has received numerous awards, including the AIAA Systems Effectiveness & Safety Award. Dr. Stracener received his PhD and MS degrees in statistics from SMU, and a BS in mathematics from the University of Texas at Arlington. [jerrell@lyle.smu.edu]

Junfang Yu—Yu is an assistant professor in the Department of Engineering Management, Information, and Systems at SMU. He completed his BS in electrical engineering and MS in operations research at Shanghai Jiao Tong University in 1988 and earned his MS in computer science and PhD in industrial engineering at Louisiana State University in 1999. He worked as a supply chain and logistics solution architect at i2 Technologies for six years and as an assistant professor at Louisiana State University for one year before he joined SMU. He also worked as a faculty member at Shanghai Jiao Tong University. His research interests are in the areas of supply chain and logistics optimization and supply chain systems engineering. At i2 Technologies, he provided many educational and implementation consultations to companies like IBM, Northrop Grumman, Honeywell, Cardinal Health, and others. [yuj@lyle.smu.edu]

Carly Jackson—Ms. Jackson is a systems engineer with SSC Pacific and a Distributed Surveillance Systems branch supervisor. She 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]

Abstract

This paper addresses the need for predicting performance in a system of systems (SoS) during incremental development and for dealing with the inherent variability associated with predicting performance. Historically, senior decision-makers have used technical performance measures (TPM), along with modeling and simulation, to predict whether a system under development will meet performance requirements. This methodology does not appear to be directly translatable to SoS for several reasons, including the inherent complexity of the SoS and the operational flexibility the end user may have in employing the SoS. An approach for dealing with the SoS performance prediction has been presented

previously. It laid out a notional approach to dealing with this issue. This approach has been generalized to address the use and integration of multiple technologies into an SoS and into the decision-maker's options in the use of these technologies that is rooted in using subject matter expert input and historical data. This methodology is used to develop a metric defined as an SoS performance measure (SPM), which serves as an equivalent in functionality to a TPM for a SoS. Similar to TPMs, an approach to developing tolerance bands is presented to be used for predicting the status of development as a function of time. The methodology is first presented as a deterministic method for predicting SoS performance during development. This method is then demonstrated using an example case to illustrate the methodology. However, many of the component variables have significant uncertainty associated with them during SoS development and integration into the SoS. The paper provides an approach for expanding the SPM concept to account for this uncertainty using a stochastic approach to address this issue.

A Constraining Environment Within Defense Acquisition

As one looks over the span of human history, one can see that human society has transitioned from a simple hunter-gather society to basic communal organizations, to the nation states, and to the international organizations of today. Directly related to the growth of mankind's increased societal relationships has been the increasingly complex infrastructure and systems that are required to support and enable those relationships. Engineering, as a field of endeavor, has had a role solving the problems that this increase in complexity has created. This relationship goes back to the earliest known civil engineer, Imhotep, who is credited with the design and management of the construction of the Pyramid of Djoser ("Engineering," 2012). As can be seen in Figure 1, the rate of complexity in systems has increased rapidly since the start of the Industrial Age. Since World War II, the growth has been almost exponential, so much so that the 21st century is being referred to as "The Systems Century" (Tetlay & John, 2009).

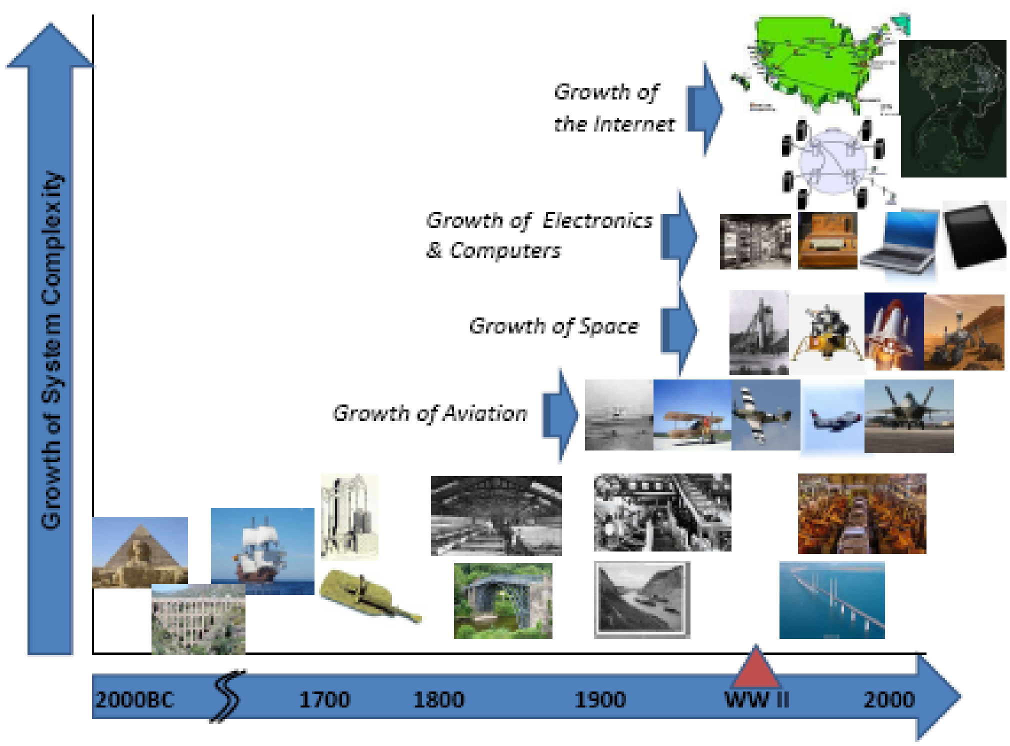


Figure 1. Growth of System Complexity

The emergence of systems engineering as a field has helped in controlling the effective development of complex systems, but, as Smith and Meyers (2008) noted, “large, complex systems development has always been challenging, even when the ‘only’ thing a program manager had to worry about were cost, schedule, and performance within a single program.” Today, just as the interaction and exchange of information within societies continues to increase, system complexity and interdependence continues to increase. Fielded capabilities are now often comprised of multiple independent systems working together to provide specific sets of capabilities to the end user. This is leading to the development of a new field of knowledge within systems engineering that focuses on the technical understanding and management of complex systems of systems (SoS). This is especially true within the Department of Defense (DoD), where SoS have emerged as the preferred approach for the acquisition of capabilities. This shift is driving the need for new tools to aid the SoS program manager (PM)/system engineer, but let us first understand the DoD definition of an SoS and why SoS are DoD’s preferred way of acquiring capability.

Drivers of SoS Development Within Defense Acquisition

The U.S. defense acquisition system is operating in an environment of increasing fiscal constraint while being challenged to meet increasingly complex, adaptive, and capable threats (DoD, 2011). The overall trend of DoD budgets has been declining as a percentage of gross domestic product (GDP), falling from approximately 15% in the mid-1950s to around 4% today. As can be seen in Figure 2, the Congressional Budget Office (CBO) anticipates that the portion of GDP dedicated to the DoD will continue to decrease over the next several decades. This will intensify the motivation to obtain greater utility from systems developed and procured. Additionally, while the overall DoD budget decreased, the amount available for systems development and acquisition is expected to be further reduced as operations, maintenance, and personnel costs are expected to increase within the constrained budget.

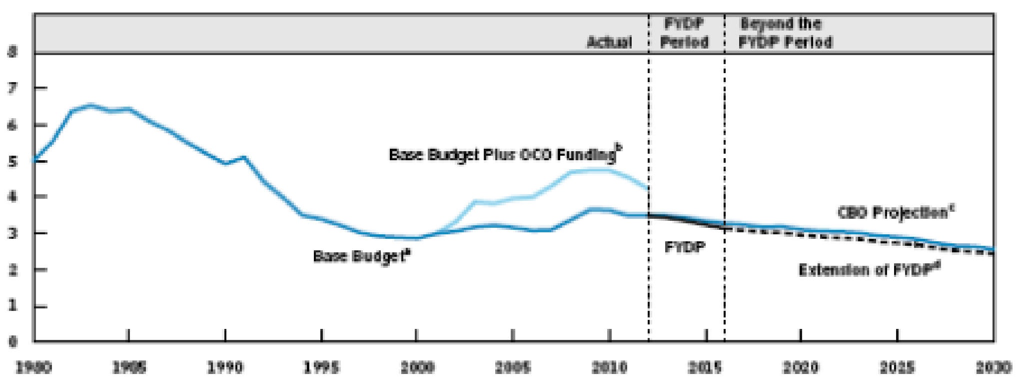


Figure 2. Costs of DoD Plans as a Share of Domestic Output

In addition to the fiscal constraints facing the DoD, the areas where the U.S. has historically maintained advantages due to its technological edge are decreasing (Davis & Wilson, 2011). This means that asymmetrical warfare options are increasing as the cost to obtain and implement the enabling technologies decrease. Against this environment, the present U.S. general force structure and its underlying operational concepts are becoming obsolete (Krepinevich, 2009). To address these issues, the DoD has started to shift away from traditional system-based acquisitions towards capability-based acquisitions (Chairman of the Joint Chiefs of Staff [CJCS], 2007). This shift seeks to better leverage existing investments in procurement systems while providing the DoD with increased capabilities and performance, which, as a result, inherently moves the DoD towards an SoS-based acquisition approach. Recognizing this, the DoD developed the *Systems Engineering Guide* (Office of the Deputy Under Secretary of Defense for Acquisition and Technology, Systems and Software Engineering [ODUSD(A&T) SSE], 2008) to help defense acquisition programs understand the emerging SoS concept and to aid in achieving program success.

It should be recognized that SoSs are not new to the DoD. Even before the term came into popular use, the DoD and the National Aeronautics and Space Administration (NASA) were developing space systems that required coordination among the launch systems, payload vehicles, and their telemetry, control, and analysis systems. Air defense and later ballistic missile defense systems drove the need to integrate sensor, weapon, and command and control data. The DoD is striving to ensure that all procured systems operate more effectively together in order to achieve greater operational capability, which is reflected in the shift away from system-level performance requirements and toward the development and implementation of capability-based requirements.

Definition and Application of SoS Within Defense Acquisition

The field of SoS engineering, development, integration, sustainment, and management requires the decision-maker to face both the traditional challenges associated with any complex system (Jamshidi, 2006) and the additional challenges associated with having to analyze, organize, and integrate the constituent systems (existing and developmental) into an integrated SoS capability. Within the larger technical community, the definition of what an SoS is varies significantly and is often problem specific (Eisner, 1993; Shenhar, 1994; Manthorpe, 1996; Maier, 1998; Kotov, 1997; Krygiel, 1999; Keating et al., 2003). Within the DoD, the U.S. *Defense Acquisition Guide* (DoD, 2011) defines an SoS as a set or arrangement of systems that results from independent systems integrated into a larger system that delivers unique capability. Based on work done by Maier (1998) and Dahmann and Balwin (2008), the DoD has defined four types of SoS: virtual, collaborative, acknowledged, and directed. Within U.S. defense acquisition, the most common SoS type is the acknowledged SoS. For this reason, understanding issues related to acknowledged SoS and developing technical and programmatic management tools supporting them is critical to enabling DoD program success. An acknowledged SoS is defined as one where there exists acknowledged and documented capability requirements and funding, and a designated lead is funded, but the individual constituent systems retain their independent developmental, performance, funding, and reporting paths (ODUSD[A&T] SSE, 2008). The objective of an acknowledged SoS is to successfully integrate the capabilities of constituent systems to provide required capabilities that the constituent systems cannot achieve independently. This ability to integrate ongoing developmental efforts with fielded systems to improve warfighting capability is one of the reasons that the DoD is seeing a continual increase in the number of acknowledged SoSs being developed. Although the SoS acquisition process has the potential to achieve this objective, monitoring the progress of an acknowledged SoS can often be problematic, as the individual component systems retain their independent developmental, funding, development, and sustainment approaches. Overall, effective SoS technical and programmatic management methodologies are still evolving to sufficiently address SoS-specific technical and programmatic issues.

System Versus SoS Development Tools, Metrics, and Methodologies

One of the recognized advantages of an SoS is that enhanced performance is achieved by the integration of the individual independent and useful systems into an integrated SoS that delivers unique capabilities. These unique capabilities are often achieved through changes to the operational mission, maintenance and support, or employment methodology of the individual system in the SoS. For example, a system originally developed for airborne use, where weight is often a critical factor, may be reconfigured for use on an unmanned vehicle (UV) in an SoS. In this application, weight may no longer be a critical factor for the SoS, but reliability may be. As 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 mission. Thus, the carryover and monitoring of the existing system level data and metrics from the constituent systems could result in an erroneous view of the SoS and its capabilities. Additionally, as constituent systems are integrated into the SoS, this may result in some of the initial capabilities of the individual systems being either enhanced (such as interfacing an improved sensor to an existing detection system) or degraded (removing a data input previously provided by another interfacing system that is not included within the SoS capability set). These factors contribute to the ineffectiveness of many system-level metrics supporting accurate prediction of SoS status. Some of these metrics and the approaches being used to address their use within an SoS are discussed as follows.

As noted by the SoS *Systems Engineering Guide* (ODUSD[A&T] SSE, 2008),

> The architecture of an SoS addresses the concept of operations for the SoS and encompasses the functions, relationships, and dependencies of constituent systems, both internal and external. This includes end-to-end functionality and data flow as well as communications. The architecture of the SoS provides the technical framework for assessing changes needed in systems or other options for addressing requirements.

As can be seen by the above, architectural definition is a key, if not *the* key, element in defining and controlling the development of an SoS. Although a non-trivial task, the development of the architectures for the SoS provides the basis for evaluation of the SoS. SoS practitioners have started to look at how to use various architectures for optimizing performance over various high-level capability-based metrics using approaches such as process modeling (Osmundson & Huynh, 2005; Bindi et al., 2008) and multi-attribute utility theory (Morrice, Butler, & Mullarkey, 1998). Additionally, analysis has been conducted on methodologies that can support the conduct of cost/performance trades for the SoS (Luman, 2000) based on requirements allocations. Although these methods all show potential for assisting the SoS decision–maker, they tend to be point-specific evaluation tools and do not appear to provide the decision-maker with a tracking and predictive capability method similar to the technical performance measure (TPM) used at the system level for predicting capability during development. In part, this is because the SoS requirements decomposition process is not a well-understood practice, as noted by participants in a U.S Army Workshop on exploring enterprise, system of systems, and system and software architectures (Bergey, Blanchette, Clements, & Klein, 2009). However, such an SoS performance prediction methodology is needed as the demand for predicting capability during SoS development is a constant data call from management.

Historically, M&S has often been used in the early stages of system development to aid with performance prediction of the system with the anticipation that effective M&S can reduce programmatic risk and cost. However, the extension of M&S into an SoS application is challenging. If not done in a way that accurately represents the status of the individual systems' capabilities, the SoS interfaces, and the planned operational employment can result in erroneous outputs. This is driven by the need of the constituent system program managers to focus their M&S efforts on activities directly related to their individual programmatic needs. Furthermore, the lack of an institutional mandate for interoperable M&S tools means that this SoS-specific need is often not funded and may not be perceived as a benefit to the constituent system (Oswalt et al., 2011). Even if desired, as noted by Erhardt, Flanigan, and Herdklick (2010), "the development of a federated model representing the SoS can also be expensive and time consuming.” Erhardt et al. (2010) noted that for accurate representation of the SoS performance, there existed the need for the modeling to account for multiple aspects of the design at all stages of development, including the accurate representation of the constituent systems within the SoS, the integration method used to create the SoS, the operating environment, and the physical environment. Even if this data were available, Erhardt et al. (2010) noted that there would exist a risk that integrations of the system level models into an SoS model could result in erroneous data outputs due to difference in fidelity among the system level models and issues such as differing baseline assumptions and methods of dealing with rounding error. Therefore, physics-based M&S as a tool for use in predicting the performance of an SoS may not be the tool that it is often envisioned as an aid to the decision-maker.

For standalone systems, TPMs are often used during development as a leading indicator, providing the PM with confidence that the configuration end item will meet its stated required capabilities. The concept of TPMs was originally developed by the Program Executive Office for Air ASW, Assault, and Special Mission Programs during the mid-90s (Pisano, 1995) in response to the identification of the existence of a gap in information from earned value data that was not tied to technical performance. The International Council on Systems Engineering (INCOSE) has published a technical measurement guide (Roedler & Jones, 2005) that lays out the standard acquisition approach for relating operator requirements to quantifiable and measureable data that can be obtained during development. Traditionally, performance expectations for a developmental program are established by defining a set of criteria called the measures of effectiveness (MOEs). MOEs are generally used 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 and represent the end users’ desires for system capability in terms of operational value. Critical elements of the MOEs 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. Verification of performance, however, generally occurs late in the program development cycle, and an indicator of the desired performance attainability prior to testing is desired to justify the ongoing investment. For the independent system level, this is obtained through the selection of TPMs that represent selected physical and functional characteristics. Trend monitoring of the various TPMs is then used to provide the PM with confidence that the system should eventually deliver its required capability. This methodology presents challenges when applied to an SoS for several reasons. First, the SoS PM does not have direct control over the developmental PMs, thus 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 how the constituent systems are used within the SoS. MITRE (Garvey & Cho, 2005) proposed an approach to resolving this issue with the development of a TPM risk index (TRI) that proposes a methodology for integrating constituent system TPMs into a single value to define the overall performance risk for the SoS.

Although this method provides insight into the developmental risk of a SoS based on the constituent system TPMs within each system, it does not appear to account for several factors that may influence the performance of an acknowledged SoS, including any changes in the mission scenarios or planned operational use of the SoS and how the individual system’s performance may be modified by their integration within an SoS. Alternatively, for a complex SoS (Jamshidi, 2006) proposed approach to determining the effectiveness of the SoS that treated the MOE as an SoS-level feature and MOPs as constituent-level components with TPMs being at a subsystem level (Jackson, Sedrick, & Tayeb, 2009) and proposed the incorporation of Measures of Suitability (MOS) as a measure to the extent to which the system integrated with the operational environment. However, the proposed method was focused on determining the “best” design for a SoS, considering the component capabilities and their interactions using a relaxed multi-objective optimization process, not as a performance prediction/monitoring tool.

A Missing Link: SoS Performance Prediction Measures

Historically, system-level programs have used TPM tracking and M&S results during development to predict whether a system will meet the required performance objectives. As noted above though, the use of system-level M&S and TPMs does not appear to be directly translatable to SoS due, in part, to the inherent complexity of the SoS and the operational flexibility the end user has in employing the SoS. This means that a predictive methodology for developing SoS performance is needed. The methodology needs to address the use and integration of the constituent systems into the SoS and the decision-maker’s and user’s options in the use of these systems. As noted in the SoS *Systems Engineering Guide* (ODUSD[A&T] SSE, 2008), “the SoS systems engineer needs to establish metrics and methods for assessing performance of the SoS capabilities which are independent of alternative implementation approaches. A part of effective mission capability assessment is to identify the most important mission threads and focus the assessment effort on end-to-end performance.” This is especially important, as one of the key challenges a PM faces is the need to continually defend his or her programs in terms of their viability against not only the threats for which the system was designed to counter at program initiation, but against any emergent threats occurring since program initiation. This viability needs to be shown in terms of predicted performance during development, or the SoS faces an increased risk of cancellation.

Just as at the constituent system program must decide on what attributes are measureable during development, the SoS PM must decide what technical measures need to be monitored and predicted in order to gain insight into whether the SoS will yield the required performance. In seeking to address this need, the authors proposed a deterministic SoS performance methodology for use by an SoS in the area of performance prediction during development (Volkert, Stracener, & Yu, 2012). The methodology, summarized in the section on SoS Performance Measure Development, develops a single-point SoS performance measure (SPM) value that can be predicted over time to support evaluation and monitoring of an SoS. The nature of SoS development means that this metric will need to operate in the realm of imperfect knowledge; thus, an understanding of the impact of variability on each of the input values will be required to understand the range of responses that may actually be present. A literature review was conducted to verify that a metric-based approach was an appropriate decision-making aid in determining what analysis was presently missing that a methodology should address to be of benefit. It was determined that the developed methodology should

- begin with the establishment of a defined mission thread and it mission states;
- address the system level components in terms of performance, sustainability, and usage within each state of the mission; and
- introduce variability into the calculations to understand the impact of multiple mission scenarios.

Having defined the need and desired capabilities for an SoS metric equivalent to that of the TPM, let’s look at a proposed methodology for developing the SPM value.

SoS Performance Measure Development, a TPM Equivalent

For an SoS, the need to focus on end-to-end performance requires that the SPM be evaluated across the range of potential operations (herewith called *mission states* [M_i]) that comprise the end-to-end mission (M) such that $M_i \subset M$ for mission states i = 1, 2, …, n, where the performance of the each mission ($P_{mission}$) can be expressed as a function of the level of performance capabilities of the mission states $P_{mission\ state(i)}$ (for future ease referred to as $P_{ms(i)}$), which can in turn be expressed as a function of the individual performance capabilities (C^S_{ij}) used in a specific mission state (M_i), the supportability of the individual capabilities (S^S_{ij}) within that mission state, and the operational usage of the individual capabilities (U^k_{ij}) within that mission state, or mathematically as shown in Equation 1.

$$P_{mission} = g(P_{ms(1)}, P_{ms(2)}, \dots, P_{ms(n)}) \tag{1}$$

where $P_{ms(i)}$ represents the performance of the SoS in the conduct of a specific mission state i and j represents the factors associated with a specific capability or integrated capability for the set of system j = 1, 2, ..., m that are within a specific mission state. This hierarchical arrangement is shown in Figure 3. Within the mission, each mission state must be represented by a unique performance value such that the characteristics of that mission state cannot be directly compared against any other mission state within the mission. Thus, we can derive the expression of performance for a single specific mission state, as shown in Equation 2.

$$P_{ms(i)} = f_i(C^S_{i1}, \dots, C^S_{im};\ S^S_{i1}, \dots, S^S_{im};\ U^k{}_{i1}, \dots, U^k{}_{im}), \text{ for } i = 1, 2, \dots, n \tag{2}$$

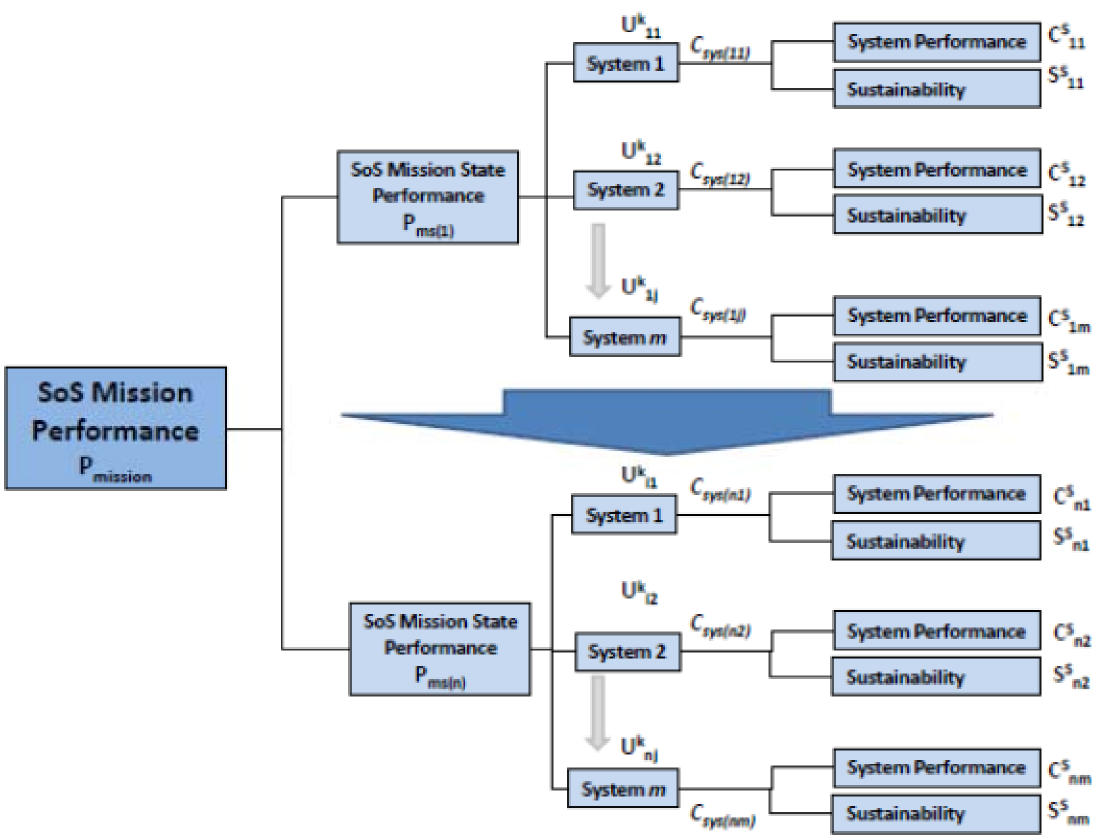


Figure 3. Hierarchical Mapping of the SoS to System-Level Attributes

Let us now look at the functional elements (C^S_{ij}, S^S_{ij}, U^k_{ij}) within each mission state and how these values may be determined.

Mission State Parameters

Let C_{ij}^S be the performance of an individual system *j* within mission state *i* as part of the SoS as a time-specific value within the specific mission. The factors impacting C_{ij}^S include the system-level performance capability, C_{ij}^B, and how that capability is impacted by its inclusion within the SoS (either due to a different operational environment or the impact of integration with other SoS components). Generically, we can state that for any given system

$$C_{ij}^S(t) = \omega_{ij} \times C_{ij}^B(t) \quad (3)$$

where $C_{ij}^B(t)$ represents the performance capability of the system *j* as a standalone system at a specific period of time, the impact of its inclusion within a SoS is corrected for by the adjustment weight ωij. The weighting factor ωij can represent either an increasing or decreasing impact to the performance capability of $C_{ij}^B(t)$ due to its incorporation into the SoS. The challenge to the practitioner is determining how to evaluate these parameters within the SoS and with the limitations in data that may be available in determining these values. To determine the system's expected performance, C_{ij}^S, the SoS PM could either use input performance data (present and predicted) from the standalone capabilities PM or, in the absence of detailed performance data, use a performance growth chart based on the capabilities expected value at maturity and knowledge of its present developmental status. One method of determining where a capability stands in reference to its projected end state performance is through the use of technology s-curves. Technology s-curves are one method used to portray the maturation of new technology as it progresses from concept to onset of production, through rapid growth, to the onset of maturity and finally maturity, as shown in Figure 4.

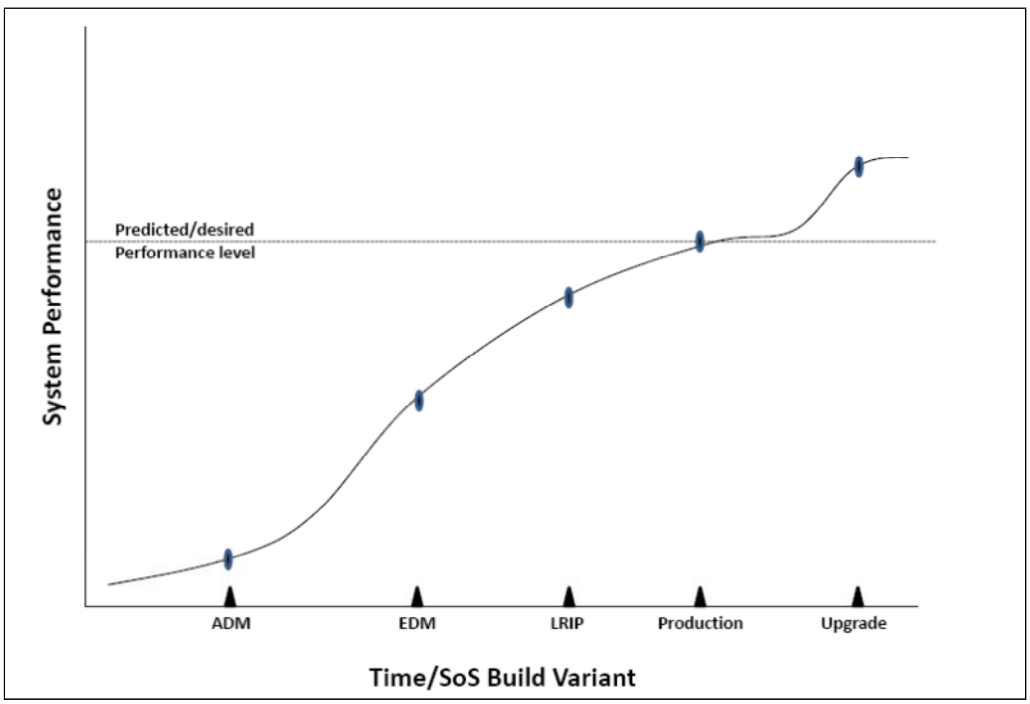


Figure 4. Notional Technology S-Curve Mapped to Developmental Events

For capabilities that are integrated with others to deliver required capability within a mission state, this issue becomes more complex. Equation 3 can still be used for an evaluation of the impact of integration, and its impact on maturity should occur. One methodology for assisting in this evaluation already exists, which the practitioner may wish to consider. Specifically, as noted within the SoS *Systems Engineering Guide* (ODUSD[A&T] SSE, 2008): "A part of effective mission capability assessment is to identify the most important mission threads and focus the assessment effort on end-to-end performance." This use of mission threads lends itself to the evaluation of the status of integrated capabilities using a systems readiness level (SRL) methodology (Sauser, Ramirez, Henry, & DiMarzio, 2008), which evaluates the impact of integrating capabilities based upon the individual capabilities linked within a mission thread and their assessed technology readiness level (Director, Research Directorate [DRD] Office of the Director, Defenes Research and Engineering [DDR&E], 2009) and integration readiness level (Sauser et al., 2010).

The second functional element S_{ij}, or as a time variant factor $S_{ij}^{S}(t)$, can be shown as seen in Equation 4, which reflects the integration of a standalone capability sustainment approach into an SoS. Similar to the performance capability, this incorporation may result in a change of its sustainability performance due to changes in how the capability is now going to be sustained within the SoS. This change in sustainment can result in increase or decrease to the system's reliability and operability dependent on the SoS approach to these issues. Thus, the impact at a system level can be defined as

$$S_{ij}^{S}(t) = \beta_{ij} \times S_{ij}^{B}(t) \tag{4}$$

where $S_{ij}^{B}(t)$ reflects the existing level of sustainability for the known product at a specific point in time, and β_{ij} reflects the weighting value applied to the existing sustainment method of the baseline capability to reflect the impact of incorporating the capability into the SoS sustainment philosophy. In the early stages of SoS development, understanding this sustainment delta may not be quantifiable in terms of impact, but as the SoS develops over time, this issue should become clearer to the PM. In general, sustainability for a system is often reflected in terms of the products reliability. Thus, if the SoS PM is required to operate in a knowledge gap, the reliability bath tub curve (see Figure 5) could be used as a general methodology by a PM for estimating where a technology stands in relation to its end maturity objectives in the absence of other data. This means that the practitioner could evaluate where the specific capability is with respect to maturity and select the appropriate hazard function for modeling.

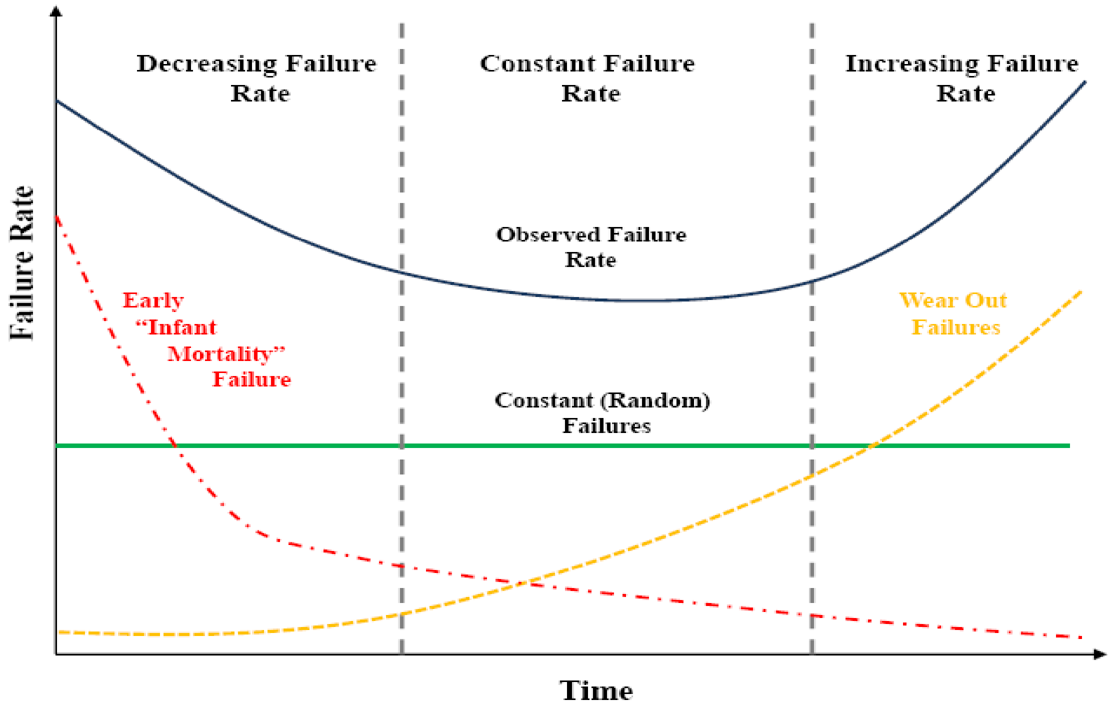


Figure 5. Reliability Bathtub Curve

The third functional element U_{ij} is designed to reflect that the end user may choose to use the SoS capabilities applicable to a specific mission state in multiple ways when executing that mission state. The need for this element is driven by the inherent flexibility that exists within many SoS in that the collective capabilities of the SoS often enable it to achieve the desired performance of the SoS in multiple ways. This flexibility is generally viewed as a positive, as it enables the end user to adjust the SoS employment to deal with operational contingencies. Indeed, when seeking to model how the systems composing an SoS will be used, the developmental community often turns to the user community to solicit these inputs. For defense systems, these inputs are often defined in terms of a concept of operations (CONOPS) document that indicates how the delivered capability is intended to be used. For the SoS engineer, it defines the need to be able to evaluate this impact on the accomplishment of the requirements allocated to a specific mission state and set of capabilities. For this analysis, we modeled it by representing the utilization of the capability. Thus $0 \leq U^k_{ij} \leq 1$ reflecting the use of capability *j* in mission state *i* of between 0 and 100% of the time. U^k_{ij} differs from the other two elements of mission state performance in that its value is generally held to be time independent within the specific analysis but could be variable across multiple analyses. This reflects that for any specific operational condition, the various end users may choose to employ the capabilities in different combinations to achieve mission objectives resulting in a *k*-number of CONOPS requiring analysis with respect to the mission state. When a specific operational usage scenario and set of usage rates from the range of usage options is applied to the individual systems used within a mission state, the value of U^k_{ij} can be incorporated into the system-level determination of performance based on the operator inputs.

Developing a Single Point SPM Value for a Mission State

As shown in Figure 3, each system within a mission state is assumed to have performance that is modeled as determined by the status of the input variables $C^S_{ij}(t)$ and

$S_{ij}^{S}(t)$ as defined by Equations 3 and 4. For the simplicity of notation, we drop the time parameter and consider only the random variables C_{ij}^{S} and S_{ij}^{S}. Thus, at any specific time *t* the performance value, independent of the planned system usage, can be defined as

$$C_{sys(ij)} = C_{ij}^{S} \times S_{ij}^{S} \tag{5}$$

where $C_{sys(ij)}$ represents the combined aspects of sustainability and performance for the individual system *j* in mission state *i*.

The next step of the methodology incorporated the impact of the operational use of the various systems. This allowed us to develop a single point value for the systems performance at any given time within the mission state for a given usage value of the system as the operator specified. For this example, we assumed that the values of each capability can be linearly summed to produce the mission state performance value $P_{ij}(t)$, referred to for simplicity as P_{ij}. Therefore, each system *j* performance in mission state *i* could be defined as

$$P_{ij} = C_{sys(ij)} \times U_{ij}^{k} = C_{ij}^{S} \times S_{ij}^{S} \times U_{ij}^{k} \tag{6}$$

for that set of system capabilities at that specific point in time and for the specific usage rate represented by a specific U^{k}_{ij}.

Let us now expand on Equation 2 for a mission state where the systems provide independent levels of capability designed to achieve a specific level of performance. Although it is recognized that a range of values could contribute to determining $C_{sys(ij)}$, it is assumed that at any specific point in time the program will only be sequentially evaluating single sets of inputs. Thus, the combined performance for the systems for any single set of data can be defined by summing the individual system performance values such that

$$P_{ms(i)} = \sum_{j=1}^{m} P_{ij} = \sum_{j=1}^{m} C_{sys(ij)} \times U_{ij}^{k} = \sum_{j=1}^{m} C_{ij}^{S} \times S_{ij}^{S} \times U_{ij}^{k} \tag{7}$$

Using Operational Drivers to Develop a Range of SPM Values

With the elements of each mission state now defined, and with a methodology of determining a single value for a mission state shown, a projection of performance over time and the development of tolerance bands similar to those used in a TPM chart can now be developed. The tolerance boundaries are established by incorporating the fact that a variety of operational employment schemas may be used in employing the SoS and its collective capabilities. We can model this by stating that for each M_i there is associated with it a specific set of U^{k}_{ij} values reflecting the unique CONOPS modeled within the specific analysis. Thus, for any designated family of potential CONOPS relevant to the SoS operations within the mission state as determined by the user community, a new value, as shown in Equation 8, must be defined, which we call $P(t)_{ms(i)set}$, for ease referred to as $P_{ms(i)set}$, reflects the averaged impact on performance of all potential applicable CONOPS of the M_i combined such that

$$\overline{P}(t)_{ms(i)set} = \sum_{k=1}^{o} \gamma_k P_{ms(i)} = \sum_{k=1}^{o} \sum_{j=1}^{m} \gamma_k C_{sys(ij)} U^{k}{}_{ij} \tag{8}$$

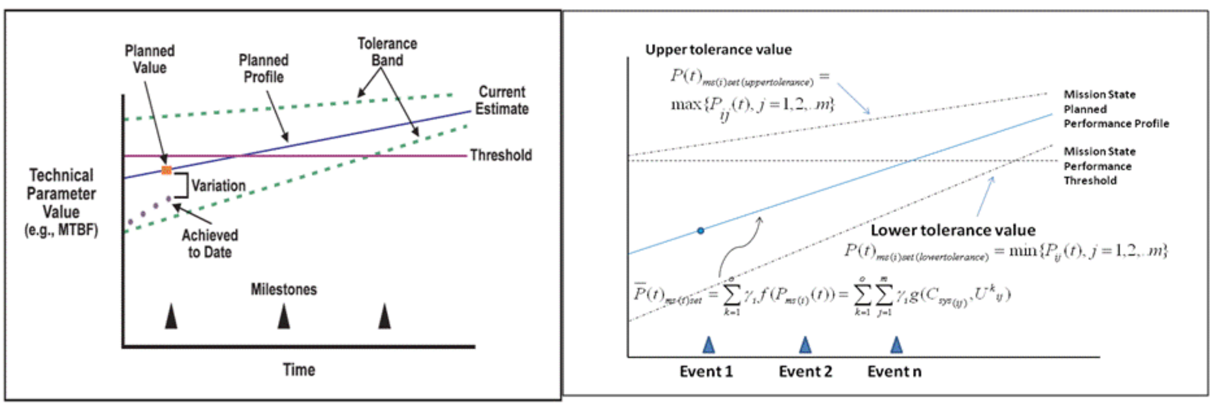
where for each mission state *i* there exists a unique set of U^{k}_{ij} values such for each $P_{ms(i)}$, *k* reflects the maximum number of CONOPS modeled and that γ_i reflects the weight given to any specific set of U^{k}_{ij} values such that $\sum \gamma_i = 1$. This single point value is what we refer to as the mean performance value for the mission state. The value may, as desired, be normalized against mission state the KPP requirements and effectively represents what we are classifying as the SPM value for the mission state. Assuming that all modeled CONOPS support development of the required level of performance, the upper and lower tolerance bands can now be determined using Equations 9 and 10 for the SoS by reviewing the individual values of $P_{ms(i)}$ for each unique set of U^k_{ij} values and using the maximum and minimum of these normalized terms as the upper and lower tolerance points such that

$$P(t)_{ms(i)set(uppertolerance)} = \max\{P_{ms(i)}(t), k = 1,2,..,o\} \tag{9}$$

and

$$P(t)_{ms(i)set(lowertolerance)} = \min\{P_{ms(i)}(t), k = 1,2,..,o\} \tag{10}$$

for the set of values at time (*t*) contributing to that mission set and for all operational usage sets evaluated. The determination of the projected values of SPM over time for a mission state is thus documentable by the fact that the individual capability's within each mission state are considered time variant for performance $C^S_{ij}(t)$ and for sustainability $S^S_{ij}(t)$. By determining the predicted values for each component system within each mission state over the SoS development cycle ($t_1, t_2, ..., t_k$), a time variant value of each of the mission states can be determined. The combination of the mission state values allows for a single-mission performance value for an SoS to be defined and plotted. This provides that the SPM curve then has the potential to provide the PM with insight, similar to the traditional TPM chart (see Figure 6).



Notional TPM Chart **Notional SPM Chart**

Figure 6. TPM to SPM Chart Comparison

Developing a Mission-Level SPM Value

To date, the SPM metric seems to provide optimal value at the mission state level as the combination of data to a single non-dimensional value at the mission level starts to significantly remove the end value from its causes and diminishes the insight provided to the SoS PM. As such, we will not spend much time in this paper on the development of the mission-level SPM value. Basically, to develop the mission-level SPM value, the mission state values need to be combined. Many methods exist for combining data from various sources and types dependent on the data type. For our purposes, because the intent of SPM is to use it as a leading metric, the normalization of the data against a base value for each mission state offers potentially the easiest and most meaningful approach. This approach allowed us to define the capabilities within a mission state with an objective value and allows the mission state to be represented by a value against which present performance can then be measured, and against which progression during development can be predicted. This approach appears to be in line with existing DoD guidance (ODUSD[A&T] SSE, 2008), which stated that for SoS, "SoS requirements are often cast in terms of broader capability objectives." The methodology related to development of a single mission value was developed and documented by Volkert, Stracener, and Yu (2012).

Having now laid out a methodology for calculating SPM, let us use an example to help demonstrate the concept using a mission state within a notional detection-to-engagement sequence as the basis for demonstrating this deterministic model.

Mission State SPM Use in a Generic Anti-Air Mission Example

We bound the limits of this example by defining a notional detect-to-engagement mission that is combined of the following mission states: search, detect, classify, track, and attack/neutralization. This defines our mission ($P_{mission}$) as being composed of n = 5 mission states ($P_{ms(i)}$). The hierarchical layout of the mission to mission state of interest (track) to its component capabilities is shown in Figure 7. To further bound the example, within this set of mission states we will focus on the development of the SPM chart for the track mission state. Although the capabilities, their performance, and sustainability varies from mission state to mission state, the methodology demonstrated is expected to be tailorable to each mission state and to its component and interfacing systems.

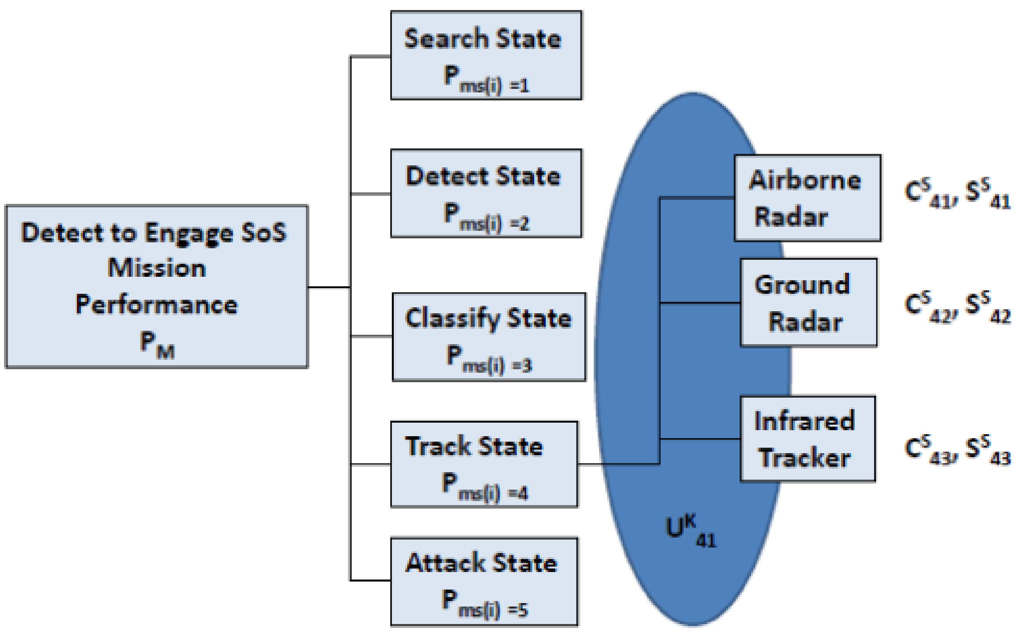


Figure 7. Example SoS Mapped to Mission States and Search State Systems

Track Mission State Capabilities and Analysis Assumptions

For the track mission state, we notionally defined the desired SoS as being composed of n = 3 capabilities. The three sensor capabilities selected as part of this mission state include an infrared tracking system, an airborne radar, and a ground-based phased array radar that all provide inputs to a common command and control (C&C) system to which they are being interfaced with. The systems were selected to reflect the capabilities that would be representative of a range of mature systems that were in production to those under development or would require significant integration with other capabilities. All values with respect to performance, CONOPS, supportability, and so forth, were chosen purely to aid in the demonstration of the methodology and do not reflect any specific system performance parameters. Table 1 provides this initial mapping of systems to their anticipated performance and adjustments with respect to being in the SoS (i.e., integrated into a common C&C system), while Table 2 provides a set of notional operational usage rates reflective of operator CONOPS. The next stage was to map the capabilities performance improvement over time and determine the projected end value when adjusted for the weighting values reflecting the base capabilities inclusion within the SoS. Table 3 provides this notional developmental mapping of performance/sustainment ($CSij(t)$ and $SSij(t)$) over the developmental timeline. Note that for ease of calculation, the maximum expected base sustainment was arbitrarily set to 1.

Table 1. Notional Tacking Mission Stage Capabilities

Capability (integrated w/C&C)	Max. Base Capability (C_{ij}^{B})	Units	Max. Base Sustainability (S_{ij}^{B})	Performance Adjustment due to SoS Inclusion/ Integration (ω_{ij})	Sustainability Adjustment due to SoS inclusion (β_{ij})
Infrared Sensor	300	tracks/hr	1	0.6	0.8
Airborne Radar	500	tracks/hr	1	0.8	0.9
Ground Radar	1000	tracks/hr	1	0.9	1.0

Table 2. Proposed Tracking Mission State System Usage Rates (%)

Capability	CONOPS 1 (U^{1}_{4j})	CONOPS 2 (U^{2}_{4j})	CONOPS 3 (U^{3}_{4j})
Infrared Sensor	20	50	20
Airborne Radar	10	10	10
Ground Radar	20	10	10
C&C System	30	25	50

Table 3. SoS Performance and Sustainability Capability Adjustment at Time (t)

Capability	$C^{S}_{ij}(t_1)$	$S^{S}_{ij}(t_1)$	$C^{S}_{ij}(t_2)$	$S^{S}_{ij}(t_2)$	$C^{S}_{ij}(t_3)$	$S^{S}_{ij}(t_3)$	$C^{S}_{ij}(t_4)$	$S^{S}_{ij}(t_4)$
Infrared Sensor	0.5	0.2	0.6	0.4	0.7	0.6	0.8	0.8
Airborne Radar	0.6	0.5	0.7	0.6	0.8	0.7	0.9	0.8
Ground Radar	1	1	1	1	1	1	1	1

For this example, the growth scale factor was taken on basically a linear scale if the capability was deemed developmental. For capabilities that were viewed as "mature," the values were set to 1. With the baseline assumptions and growth patterns for performance and sustainability defined, we could calculate mission state values for each capability with performance represented in terms of target tracks maintained per capability and sustainability as a non-dimensional value at each specific analysis timeframe. Table 4 documents these results as shown across the notional developmental timeline.

Table 4. Calculated Values for Growth of Performance and Sustainability of Capabilities

Capability	$C^S_{ij}(t_1)$	$S^S_{ij}(t_1)$	$C^S_{ij}(t_2)$	$S^S_{ij}(t_2)$	$C^S_{ij}(t_3)$	$S^S_{ij}(t_3)$	$C^S_{ij}(t_4)$	$S^S_{ij}(t_4)$
Infrared Sensor	90	0.16	108	0.32	126	0.48	144	0.64
Airborne Radar	240	0.45	280	0.54	320	0.63	360	0.72
Ground Radar	900	1	900	1	900	1	900	1

Incorporation of CONOPS Impact

The next step of the methodology incorporated the impact of the operational use of the various capabilities as defined in Table 2. This allowed us to develop the value for the capabilities performance at any given time within the mission state. For this example, we assumed that the values of each capability can be linearly summed to produce the mission state performance value $P_i(t)$. For each capability, we created an interim calculation, Equation 11, defined as

$$P_i(t) = \sum_{j=1}^{m} C^S_{ij}(t) \times S^S_{ij}(t) \times U^k_{ij} \qquad (11)$$

which, when summed across the n = 3 capabilities used within the mission state yields $P_i(t)$ for that set of capabilities at that specific point in time and that specific CONOPS represented by a specific U^K_{ij}. Table 5 summarizes the resulting calculations for this example.

Table 5. Basic Mission State Performance Calculation per Implemented CONOPS

	t_1			t_2			t_3			t_4		
Capability	**$P_4(t)$ for (U^1_{1j})**	**$P_4(t)$ for (U^2_{1j})**	**$P_4(t)$ for (U^3_{1j})**	**$P_4(t)$ for (U^1_{1j})**	**$P_4(t)$ for (U^2_{1j})**	**$P_4(t)$ for (U^3_{1j})**	**$P_4(t)$ for (U^1_{1j})**	**$P_4(t)$ for (U^2_{1j})**	**$P_4(t)$ for (U^3_{1j})**	**$P_4(t)$ for (U^1_{1j})**	**$P_4(t)$ for (U^2_{1j})**	**$P_4(t)$ for (U^3_{1j})**
Infrared	2.9	7.2	2.9	6.9	17.3	6.9	12.1	30.2	12.1	18.4	46.1	18.4
Airborne	10.8	10.8	10.8	15.1	15.1	15.1	20.2	20.2	20.2	25.9	25.9	25.9
Ground	180.0	90.0	90.0	180.0	90.0	90.0	180.0	90.0	90.0	180.0	90.0	90.0
P_4 (t)=	193.7	108.0	103.7	202.0	122.4	112.0	212.3	140.4	122.3	224.4	162.0	134.4

The results of this data could now be plotted into a growth curve of SoS performance over time against which test and developmental data could be applied to provide the SoS PM with insight into the likelihood of meeting performance requirements. Having determined the individual values of performance for specific CONOPS associated with the set of capabilities within the mission state over time, we could determine the average, maximum, and minimum values at each period of time to enable the creation of the SPM chart. Table 6 provides a summary of the performance values for the search mission state in terms of the maximum, minimum, and average value.

Table 6. Calculated Mission State Performance Values

	U^1_{4j}	U^2_{4j}	U^3_{4j}	$\sum P/k$	P_{min}	P_{max}
P_4 @ t_1	193.7	108.0	103.7	135.1	103.7	193.7
P_4 @ t_2	202.0	122.4	112.0	145.5	112.0	202.0
P_4 @ t_3	212.3	140.4	122.3	158.3	122.3	212.3
P_4 @ t_4	224.4	162.0	134.4	173.6	134.4	224.4

Incorporating Uncertainty Into the SoS Performance Measure Metric

So far, the development of SPM has focused on a deterministic approach to the prediction of single-point values staged sequentially over a developmental timeline for a specified mission set where the input values were deterministic. However, in the real world, inputs are seldom deterministic in nature, and not all operational usage concepts are weighted equally. Although the above approach (Volkert et al., 2012) worked to develop the SPM metric for the deterministic state, viewing the problem stochastically requires that the performance be rephrased in terms of its value and probability of occurrence at each stage. Let us now briefly discuss how uncertainty could be introduced into the determination of SPM values. Basically, we must answer the question of whether we can define the component elements of the function and their variability in a meaningful way, such that when the variability is accounted for, the SPM metric will provide an improved value added insight to the PM. To do this, we would need to reexamine how we define the performance of a mission as being composed of the performance of a set of defined mission states ($P_{ms(i)}$) that are composed of individual and/or integrated systems functioning as independent capabilities.

At the system level, we could expect the development of the individual systems or their integrated capabilities as reflected in the factors $C_{ij}^{S}(t)$ to vary, as few systems actually produced the exact level of predicted performance expected at the predicted time. This means that $C_{ij}^{S}(t)$ would be expected to have a degree of variability associated with it. Therefore, we will need to represent the value of $C_{ij}^{S}(t)$ as an effective value, denoted as $C_{ij}^{ES}(t)$, with a target of $c_{ij}^{S}(t)$, which could be expressed as a function of the instance value ($c_{ij}^{S}(t)$) and the probability of having such an instance ($P(c_{ij}^{S}(t))$) such that

$$C_{ij}^{ES}(t) \ = f(c_{ij}^{S}(t), P(c_{ij}^{S}(t)) \qquad (12)$$

Similarly to $C_{ij}^{S}(t)$, the ability to predict the effective value of $S_{ij}^{S}(t)$, denoted as $S_{ij}^{ES}(t)$, for the SoS based on the individual system sustainment plans and their system sustainability factor will of necessity be an imprecise prediction during the developmental stage of a SoS development and contain an element of variability

$$S_{ij}^{ES}(t) \ = f(s_{ij}^{S}(t), P(s_{ij}^{S}(t)) \qquad (13)$$

Introducing a degree of variability associated with $C_{ij}^{S}(t)$ and $S_{ij}^{S}(t)$ means that we need to account for that variability in the combined value $C_{sys(ij)}$. This issue can become complicated because the maturation of sustainment is often independent of the maturation of performance during the developmental effort. However, as the SoS design matures and proceeds into production and fielding, sustainment and performance often become closely linked.

For the usage equation, we needed to look at how the operators view the system and how that introduces variability. Generally, when modeling how the systems composing a SoS are used, a survey of potential users with respect to potential operational usage concepts that may be employed by the operators of the systems within a given mission state is taken. The users then specify a range of values for the usage of each system reflecting their personal experiences and assumptions. As with the values for sustainment and performance, operational usage is seldom achieved to the degree of accuracy defined in the initial plan by the user community. This means that U_{ij}^{k} should also be expected to have a degree of variability associated with it for any discrete system usage set k, and its effective value, denoted as U_{ij}^{Ek}, can be expressed as

$$U_{ij}^{Ek} = f(u_{ij}^{k}, P_k(u_{ij}^{k})) \quad (14)$$

where $P_k(u_{ij}^{k})$ represents the probability of occurrence of event U_{ij}^{k} for any specific usage value u_{ij}^{k}. Unique to the usage value is the question of how to combine the independent values into a single representative value that can represent the overall probability range of the user community. Fortunately, the issue of how to combine experts' probability distributions has been extensively studied. Clemen and Winkler (1999) reviewed and summarized a variety of issues inherent in mathematical and behavioral-based approaches that need to be considered in developing a combinational process for use in practice. Their analysis tended to indicate that mathematical methods performed better than behavioral methods. In addition, it indicated that although more complex combinational methods may be more accurate, they can be somewhat sensitive, and simple combinational methods tend to perform well. Because the purpose of the SPM metric is to provide the PM with a simple tool for obtaining insight into the likelihood of the SoS performing as desired upon completion, the approach of using a simplified tool for correlating users' inputs into a single value and a representation of their probability of achieving that value may be a usable approach. Supporting this approach, a combinational method called the linear opinion pool (Stone, 1961) will be looked at as an option for supporting the combination of the probabilities.

Once an acceptable method is determined, and accepting that the usage determination is independent of the combined performance and sustainability vectors, a method of determining the system level variability for each system within the mission state can then be developed to generate a value of $P(p_{sys(ij)})$, which will represent the overall probability of achieving the desired level of system performance for system *j* within a given mission state *i* using subject matter expert input on system usage options for the averaged usage of the system in that mission state. If we view the individual system contributions as independent events within each operational usage concept, the probability for the specific mission state usage scenario of *m* systems achieving that performance could then potentially be developed and expressed by $P(p_{ms(i)})$. This would allow us to then represent the mission state's combined probability of achieving the predicted performance level; and assuming that the usage of capabilities within a mission state are mutually exclusive, we could derive the variability in the SPM value for the mission, defined as $P(p_{m(i)})$. Developing the analysis and methodology supporting this determination is the planned subject of the authors' future research.

Conclusion

This paper focused on developing a technical performance methodology applicable to the acknowledged SoS. The SoS PM is developed as a leading indicator to assist the SoS PM by providing insight into the risks related to the ability to obtain desired performance. First, a deterministic method was developed to define the concept and approach. Using a generic mission, specifically a tracking mission state as an example, the SPM methodology was then demonstrated. The data developed indicates that the methodology does provide the SoS PM with the opportunity to gain additional insight into the ability to achieve the desired performance for the SoS, without the need for intensive modeling and simulation. This insight would assist the SoS PM in better understanding the degree of risk he or she faces as developmental test data becomes available. Additionally, it could serve as a tool for quickly understanding the impact of CONOP changes and/or the impact of new capabilities (threat or constituent systems) on SoS performance. The authors introduced the need for, and proposed approach to, extending the methodology into a stochastic method to introduce the real-world impact of variability into the analysis as an area of follow-on study. In summary, the SPM metric seems to provide value for a PM, optimally at the mission state level, as the combination of data to a single non-dimensional value at the mission level starts to significantly remove the end value from its causes, diminishing the insight provided to the SoS PM. It is suggested that further research on this area and validation of the approach against real-world case studies would be of value to the SoS management community.

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