NPS-AM-11-C8P09R02-040

EXCERPT FROM THE
PROCEEDINGS
OF THE
EIGHTH ANNUAL ACQUISITION RESEARCH SYMPOSIUM
WEDNESDAY SESSIONS
VOLUME I

Analysis of Alternatives in System Capability Satisficing for Effective Acquisition

Brian Sauser, Jose Ramirez-Marquez, and Weiping Tan, Stevens Institute of Technology

Published: 30 April 2011

Prepared for the Naval Postgraduate School, Monterey, California 93943

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

The research presented at the symposium was supported by the Acquisition Chair of the Graduate School of Business & Public Policy at the Naval Postgraduate School.

To request Defense Acquisition Research or to become a research sponsor, please contact:

NPS Acquisition Research Program
Attn: James B. Greene, RADM, USN, (Ret.)
Acquisition Chair
Graduate School of Business and Public Policy
Naval Postgraduate School
555 Dyer Road, Room 332
Monterey, CA 93943-5103
Tel: (831) 656-2092
Fax: (831) 656-2253
E-mail: jbgreene@nps.edu

Copies of the Acquisition Sponsored Research Reports may be printed from our website www.acquisitionresearch.net

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:

- Office of the Under Secretary of Defense (Acquisition, Technology & Logistics)
- Program Executive Officer SHIPS
- Commander, Naval Sea Systems Command
- Army Contracting Command, U.S. Army Materiel Command
- Program Manager, Airborne, Maritime and Fixed Station Joint Tactical Radio System

- Program Executive Officer Integrated Warfare Systems
- Office of the Assistant Secretary of the Air Force (Acquisition)
- Office of the Assistant Secretary of the Army (Acquisition, Logistics, & Technology)
- Deputy Assistant Secretary of the Navy (Acquisition & Logistics Management)
- Director, Strategic Systems Programs Office
- Deputy Director, Acquisition Career Management, US Army
- Defense Business Systems Acquisition Executive, Business Transformation Agency
- Office of Procurement and Assistance Management Headquarters, Department of Energy

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

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

Analysis of Alternatives in System Capability Satisficing for Effective Acquisition

Brian Sauser—Assistant Professor, School of Systems and Enterprises, Stevens Institute of Technology. He received his BS in Agriculture Development from Texas A&M University, MS in Bioresource Engineering from Rutgers, The State University of New Jersey, and PhD in Technology Management from Stevens Institute of Technology. [bsauser@stevens.edu]

Jose Ramirez-Marquez—Associate Professor, School of Systems and Enterprises, Stevens Institute of Technology. He received his BS in Actuarial Science from Universidad Nacional Autónoma de México, MS in Statistics, and MS and PhD in Industrial and Systems Engineering from Rutgers, The State University of New Jersey. [jmarquez@stevens.edu]

Weiping Tan—received his BE in Automation (first-class honors) in 2006 from Beijing Institute of Technology and received his ME in Engineering Management from Stevens Institute of Technology in 2009. He is currently pursuing his PhD in Engineering Management at Stevens Institute of Technology in the School of Systems and Enterprises. [wtan@stevens.edu]

Abstract

Most systems now provide multiple functions and multiple capabilities (MFMC) in a single solution. Yet, it has become increasingly challenging for managers to properly assess the development and acquisition of these systems to ensure the achievement of adequate system maturity. Moreover, such a challenge is compounded when the systems are not only comprised of MFMC but have multiple or competing technology and integration alternatives. This challenge then raises a fundamental question: How do we effectively assess the maturity of a system for acquisition when considering technology and integration alternatives or trade-offs in a MFMC system? This paper introduces an approach to begin to address this question and provide results that can be used to evaluate systems development maturity, track progress, and form corresponding strategies for further development and trade-offs in technology and integration alternatives.

Introduction

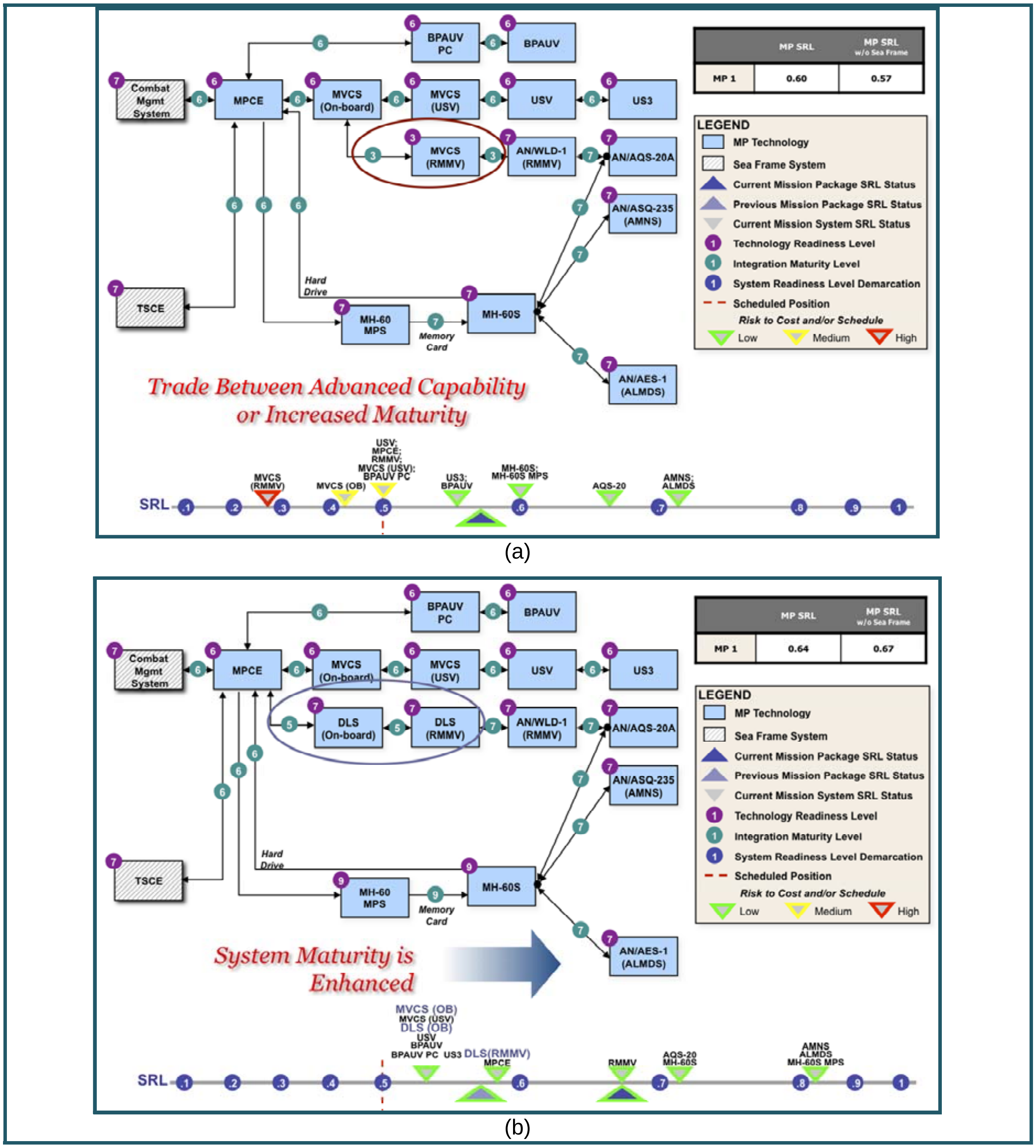
In practice, a system evolves with time from a single capability or a specific function to a more complicated one that affords multiple functions with an operational performance of several capabilities. These systems comprise a number of subsystems and components that are interconnected in such a way that affords the system to be able to perform multiple required functions (Kim, Kim, & Kim, 2009). Moreover, in order to ensure the success of the development or acquisition of a system, even for a specific function, these systems are often required to be open and flexible to further integration of other mission packages in order to satisfy future requirements for a yet-to-be-defined service (GAO, 2008). In the evolution of systems development, the advancement of technology options is progressing faster than the systems themselves, and the engineering knowledge of systems is rapidly advancing beyond our understanding of traditional systems engineering. Conversely, our ability to effectively acquire these systems is challenged with the increasing complexities of and integration among the systems themselves. Thus, multiple functions and capabilities are common to the development of most systems, which raises the need to balance development objectives when facing multiple component alternatives. As a result, managers require metrics that enable the assessment of multi-function, multi-capability (MFMC) system development to manage the potential risks in life cycle management (Volkert, 2009).

In recent development, a System Readiness Level (SRL) and supporting methods have been proposed and accepted as a valid metric to measure the readiness of a system throughout its development life cycle (implementations of this metric have been performed by U.S. Navy-PMS420, U.S. Army-ARDEC, Lockheed Martin, and Northrop Grumman; Sauser, Ramirez-Marquez, Magnaye, & Tan, 2008). However, to date, this scale has focused on the management of a system as a whole or its technology and integration components and lacks the ability to measure development maturity from a system's function or capability viewpoint. The relevance of SRL is limited considering that MFMC systems are common in today's system development and the managers are usually concerned with the progression of critical functions and capabilities for meeting stakeholder needs. Even the most basic weapons, such as assault rifles, have become multi-functional. As such, during the development process, these systems may be called upon to deliver some of their capabilities, even as the development of other capabilities is still behind. Often, this requires an Analysis of Alternatives (AoA) among technology choices and architectures to take advantage of those systems that are already mature, though not originally intended for use in the development of the desired function. This, in turn, requires a thorough understanding of the technical aspects of the components but, more significantly, the relative importance of each choice on the readiness of the system vis-à-vis its desired capability.

In this paper, we present the development of a MFMC approach for systems maturity assessment to be used in a typical AoA process in order to begin to address these fundamental questions in system development and acquisition: Will a new, more functional system or technology supersede the old? Has the system or technology become inadequate due to changes in other systems or technologies? Is it more effective to invest in the development of a new technology or system? Has the system or technology lifetime been shortened by recent developments? What is a robust methodology that can effectively and efficiently analyze, compare, and trade off technology alternatives?

System Maturity for MFMC Systems

Previously, the metric of System Readiness Level (SRL) has been defined as the function of TRLs of the technologies and IRLs of the integrations that constitute the system (Sauser et al., 2008). This research builds on this SRL definition and enhances it to a SRL hierarchy that adds two layers to measure capability and function maturity. The motivation for this approach is predicated on a common scenario described by Forbes et al. (2009). They described a system with six capabilities that are realized by six threads of components. The architecture of this system is represented in Figure 1. As described in their paper, this system had undergone a system maturity assessment with summary charts also depicted in Figure 1. The initial system architecture represented in Figure 1(a) resulted in an assessment with an overall SRL of 0.60 (see MP SRL in the upper right box); the identification of an insufficiently mature technology and supporting integrations (circled); and analysis of the technology-integration maturity of all the system components (horizontal line at the bottom of the diagram). An alternative systems solution based on a trade-off, see Figure 1(b), considered replacing a single technology (i.e., MVCS) with another two technologies (i.e., DLS OB; DLS RMMV). This alternative does not significantly improve the overall SRL value (increase of only 0.04), but it does improve the technology-integration maturity of all the lagging system components (horizontal line at the bottom of the diagram). While this analysis may seem sufficient in increasing systems maturity toward an effective acquisition decision, it does not consider the maturity of system functions or capabilities and the influence of different alternatives on various capabilities' and functions' current or future maturity. Thus, a decision made purely on an increase in maturity for the whole system may be insufficient and cannot accommodate the current systems development reality. This proposed research intends to address this concern by enhancing the SRL approach to take into account the multiple system functions and capabilities that allow for the opportunity to better understand an analysis of alternatives in technologies and integrations to more effectively manage system maturity and acquisition.



(a)

(b)

Figure 1 (a & b). Technology/Integration Trade-Off Analysis

Taking into consideration the notions of function and capability in a system, we propose a hierarchical SRL (see Figure 2), where the SRL is defined at three different levels: capability-based SRL (SRL_C), function-based SRL (SRL_F), and the whole system-based SRL. The capability-based SRL calculates the SRL for a particular capability thread that includes a set of components to enable an intended capability. Based on the calculation of SRL_C's, the function-based SRL addresses the SRL for a specific function that encompasses one or several capability threads. The Composite SRL indicates the SRL for the whole system, which includes multiple functions with multiple capabilities. We adopt and extend the rationale from Ramirez-Marquez and Sauser (2009) for calculating the SRL at capability, function, and system levels.

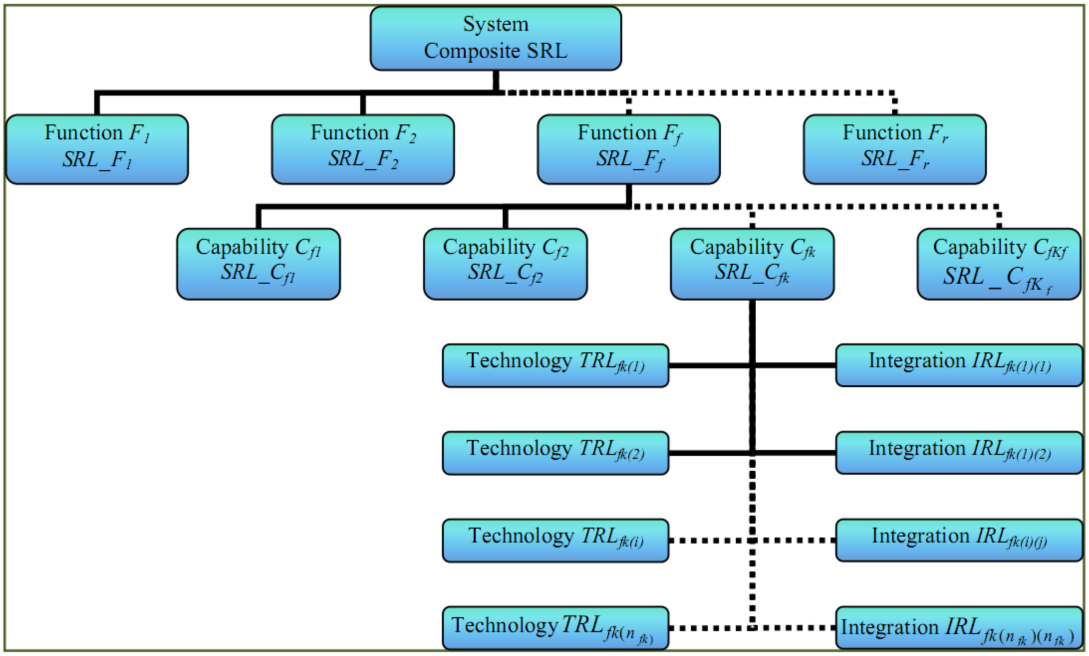


Figure 2. SRL Hierarchy

Procedurally, this approach can be described as the following:

1. Quantifying how a specific technology is being integrated with every other technology to develop the system (i.e., Integration-Technology Readiness Level, ITRL). Note that this quantifier should be a function of both the integration of a technology with every other technology that it has to be integrated with (as dictated by the system architecture) and the maturity of the different technologies. That is, for each technology, this metric should be a function of both TRLs and IRLs. Thus, for technology fk(i), one can view this metric ($ITRL_{fk(i)}$) as "subsystem" measurement of this technology integrates within the system. In a mathematical representation: $ITRL_{fk(i)} = f(TRL_{fk(j)}, IRL_{fk(i)(j)})$.
2. Based on such a metric ($ITRL_{fk(i)}$), SRL_C should provide a capability level measurement of readiness. Note that this new metric should be a function of the different ITRLs of each technology, or in a mathematical representation: $SRL\_C_{fk}=f(ITRL_{fk(1)}, ITRL_{fk(2)},\ldots, ITRL_{fk(n_{fk})})$ under the assumption that the capability contains n_{fk} technologies.
3. Given that the Capability SRL, SRL_C_{fk}, the Function SRL, SRL_F_f, is to provide a function level measurement of readiness. Since there are multiple capabilities to back up a specific function, this metric should be a function of the different SRLs of each capability, or in a mathematical representation:

$SRL\_F_f=f(SRL\_C_{f1}, SRL\_C_{f2},\ldots, SRL\_C_{fK_f})$ with the assumption that the function contains K_f capabilities.

4. Based on the calculation of Capability and Function SRL, the system composite SRL is to provide a holistic picture of the system by enabling system level measurement of readiness. Since there are multiple functions with multiple capabilities to be performed by a composite system, this metric should take into account all functions and capabilities, or in a mathematical representation: *Composite* $SRL=f(SRL\_C_{fk})$ where $f=1,\ldots,r$ and $k=1,\ldots,K_f$ with the assumption that the system contains r functions and $\sum_{f=1}^{r} K_f$ capabilities.

Mathematically, the enhanced procedure to calculate SRL is defined as follows:

System Definition

Assume that a system includes a total of n technologies, and let T denote the technology set: $T=\{TRL_i,\ i=1,2,\ldots,n\}$.

The system includes r functions and let F denote the function set: $F=\{F_f,\ f=1,\ 2,\ldots,r\}$.

Within each function F_f, there are K_f Capabilities: $F_f=\{C_{fk},\ k=1,2,\ldots,K_f\}$.

Within a set C_{fk}, there are n_{fk} technologies and integrations among these technologies: $C_{fk}=\{TRL_{fk(i)},\ IRL_{fk(i)(j)},\ i,\ j=1,2,\ldots,n_{fk}\}$. Finally, $m_{fk(i)}$ is the number of integrations of technology $T_{fk(i)}$ with itself and all other technologies within Capability C_{fk}.

SRL Calculation Procedure

Note, those formatted in italic and bold denote matrices.

1. Normalize the [0, 9] scale original TRLs and IRLs into [0,1] scale TRLs and IRLs by dividing each of them by 9 and denoting them by matrices:

$$\boldsymbol{TRL_{fk}} = [TRL]_{n_{fk}\times 1} = \begin{bmatrix} TRL_{fk(1)} \\ TRL_{fk(2)} \\ \cdots \\ TRL_{fk(n_{fk})} \end{bmatrix} \xrightarrow{Normalize} \boldsymbol{TRL'_{fk}} = \frac{\boldsymbol{TRL_{fk}}}{9} = \begin{bmatrix} TRL'_{fk(1)} \\ TRL'_{fk(2)} \\ \cdots \\ TRL'_{fk(n_{fk})} \end{bmatrix}$$

$$\boldsymbol{IRL_{fk}} = \left[IRL\right]_{n_{fk}\times n_{fk}} = \begin{bmatrix} IRL_{fk(1)(1)} & IRL_{fk(1)(2)} & \dots & IRL_{fk(1)(n_{fk})} \\ IRL_{fk(2)(1)} & IRL_{fk(2)(2)} & \dots & IRL_{fk(2)(n_{fk})} \\ \dots & \dots & \dots & \dots \\ IRL_{fk(n_{fk})(1)} & IRL_{fk(n_{fk})(2)} & \dots & IRL_{fk(n_{fk})(n_{fk})} \end{bmatrix} \xrightarrow{Normalize}$$

$$\boldsymbol{IRL'_{fk}} = \frac{\boldsymbol{IRL_{fk}}}{9} = \begin{bmatrix} IRL'_{fk(1)(1)} & IRL'_{fk(1)(2)} & \dots & IRL'_{fk(1)(n_{fk})} \\ IRL'_{fk(2)(1)} & IRL'_{fk(2)(2)} & \dots & IRL'_{fk(2)(n_{fk})} \\ \dots & \dots & \dots & \dots \\ IRL'_{fk(n_{fk})(1)} & IRL'_{fk(n_{fk})(2)} & \dots & IRL'_{fk(n_{fk})(n_{fk})} \end{bmatrix}$$

where $IRL_{fk(i)(j)} = IRL_{fk(j)(i)}$. When there is no integration between two technologies, an original IRL value of 0 is assigned; for integration of a technology to itself, an original IRL value of 9 is used, that is original $IRL_{fk(i)(i)} = 9$.

2. ***ITRL_C$_{fk}$*** matrix is the product of ***TRL'$_{fk}$*** and ***IRL'$_{fk}$*** matrices:

$$\boldsymbol{ITRL\_C_{fk}} = \boldsymbol{Norm_{fk}} \times \boldsymbol{TRL'_{fk}} \times \boldsymbol{IRL'_{fk}}$$

That is,

$$\boldsymbol{ITRL\_C_{fk}} = \begin{bmatrix} ITRL\_C_{fk(1)} \\ ITRL\_C_{fk(2)} \\ \dots \\ ITRL\_C_{fk(n_{fk})} \end{bmatrix}$$

$$= \begin{bmatrix} 1/m_{fk(1)} & 0 & \dots & 0 \\ 0 & 1/m_{fk(2)} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 1/m_{fk(n_{fk})} \end{bmatrix} \times \begin{bmatrix} IRL'_{fk(1)(1)} & IRL'_{fk(1)(2)} & \dots & IRL'_{fk(1)(n_{fk})} \\ IRL'_{fk(2)(1)} & IRL'_{fk(2)(2)} & \dots & IRL'_{fk(2)(n_{fk})} \\ \dots & \dots & \dots & \dots \\ IRL'_{fk(n_{fk})(1)} & IRL'_{fk(n_{fk})(2)} & \dots & IRL'_{fk(n_{fk})(n_{fk})} \end{bmatrix} \times \begin{bmatrix} TRL'_{fk(1)} \\ TRL'_{fk(2)} \\ \dots \\ TRL'_{fk(n_{fk})} \end{bmatrix}$$

$$= \begin{bmatrix} (IRL'_{fk(1)(1)}\,TRL'_{fk(1)} + IRL'_{fk(1)(2)}\,TRL'_{fk(2)} + \dots + IRL'_{fk(1)(n_{fk})}\,TRL_{fk(n_{fk})})/m_{fk(1)} \\ (IRL'_{fk(2)(1)}\,TRL'_{fk(1)} + IRL'_{fk(2)(2)}\,TRL'_{fk(2)} + \dots + IRL'_{fk(2)(n_{fk})}\,TRL'_{fk(n_{fk})})/m_{fk(2)} \\ \dots \\ (IRL'_{fk(n_{fk})(1)}\,TRL'_{fk(1)} + IRL'_{fk(n_{fk})(2)}\,TRL'_{fk(2)} + \dots + IRL'_{fk(n_{fk})(n_{fk})}\,TRL'_{fk(n_{fk})})/m_{fk(n_{fk})} \end{bmatrix}$$

where $m_{fk(i)}$ is the number of integrations of technology $TRL_{fk(i)}$ with itself and all other technologies within capability C_{fk}, and ***Norm$_{fk}$*** is to normalize the $SRL\_C_{fk(i)}$ from [0, $m_{fk(i)}$] scale to [0, 1] scale for consistency. Thus, matrix $\boldsymbol{Norm_{fk}} = diag[1/m_{fk(1)},\ 1/m_{fk(2)},\ \dots,\ 1/m_{fk(n_{fk})}]$.

3. *SRL_C$_{fk}$* denotes the SRL for capability *C$_{fk}$*. It is defined as the average of the all the normalized technologies' ITRL values, which is given by the following:

$$SRL\_C_{fk} = \frac{ITRL\_C_{fk(1)} + ITRL\_C_{fk(2)} + \ldots + ITRL\_C_{fk(n_{fk})}}{n_{fk}} = \frac{\sum_{i=1}^{n_{fk}} ITRL\_C_{fk(i)}}{n_{fk}}$$

4. SRL_F_f is the *SRL* for function F_f. With Consideration 3 in mind, although there are multiple capabilities to ensure the same function, the maximum of these Capability SRLs represents the readiness of that function and is defined as

   $$SRL\_F_f = Max(SRL\_C_{fk}),\ k = 1,2,\ldots,K_f$$

   SRL_F matrix includes all the Function SRLs and is denoted by the following:

   $$\boldsymbol{SRL\_F} = \begin{bmatrix} SRL\_F_1 \\ SRL\_F_2 \\ \ldots \\ SRL\_F_r \end{bmatrix}$$

5. Finally, the Composite SRL for the whole system is the average of all Capability SRLs to address Consideration 4:

$$Composite\ \ SRL = \frac{(\sum_{k=1}^{K_1} SRL\_C_{1k}) + (\sum_{k=1}^{K_2} SRL\_C_{2k}) + \ldots + (\sum_{k=1}^{K_r} SRL\_C_{rk})}{K_1 + K_2 + \ldots + K_r} = \frac{\sum_{f=1}^{r}\sum_{k=1}^{K_f} SRL\_C_{fk}}{\sum_{f=1}^{r} K_f}$$

This enhanced SRL hierarchy enables more accurate system maturity assessment by adding two layers to the previous definition. It accommodates the development of MFMC systems.

Analysis of Alternatives

According to Ullman (2006), AoA is an effort of military process to move from narrowing to a single solution for the examination of multiple alternatives so acquisition agencies have a basis for funding the best possible solutions in a rational, defensible manner considering risk and uncertainty. It is mandated by the DoD in support of each decision milestone and serves as the primary input to the program documents that direct the development of a weapons acquisition program (USD[AT&L], 2008). The AoA establishes and benchmarks metrics for Cost, Schedule, Performance (CSP) and Risk (CSPR) depending on military needs (Ullman, 2009). It also assesses critical technology elements (CTEs) associated with each proposed materiel solution, identified in the Initial Capabilities Document (ICD), including technology maturity, integration risk, manufacturing feasibility, and, where necessary, technology maturation and demonstration needs. The results of the AoA provide the basis for the Technology Development Strategy (TDS) and have to be approved by the Milestone Decision Authority (MDA) at Milestone A.

In the domain of system architecting and AoA, identifying, prioritizing, and ranking components with respect to their impact on the system is key to understanding the importance of any one component to another and is notable for suggesting trade-offs among key parameters during their development and acquisition. This research contributes to the body of knowledge by bridging the gap in the analysis of traditional system architectures with system maturity assessment. It assists in the establishment of system development and acquisition strategies from the quantification of the relationship between component maturity and system maturity and distinguishes the importance of different components for making informed decisions when deciding to trade off technology and integration alternatives without rushing to judgment on a preferred systems solution or architecture.

In an AoA, the main objective is to execute an extensive analysis that would result in preferred system architecture. What we are proposing is a variation on a traditional AoA in that the key performance indicator would be the maturity of the technologies and integrations supporting the systems' functionalities and capabilities. This paper incorporates AoA analysis to the MFMC systems development. The preferred alternative will be selected for system acquisition through the comparison of the impact of various technology and integration alternatives on the maturity of system functions and capabilities. See Figure 3 for a typical AoA that incorporates the methods proposed in this paper.

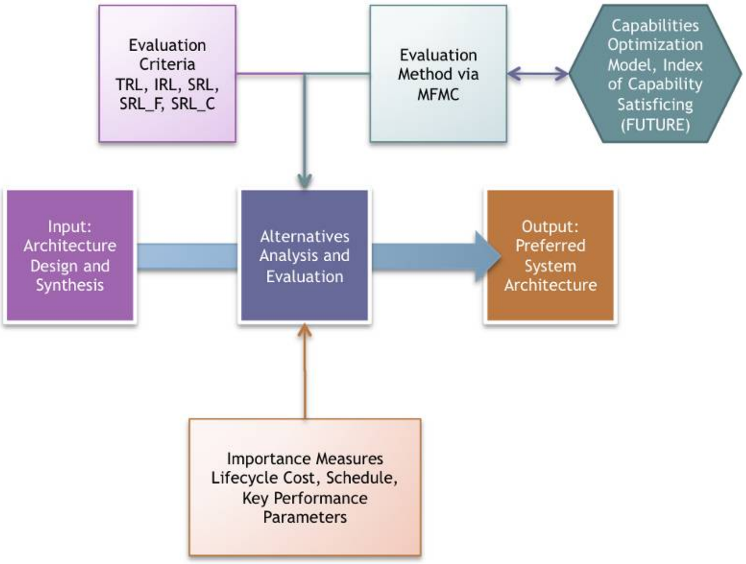
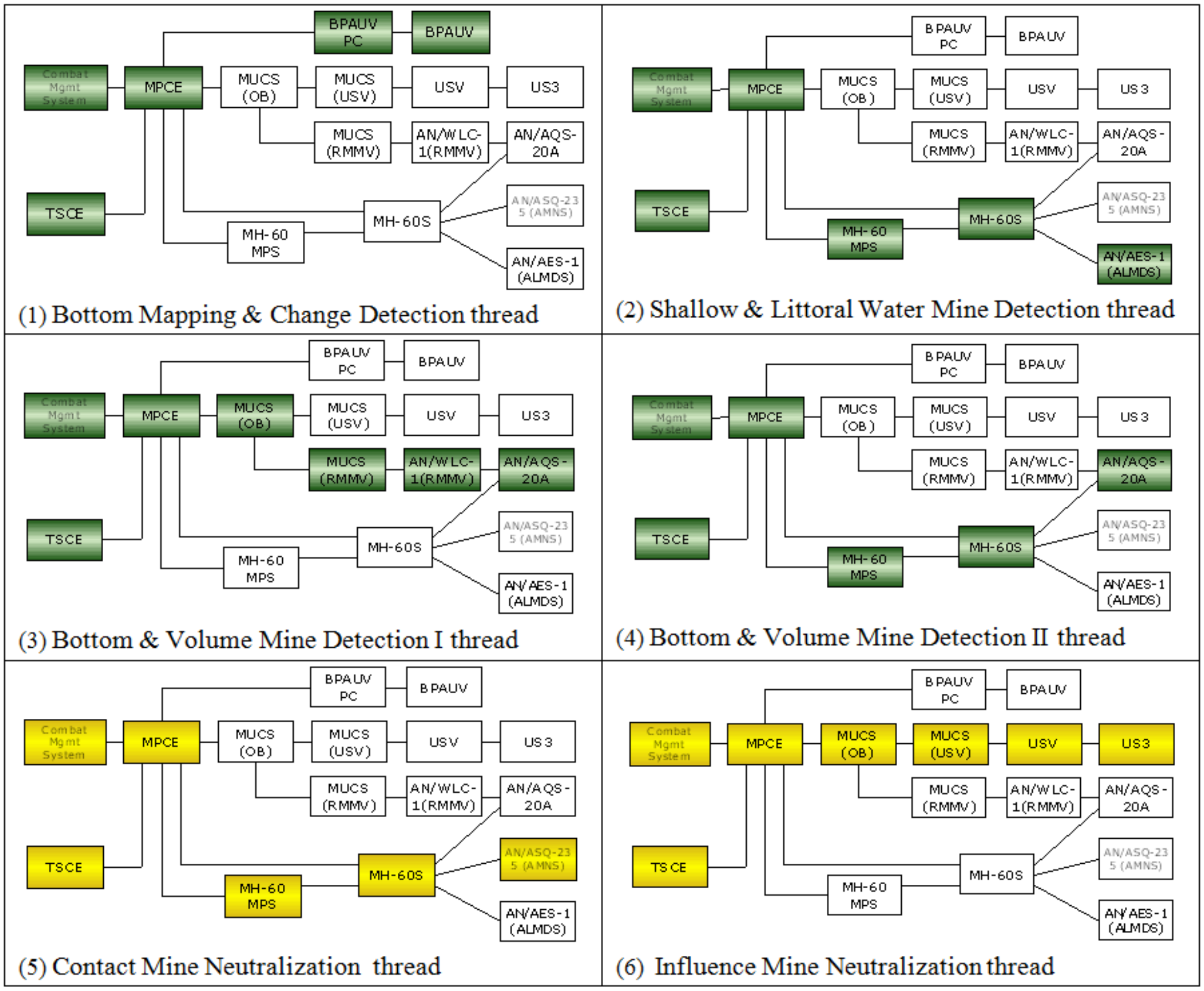


Figure 3. Alternative Analysis

Illustrative Example

The proposed MFMC AoA methodology is demonstrated with a system that was previously discussed and shown in Figure 1. There are basically two functions—Mine Detection and Mine Neutralization—to be performed by this system. There are four capabilities in the first function and two capabilities in the second, as shown in Figure 4 (the first function is shaded in green and the second is shaded in yellow). There are six capabilities that are realized by six threads of components, as listed in Figure 4: (1) Bottom Mapping & Change Detection; (2) Shallow & Littoral Water Mine Detection; (3) Bottom & Volume Mine Detection-I; (4) Bottom & Volume Mine Detection-II; (5) Contact Mine Neutralization; and (6) Influence Mine Neutralization.



(1) Bottom Mapping & Change Detection thread

(2) Shallow & Littoral Water Mine Detection thread

(3) Bottom & Volume Mine Detection I thread

(4) Bottom & Volume Mine Detection II thread

(5) Contact Mine Neutralization thread

(6) Influence Mine Neutralization thread

Figure 4. A MFMC System With Two Functions and Six Capabilities

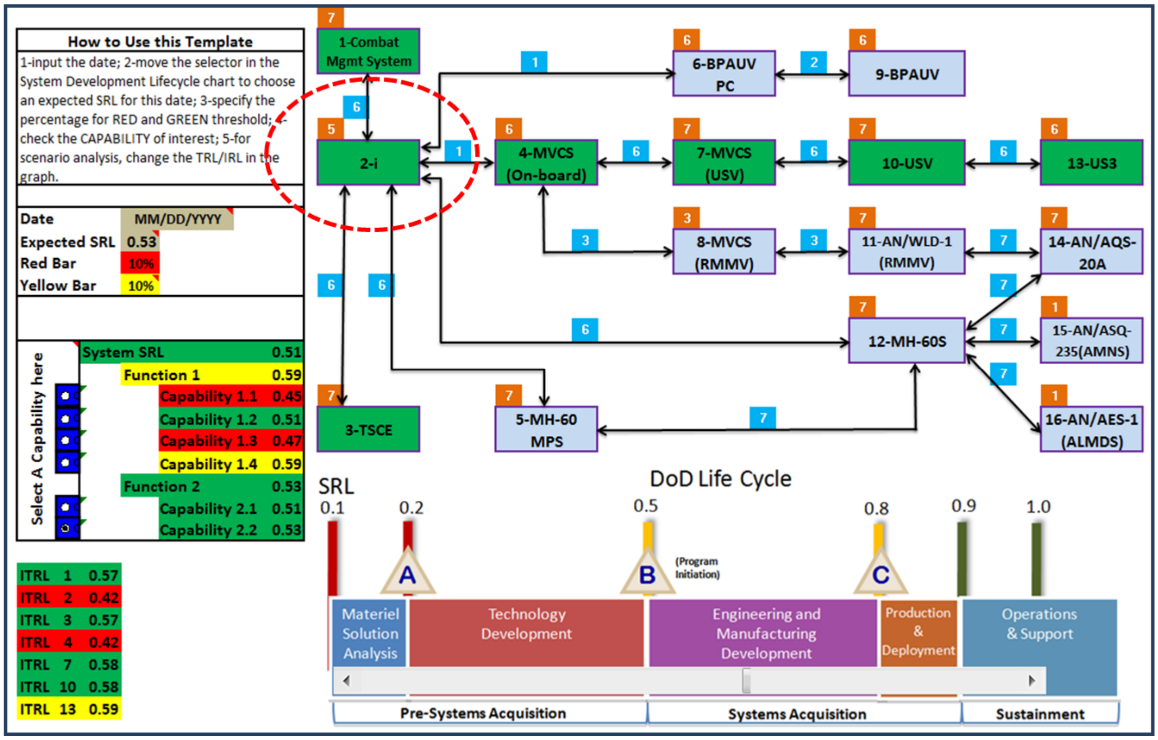
Figure 5 shows the results from using a tool that utilizes the proposed SRL hierarchy to assess system maturity. The left side of the figure displays the new hierarchy for the estimates of system development maturity at different levels: ITRL, capability, function, and system levels. It adds two layers (capability and function) to the original SRL definition to provide more accurate assessment and more insights for systems engineering managers to track the progression on life cycle of the systems development. In addition, three other user inputs are added to the assessment:

- Expected SRL: this is the SRL value that is expected at the time of the assessment or a projected time in the life cycle.
- Red Bar: this is the lower threshold value of the SRL. If an ITRL, capability, or function assessment falls below this level, it is indicated in red.
- Yellow Bar: this is the upper threshold value of the SRL. If an ITRL, capability, or function assessment falls above this level, it is indicated in yellow.

Any value for the ITRL, capability, or function assessment that falls within the thresholds is indicated in green. The development of this illustrative system is mapped to the DoD Acquisition Life Cycle to determine the development progression. As shown in Figure

5, with a 10% margin of the expected SRL 0.53 as the risk thresholds, we can observe the following:

1. The system level SRL indicates that the whole system is progressing on schedule, with a SRL value of 0.51 compared to the expected value on this particular assessment date.
2. Although the development of Function 1 is ahead of schedule, with an SRL value of 0.59, there is variability in the development of the individual capabilities that make up Function 1.
3. The ITRLs in Figure 5 are for the selected Capability 2.2, which is within the target threshold, but ITRLs 2 and 4 indicate a risk in falling behind, though the rest of the ITRLs in this capability are being developed as planned.



How to Use this Template

1-input the date; 2-move the selector in the System Development Lifecycle chart to choose an expected SRL for this date; 3-specify the percentage for RED and GREEN threshold; 4-check the CAPABILITY of interest; 5-for scenario analysis, change the TRL/IRL in the graph.

Date	MM/DD/YYYY
Expected SRL	0.53
Red Bar	10%
Yellow Bar	10%

Select A Capability here

	System SRL	0.51
	Function 1	0.59
○	Capability 1.1	0.45
○	Capability 1.2	0.51
○	Capability 1.3	0.47
○	Capability 1.4	0.59
	Function 2	0.53
○	Capability 2.1	0.51
●	Capability 2.2	0.53

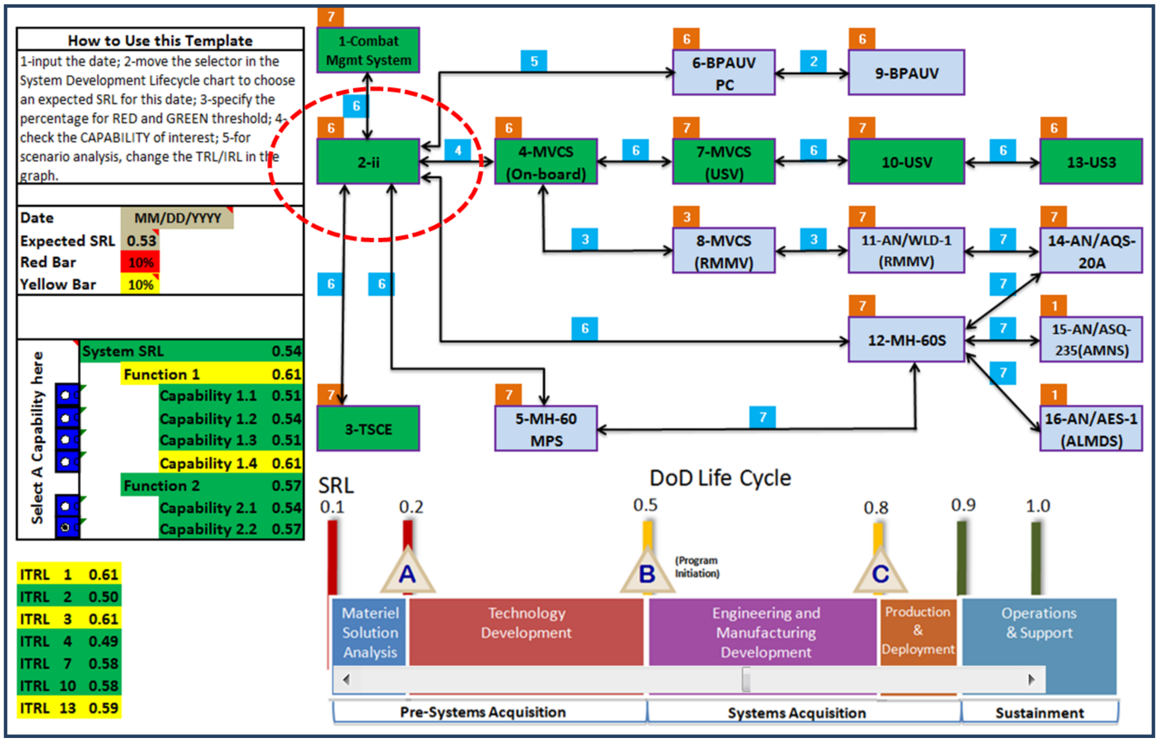
ITRL	1	0.57
ITRL	2	0.42
ITRL	3	0.57
ITRL	4	0.42
ITRL	7	0.58
ITRL	10	0.58
ITRL	13	0.59

Figure 5. Alternative i

The use of the enhanced SRL hierarchy and the employed assessment tool provides developers and managers with a holistic picture to investigate the system development and the ability to easily identify system development weaknesses as indicated by variations around a threshold. This example also manifests the multi-dimensional nature of system maturity assessment, which should be examined at different levels within the same system architecture for which an assessment using a single number would have overlooked.

This tool and approach facilitates the aforementioned AoA to examine multiple alternatives to get the best possible solution to satisfy customer requirements. Figure 6 shows the assessment of a different alternative to Figure 5 with only replacing Technology 2-i with 2-ii that is assumed to provide the same functionality (see the circled technology). While more mature in its TRL and IRLs with Technologies 4 and 6, the inclusion of Technology 2-ii leverages the progression of Capabilities 1.1 and 1.3, which were previously identified to be lagging in Alternative-i (Figure 5). Meanwhile, at the ITRL level for Capability

2.2, all ITRLs are balanced to be either on or ahead of development schedule. Compared with Alternative-i, Alternative-ii (Figure 6) significantly outperforms in terms of meeting and balancing development maturity and potentially mitigates some of the risk of meeting customer expectations. Therefore, based on the analysis of these two alternatives, the second option with Technology 2-ii is the preferred alternative.



How to Use this Template

1-input the date; 2-move the selector in the System Development Lifecycle chart to choose an expected SRL for this date; 3-specify the percentage for RED and GREEN threshold; 4-check the CAPABILITY of interest; 5-for scenario analysis, change the TRL/IRL in the graph.

Date	MM/DD/YYYY
Expected SRL	0.53
Red Bar	10%
Yellow Bar	10%

Select A Capability here

System SRL	0.54
Function 1	0.61
Capability 1.1	0.51
Capability 1.2	0.54
Capability 1.3	0.51
Capability 1.4	0.61
Function 2	0.57
Capability 2.1	0.54
Capability 2.2	0.57

ITRL	1	0.61
ITRL	2	0.50
ITRL	3	0.61
ITRL	4	0.49
ITRL	7	0.58
ITRL	10	0.58
ITRL	13	0.59

Figure 6. Alternative ii

It should be noted that although it seems quite simple and intuitive from the comparison of these two alternatives, this example is only for illustration purposes. In practice, the method presented in this paper will have more value when utilized on more complicated architectures that involve a number of different components (i.e., technologies and integrations) and the interplay among them. In such situations, it will not be straightforward and intuitive like this one and can hardly be cognitively comprehended, where the use of such a tool and multi-layer-hierarchy is very necessary for trade-offs in MFMC systems acquisition.

Conclusion and Future Research

In order to address a challenging system acquisition problem of effectively assessing the development maturity with the consideration of technology and integration alternatives in MFMC systems, this paper proposes an enhanced SRL hierarchy and an AoA methodology. With the use of a tool, the proposed methodology was demonstrated with an illustrative example. As evidenced, this methodology moves use closer to facilitating more informed maturity assessments for MFMC systems development and AoA that can assist the acquisition of DoD weapon systems.

Previous efforts funded by the Acquisition Research Program addressed some recurring issues that were revealed through conversations with our industry and government research partners. In essence, we were answering the question: What are the effects of necessary trade-offs in functionality, capability, cost, schedule, and maturity that will allow the acquisition of a system that can still satisfy warfighters' needs? Our research funded via the Acquisition Research Program helped to answer the question by 1) identifying the critical components to system maturity, that is, which components (i.e., technologies or integrations) have the greatest impact on system maturity; 2) prioritizing component development based on constrained resource availability; and 3) balancing between system capabilities and functions with a given developmental budget.

While the previous research has proven necessary and relevant for a better understanding of how to achieve effective maturity, capability, and functionality of a system for acquisition, it does not address the fundamental activity in the development of system solutions that this paper introduces. To clarify, in any systems solution, a systems engineer or acquisition manager must make critical, necessary, and sufficient trade-offs with respect to technologies and integrations based on AoA, and these trade-offs come at a cost/benefit to the functionality and capability of the system and its existing architecture. There is increasing development and acquisition of systems that are built upon open and flexible platform designs that can accommodate multiple functions and capabilities as well as the ability for adopting future mission packages (e.g., modularity, system of systems). With such a trend, decisions to trade off among multiple alternatives that enable necessary functions and capabilities will be unavoidable. In conclusion, Figure 7 represents the gestation and evolution of the research funded by the Acquisition Research Program in the exploration and development of innovative concepts in system maturity assessment.

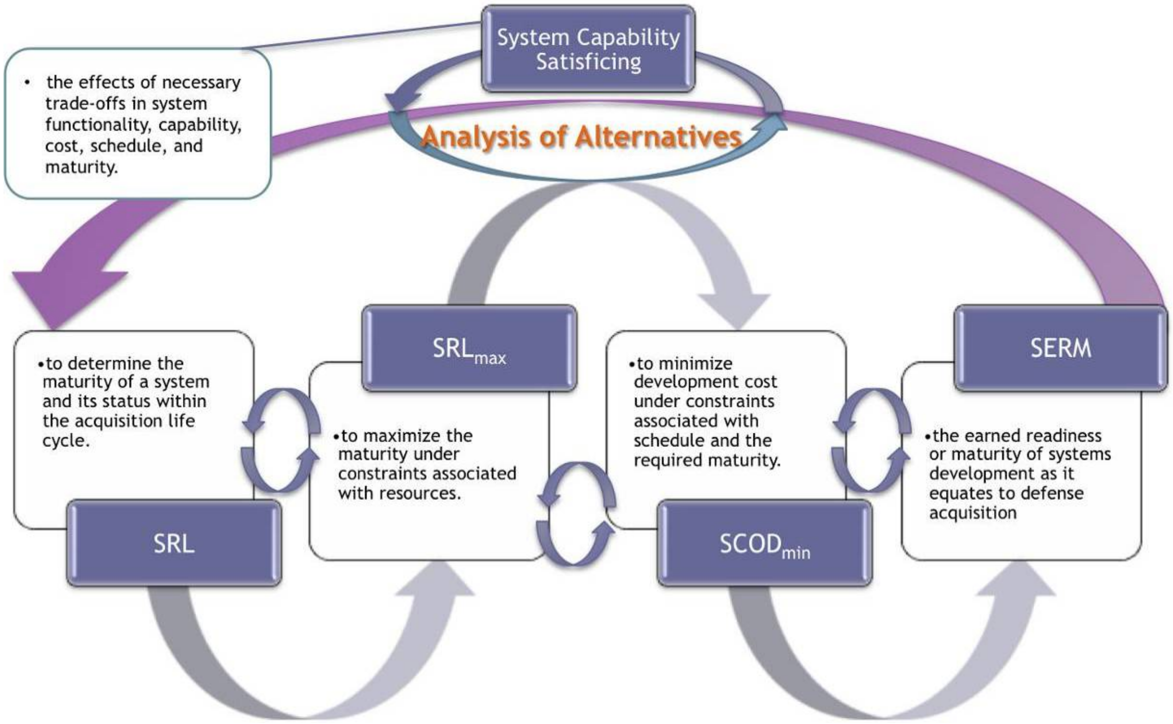


Figure 7. Evolutionary Development Plan

References

Forbes, E., Volkert, R., Gentile, P., & Michaud, K. (2009). Implementation of a methodology supporting a comprehensive system-of-systems maturity analysis for use by the

Littoral Combat Ship mission module program. In *Proceedings of the Sixth Annual Acquisition Research Symposium*. Monterey, CA: Naval Postgraduate School.

GAO. (2008). *Defense acquisitions: Assessments of selected weapon programs*. Washington, DC: Author.

Kim, D. J., Kim, H. C., & Kim, J. O. (2009). Evaluation of structural importance based on minimal cut set theory. Transactions of the Korean Institute of Electrical Engineers, *58*(3), 27–32.

Ramirez-Marquez, J. E., & Sauser, B. J. (2009). System development planning via system maturity optimization. *IEEE Transactions on Engineering Management*, *56*(3), 533–548.

Sauser, B., Ramirez-Marquez, J., Magnaye, R., & Tan, W. (2008). A systems approach to expanding the technology readiness level within defense acquisition. *International Journal of Defense Acquisition Management*, *1*, 39–58.

Ullman, D. G. (2006). *Making robust decisions: Decision management for technical, business, and service teams*. Victoria, B.C.: Trafford.

Ullman, D. G. (2009). Decisions based on analysis of alternatives (AoA). Retrieved from http://www.robustdecisions.com/AOA.pdf

USD(AT&L). (2008, December 8). *Operation of the defense acquisition system* (DoD Instruction 5000.02) Washington, DC: Author.

Volkert, R. (2009, September 10). Notional assessment methodology for KPP accomplishment in a SoS proposed methodology for measuring performance progress within a system of systems (SoS). *SSC-Pacific, Version 1.4*.

Acknowledgements

This material is based upon work supported by the Naval Postgraduate School Acquisition Research Program under Grant No. N00244-11-1-0002. The authors would like to thank the Naval Postgraduate School Acquisition Research Program, the U.S. Navy NAVSEA PMS 420 Program, the Systems Engineering Research Center, the U.S. Army Armament Research Development and Engineering Center, and Northrop Grumman Integrated Systems for their support in this research.