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Capability and Development Time Trade-off Analysis in Systems-of-Systems

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Preface & Acknowledgements

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

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

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

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

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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 19 – System-of-Systems Acquisition: Concepts and Tools

Thursday, May 12, 2011	
11:15 a.m. – 12:45 p.m.	**Chair: Rear Admiral David H. Lewis,** USN, Program Executive Officer, Ships ***Capability and Development Time Trade-off Analysis in Systems-of-Systems*** Muharrem Mane and Daniel DeLaurentis, Purdue University ***System-of-Systems Acquisition: Alignment and Collaboration*** Thomas Huynh, John Osmundson, and Rene Rendon, NPS ***Using Architecture Tools to Reduce the Risk in SoS Integration*** Chris Piaszczyk, Northrop Grumman

Rear Admiral David H. Lewis—Program Executive Officer Ships. Rear Admiral Lewis is responsible for Navy shipbuilding for surface combatants, amphibious ships, logistics support ships, support craft, and related foreign military sales.

Born at Misawa Air Force Base, Japan, Lewis was commissioned in 1979 through the Navy ROTC Program at the University of Nebraska–Lincoln with a Bachelor of Science degree in Computer Science.

At sea, Lewis served aboard USS *Spruance* (DD 963) as communications officer, where he earned his Surface Warfare qualification; USS *Biddle* (CG 34) as fire control officer and missile battery officer; and USS *Ticonderoga* (CG 47) as combat systems officer. His major command assignment was Aegis Shipbuilding program manager in the Program Executive Office Ships, where he helped deliver seven DDG 51 class ships and procured another 10 ships.

Lewis' shore assignments include executive assistant to the assistant secretary of the Navy (Research, Development and Acquisition), assistant chief of staff for Maintenance and Engineering, commander, Naval Surface Forces, where he also served as a charter member of the Surface Warfare Enterprise. Other ship maintenance and acquisition assignments ashore include the Navy Secretariat staff; commander, Naval Sea Systems Command staff; Aegis Shipbuilding Program Office; supervisor of Shipbuilding, Bath; and Readiness Support Group, San Diego. Upon selection to flag rank, Lewis served as vice commander, Naval Sea Systems Command. Lewis earned a Master of Science degree in Computer Science from the Naval Postgraduate School. He completed the Seminar Course at the Naval War College Command and Staff School, and received his Joint Professional Military Education certification. He is a member of the Acquisition Professional Community with Level III certifications in Program Management and Production Quality Management, and has completed his civilian Project Management Professional certification.

Lewis' personal awards include the Legion of Merit, Meritorious Service Medal, Navy and Marine Corps Commendation, Navy and Marine Corps Achievement Medal, and various service and unit awards.

Capability and Development Time Trade-off Analysis in Systems-of-Systems

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Daniel DeLaurentis—Associate Professor, School of Aeronautics and Astronautics Engineering, Purdue University. Dr. DeLaurentis received his PhD from Georgia Institute of Technology in Aerospace Engineering in 1998. His current research interests are in mathematical modeling and object-oriented frameworks for the design of system-of-systems, especially those for which air vehicles are a main element; and approaches for robust design, including robust control analogies and uncertainty modeling/management in multidisciplinary design. [ddelaure@purdue.edu]

Abstract

Capability-based acquisition has led to the simultaneous development of systems that must eventually interact within a system-of-systems (or major sub-systems that must integrate on a single platform). The necessary interdependencies between systems also generate complexity and can increase development risk. Trades between capability and risk are essential during analysis of alternatives in pre-acquisition phases. For example, while legacy assets can potentially provide a certain level of capability with relatively low risk, their eventual capability may be restricted because of some specific characteristic or inherent rigidity. These features create a trade-off space between development risk and capability potential of a system. Existing tools for such trades can be cumbersome and non-intuitive when complexity is high. The authors' prior work has developed a Computational Exploratory Model to simulate the development process dynamics for these complex networks of systems intended for a system-of-systems capability. The progress documented in this paper couples the computational model with a capability module applied to the Airborne Laser (ABL) system and presents an exemplary analysis of alternatives by comparing expected development time and capability level under certain probabilities of disruption.

Introduction

The purpose of capabilities-based acquisition, as described by Charles and Turner (2004), is to acquire a set of capabilities instead of acquiring a family of threat-based, service-specific systems. The Missile Defense Agency (MDA), for example, uses capability-based acquisition to evaluate the success of a program based on its ability to provide a new capability for a given cost, and not on its ability to meet specific performance requirements (Spacy, 2004). The Joint Mission Capability Package (JMCP) concept is another example that aims to create a joint interdependency between systems to combine capabilities in order to maximize reinforcing effects and minimize vulnerabilities (Durkac, 2005). The goal is a more efficient utilization of both human and machine-based assets and, in turn, improved combat power. In these settings, systems are increasingly required to interoperate along several dimensions, which characterizes them as systems-of-systems (SoS; Maier, 1998). SoS most often consist of multiple, heterogeneous, distributed systems that can (and do) operate independently but can also assemble in networks and collaborate to achieve a goal.

The presence of interdependencies in layered networks spanning a hierarchy of levels is one of the sources of complexity in SoS development (DeLaurentis et al., 2008a, 2008b; Ayyalasomayajula et al., 2008; Kotegawa et al., 2008). The interdependencies between component systems often result in complex networks that exhibit vulnerabilities to disruptions in the development of even one system, especially if that one system places a central role in the network. Gell-Mann (2002) defines complexity as the amount of information necessary to describe regularities of a system effectively. Rouse (2001) summarizes the complexity of a system (or model of a system) as related to the intentions with which one addresses the system, the characteristics of the representation that appropriately accounts for the system's boundaries, architecture, interconnections, and information flows, and the multiple representations of a system. We can represent degrees of complexity by examining the graphs that result when we record the intentions, characteristics, interconnections, etc., in a given situation.

Acquisition programs have struggled with complexities in both program management and engineering design (e.g., NASA's Constellation Program [Committee on Systems Integration for Project Constellation, 2004] and FAA's NextGen [NextGen Integration and Implementation Office, 2009]). While first-order impacts of decisions are nearly always considered, the cascading effects that result from complex interdependencies obscure the quantification and visibility of the higher-order impacts of developmental decisions and disruptions. Furthermore, the network structure behind the collaboration can contribute both negatively and positively to the successful achievement of SoS capabilities and, even earlier, to the developmental success. Collaboration via interdependence may increase capability potentials, but it also contains concealed risk in the development and acquisition phases.

Our approach quantifies the impact of system interdependencies in the context of system development and capability. It provides a means to conduct analysis of alternatives while navigating the decision space that simultaneously considers the potential positive impacts of interdependencies (e.g., capability) as well as the negative impacts (e.g., development time). The work comprises new improvements to a Computational Exploratory Model (CEM)—a discrete event simulation model—previously introduced in prior Acquisition Symposia (Mane and DeLaurentis, 2009, 2010) that aims to provide decision-makers with insights into the development process by propagating development risk in the SoS network. The impact that system risk, system interdependencies, and system characteristics have on the estimated completion of a program are generated. We present a proof-of-concept application that analyzes the development time of the Airborne Laser (ABL) system and conduct a trade-off study between development time and capability while considering various alternatives for the constituent systems of the ABL.

Computational Exploratory Model (CEM) Overview

The CEM is based on the 16 basic technical management and technical system-engineering processes outlined in the Defense Acquisition Guidebook (DoD, 2008a), often referred to as the 5000-series guide. However, an SoS environment changes the way these processes are applied. The Systems Engineering Guide for System-of-Systems (SoS-SE; DoD, 2008b) addresses these considerations by modifying some of the 16 processes in accord with an SoS environment. The resulting processes and respective functions consist of translating inputs from relevant stakeholders into technical requirements, developing relationships between requirements, designing and building solutions to address requirements, integrating systems into a high-level system element, and performing various managing and control activities to ensure that requirements are effectively met, risks are mitigated, and capabilities achieved.

The CEM, centered on these revised processes, is a discrete event simulation of the development and acquisition process. This process creates a hierarchy of analysis levels: SoS Level (L1), Requirement Level (L2), and System Level (L3). Component elements at each level are a network representation of the level below. The SoS Level (L1) is comprised of the numerous, possibly interdependent requirements (L2) needed to achieve a desired capability. Similarly, satisfaction of each requirement in the Requirement Level (L2) requires a number of possibly interdependent systems (L3).

At the Requirement Level (L2), *Requirements Development* contains the technical requirements of the SoS (provided externally). The technical requirements are then examined in *Logical Analysis* to check for interdependencies among the requirements. A check for inconsistencies among requirements is also performed. *Design Solution* development and *Decision Analysis* are the next processes, which belong to the System Level (L3). They produce the optimal design solution from the set of feasible solutions to meet the given requirements. The optimal design solution not only is based on the current set of requirements and solution alternatives but also takes into account all previous information available through requirements, risk, configuration, interface, and data management processes. Because most acquisitions are multi-year projects involving many different parties, the overlap between the management processes, *Design Solution* and *Decision Analysis*, allows for greater tractability of decisions. It is at this stage that system interdependencies are identified. The optimal design solution obtained from this phase is then sent to the next stage: *Technology Planning* and *Technology Assessment*. In the event that an optimal or sub-optimal design solution to successfully implement the given requirements does not exist, the feedback loop to *Requirement Development* translates into a change in the technical requirements for the SoS. *Technology Planning* and *Technology Assessment* are System Level (L3) scheduling processes that oversee the implementation, integration, verification, and validation for all the component systems in the SoS.

The *Implementation and Integration* Phases of component systems constitute the lowest level of detail modeled in the CEM. The design decisions made at earlier stages must be implemented and integrated in these phases to generate the final product of a program. Figure 1 presents an abstraction of the layered networks that result from the modeling of the acquisition process: systems are grouped to satisfy a requirement, and requirements are grouped to generate a capability.

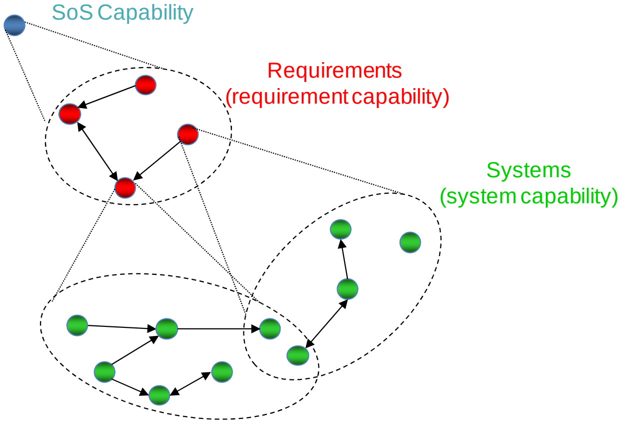

Figure 1. Layered Network Abstraction of Computational Exploratory Model

Systems can be independent, can satisfy several requirements, and can depend on other systems. The CEM simulates these layered relationships to capture the impacts that any changes—related to decision-making, policy, or development—in any of the component systems, requirements, and relationships between them have on the completion of a project. In our prior experiments, we studied the impact of different interdependency topologies. The exercise of the CEM described in this paper assumes a fixed topology and instead specifically targets variations in inherent system risk, the interdependency strength among systems, and the span-of-control of the SoS authority (if present). The next section presents the CEM model dynamics and input parameters.

Model Input Parameters

The CEM operates as a discrete event simulator of the development process. It models risk (probability of a disruption and associated consequence) present in the implementation and integration of each component system as well as the risk due to the system interdependencies. Furthermore, systems and SoS engineers are often faced with the decision of using legacy assets to satisfy a given requirement or opt for the development of brand new ones. The CEM includes parameters such as *readiness-level* to differentiate between legacy assets/platforms, new systems, and partially implemented/integrated systems (i.e., systems under development) and to investigate the impact that the inclusion of such systems in the development of an SoS has on the success of a project. Table 1 presents the input parameters, and the remainder of this section expands and explains their role in the CEM.

Table 1. Input Parameters of Computational Exploratory Model

Parameter	Notation	Description
Requirement Level (L2)		
Requirement dependencies	D_{req}	Adjacency matrix that indicates requirement interdependencies
Risk profile	R_{req}	Probability of disruptions in *Requirement Development Phase*
Impact of disruptions	I_{req}	Time penalty when disruptions hit *Requirement Development Phase*
System Level (L3)		
System dependencies	D_{sys}	Adjacency matrix that indicates system interdependencies
Development pace of design	t_{des}	Increase in completion of *Design Solutions Phase*
Design risk profile	R_{des}	Probability of disruptions in *Design Solutions Phase*
Impact of design disruptions	I_{des}	Time penalty when disruptions hit *Design Solutions Phase*
Span-of-control	soc	Indicator of how *Implementation* and *Integration* are performed (sequentially or simultaneously)
System initial readiness-level	$m^0(i,r)$	Initial readiness-level of system i to satisfy requirement r (for *Implementation Phase*)
System risk profile	$R_{sys}(i,r)$	Probability of disruptions (during implementation) of system i when satisfying requirement r
Impact of disruptions	$I_{sys}(i)$	Time penalty when disruptions hit system i during *Implementation*/*Integration*
Implementation pace	$p_{imp}(i)$	Increase in readiness-level at each time-step during implementation of system i
Integration pace	$p_{int}(i)$	Increase in completeness-level at each time-step during integration of system i
Implementation start	$l_{imp}(i,j)$	Readiness-level of system j when *Implementation Phase* of dependent system i begins
Strength of dependency	$S(i,j)$	Strength of dependency of system i on system j

The requirement dependency matrix (D_{req}) indicates how the development and satisfaction of requirements depend on each other, which impacts the sequence in which requirements are developed and satisfied. For example, if Requirement A depends on Requirement B, then development of Requirement A begins when Requirement B has been satisfied. As requirements are developed, the risk profile (R_{req}) of *Requirement Development* indicates the probability of disruptions at this stage in the development process. Disruptors signify a change in requirements or the addition of new requirements. When a requirement is changed after the acquisition process has begun, it affects all subsequent processes and causes a time delay (I_{req}) that is added to the project time. Every requirement that is implemented is fed into its own *Design Solution* and *Decision Analysis* process. The *Design Solution* and *Decision Analysis* processes feed into each other, and the risk profile (R_{des}) indicates the probability of disruptions at each time-step during the completion of the stage with a value between 0 and 1. Any disruptions at this stage indicate that the design solution provided is not feasible and a time penalty (I_{des}) that indicates a re-design of the solution is incurred. If the solution fails in multiple consecutive time-steps, then the requirement is sent back to the *Requirement Development* stage; otherwise, the set of component systems and their user-defined parameters are sent to the *Technical Planning* and *Technical Assessment* processes, based on the development-pace parameter of this stage.

The *Implementation Phase* simulates the development of each system. The nature of candidate systems may range from legacy systems to off-the-shelf, plug-and-play products to custom-built, new systems. Here, we define *legacy systems* as systems that have been developed in the past to achieve a particular requirement, and *new systems* as not-yet-developed systems envisioned to satisfy a new requirement. When considering the use of legacy systems to meet a new requirement, the capability of these systems to satisfy the new requirement is not necessarily the same as their capability to meet the original requirement for which they were designed. Additionally, the risk associated with the modification of a legacy system and the risk associated with the development of a brand new system can be quite different. Legacy systems may, however, provide cost and/or time benefits if modifications are less severe than a new development, as is the case with new systems. To delineate systems in a meaningful way, we describe the spectrum of a system's ability to satisfy a requirement in terms of its readiness-level.

System readiness-level, a concept proposed by Sauser et al. (2006), is a metric that incorporates the maturity levels of critical components and their readiness for integration (i.e., integration requirements of technologies). This is an extension of the widely used Technology Readiness-Level (TRL), a metric that assesses the maturity level of a program's technologies before system development begins (USD[AT&L], 2005). While similar in spirit to the SRL metric proposed by Sauser et al. (2006), readiness-level in the present work is defined in a different manner and with less detail. We define system readiness-level as the readiness-level of a system i to satisfy requirement r, $m(i,r)$, with a value between 0 and 1. A system with a readiness-level of 1 is a fully developed system that can provide a certain level of capability. The dynamic model starts the *Implementation Phase* of a system from its initial readiness-level and simulates its development/implementation until it reaches a readiness-level of 1. An initial readiness-level of 0 indicates a brand new system that must be developed from scratch, while a system with an initial readiness-level greater than 0 indicates a legacy system that is partially developed to satisfy a requirement r but needs further development to reach a readiness-level of 1. In general, careful research of a candidate system i will determine its initial readiness-level to satisfy a requirement r, and, therefore, the amount of development necessary to achieve a readiness-level of 1.0.

The CEM simulates the *Implementation Phase* as a series of time-steps in which a pre-determined increment of readiness ($p_{imp}(i)$) is gained at each time-step of each system i or lost if a disruption occurs (according to the system risk profile of system i in satisfying requirement r, $R_{sys}(i,r)$). This is clearly a gross simplification of the actual development process for a system; however, it adequately serves the purposes of the research, which is focused on the interdependencies between systems to develop a SoS capability and aims to capture the impact of disruptions on the development process. Accurate modeling of the *Implementation Phase* would increase the accuracy of the model for a particular application, but it would not change the nature of the observed results.

Representation of Disruptions

The risk associated with the development of a system is a function of its inherent characteristics (technology, funding, and complexity levels) and on risk levels of the systems on which it depends. The former may be estimated via a variety of analysis techniques that examine a system in detail, but the latter requires knowledge of system interdependencies that can be numerous, complicated, and often opaque. Developmental interdependencies of SoS create layered networks that often span among a hierarchy of levels (DeLaurentis et al., 2005; Butler et al., 2001; Ayyalasomayajula et al., 2008; Kotegawa et al., 2008). The complexity of these networks often hides many of the otherwise explicit consequences of risk. Depending on the network topology characteristics, disruptions to one of the critical nodes or links in the network can propagate through the network and result in degradation to seemingly distant nodes (Huang et al., 2008).

In this study, we express inherent risk as a density function that describes the probability of a disruption occurring at any time during the system development. We concentrate on the *Implementation* and *Integration Phase* as the development stage where disruptions occur. Here, inherent risk is the probability of disruptions due to the development characteristics of the subject system (e. g., technology readiness-level, funding, politics, etc.). Risk due to interdependencies, on the other hand, is the probability of disruptions during the *Implementation Phase* of a system due to disruption in the system on which the system of interest depends. This is essentially the conditional probability of a disruption, given that another system has a disruption.

This study assumes that the inherent risk of a system i in satisfying requirement r, $R_{sys}(i,r)$, is solely a function of its readiness-level, $m(i,r)$. While a somewhat simplified definition, expressing risk as a function of a system's readiness-level is logical since readiness describes the necessary development of a system to satisfy a given requirement. Therefore, risk changes as the readiness-level of a system increases. Equation 1 introduces a relationship between a system's readiness-level and inherent risk (probability of disruption).

$$R_{sys}(i,r) = \alpha_i \left(1 - m(i,r)^{\beta_i}\right) \tag{1}$$

In this relationship, α_i (with a value between 0 and 1) is a parameter that indicates the upper-bound value of risk for system i (i.e., producing maximum probability of disruption) while β_i is a shape parameter that indicates how quickly risk changes as a function of readiness-level. This formulation implies that risk is highest at the early stages of development (e.g., low readiness-levels) and it decreases (at different rates, depending on the value of the β_i parameter) as development progresses. For instance, when a system i has a readiness-level of 0.0—it is a brand new system—the probability of disruptions during development will be highest, and it will have a value α_i. However, when the system has a readiness-level of 1.0, the probability of disruptions will be 0. System inherent-risk is implemented in the CEM by using a uniform random distribution to select a value between 0 and 1 at each time-step of the *Implementation* or *Integration Phase* and passing it into a binary channel to see if the number is smaller or greater than the probability of disruption defined by $R_{sys}(i,j)$. This determines if a disruption occurs or not.

When all systems are independent, identification of the system with highest risk is trivial (e.g., the system that, on average, will contribute more to delays in completion time). However, when systems are interdependent, systems that otherwise have a low inherent risk can be greatly impacted by disturbances because of the transmission of risk from other systems. Systems are impacted by nearest neighbors (those systems on which they directly depend; first-order dependencies) and by systems that impact those nearest neighbors (higher-order dependencies).

The CEM models risk due to interdependencies in terms of the dependency strength between two given systems. Dependency strength, *S*(*i,j*), is an input parameter that takes values between 0 and 1 and is defined as the conditional probability (uniform random probability) that system *i* has a disruption, given that system *j* (on which system *i* depends) has a disruption. Risk due to interdependencies is, therefore, a function of the readiness-level of the dependent-upon system as well as the strength of that dependency.

When considering the development of different system sets that can provide a desired SoS capability, the characteristics of interdependencies must be considered because they have a large influence on both capability and development time. Quantifying the impact that such characteristics have on the development process can aid decision-makers in selecting the most promising alternative. The next section of this paper presents a proof-of-concept application of the CEM to perform an analysis of alternatives study for different constituent systems of a development network while comparing capability and development time.

Proof-of-Concept Application

The ABL program serves as the proof-of-concept problem for demonstrating the Computational Exploratory Model (CEM), equipped with a capability estimate module, for performance of trade-off analyses between capability and development time. The CEM simulates the propagation of disruptions in the network of component system interdependencies and enables a trade-off study between the completion time of the ABL and its potential capabilities when different component system alternatives are considered.

The ABL is a theater defensive weapon concept that is designed to destroy ballistic missiles in their boost phase within the first two minutes of flight from hundreds of kilometers away (Davey, 2000). The current ABL, still under development, consists of an aerial platform (a modified Boeing 747-400), infrared sensors for detecting the missile, two solid state lasers for tracking the missile and measuring atmospheric disturbances, an Adaptive Optics System (AOS) for adjusting for atmospheric disturbances, and a Chemical Oxygen Iodine Laser (COIL beam) for destroying the missile. Figure 2 presents these component systems and their layout in the Boeing B747-400, as described in (Defense Industry Daily, 2009). Note that the ABL program may not be considered a system-of-systems operationally, but developmentally, it has all of the traits required of an SoS, as described by Maier (1998). In particular, the geographic distribution, along with managerial and operational independence, qualifies the development process of the ABL as a system of systems. Development of the ABL team is undertaken by three companies, who operate and manufacture their respective pieces of the ABL across the country. The Beam Control/Fire Control (BC/FC) system is designed by Lockheed Martin, the COIL beam is designed by Northrop Grumman, and the modifications to the aircraft and integration of systems are performed by Boeing. In addition, each company has been able to, at least partially, test their portions of the ABL separately (Davey, 2000), indicating some degree of operational independence.

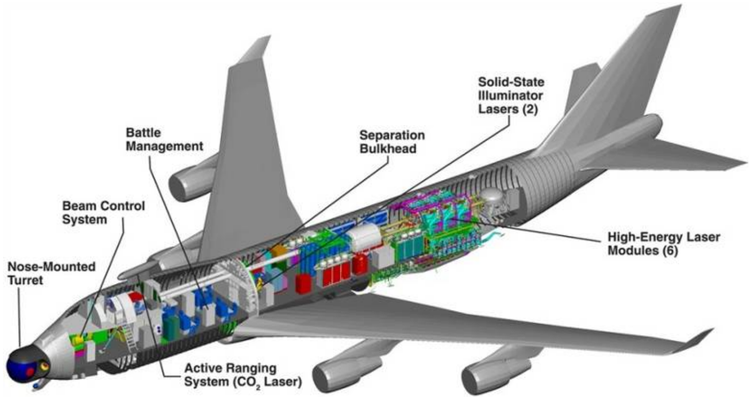

Figure 2. Airborne Laser Component Systems
(Defense Industry Daily, 2009)

The ABL operates as follows: first, several onboard Infrared Search and Track (IRST) sensors detect the heat radiated by the exhaust of the missile. Next, a solid state laser (the Track Illuminator) tracks one or more missiles, determines an aim point, and passes the information to the main ABL computers. The other solid state laser (the Beacon Illuminator) measures disturbances in the atmosphere so that they may be corrected by the AOS in order to accurately focus the main laser on the missile. This sequence adjusts the focus of the COIL beam and, together, is known as the Beam Control/Fire Control (BC/FC) system. Finally, the COIL beam—a dual line, multi-module laser—is focused onto the missile through a large turret on the nose of the vehicle until it compromises the structural integrity of the missile.

Several assumptions and simplifications are necessary to facilitate the proof-of-concept study. While the requirements of the ABL are comprised of several components/tasks—detect, track, aim and adjust laser beam, and destroy missile—here they are grouped into a single requirement. Additionally, the component systems of the ABL are grouped into four core systems: the aircraft system, the detection and tracking (D&T) system, the AOS, and the COIL beam system. Development of these four systems and their integration results in the ABL capability of detecting, tracking, and destroying theater ballistic missiles in their boost phase.

ABL Capability

The capability of a system is embodied by the quality with which it performs required functions. The required capability of the ABL, as described by Barton et al. (2004), is to disable ballistic missiles in their boost phase. Depending on the type of threat missiles, operating environment, and other operational variables, many metrics exist for describing the capability of the ABL system. In this work, we assume that the ABL capability of interest is its ability to disable threats from a range of 600 km. Tests and studies of the ABL have shown that 600 km is a reasonable performance goal (Barton et al., 2004). Hence, the achievable capability level of the ABL will be measured against this baseline value of engagement range.

Three functions are necessary on the ABL: detect and track the missile, engage the missile, and disable the missile. As previously mentioned, we assume that four constituent systems comprise the ABL system and perform the three functions. The contributions of each system to the execution of each function are presented in Figure 3.

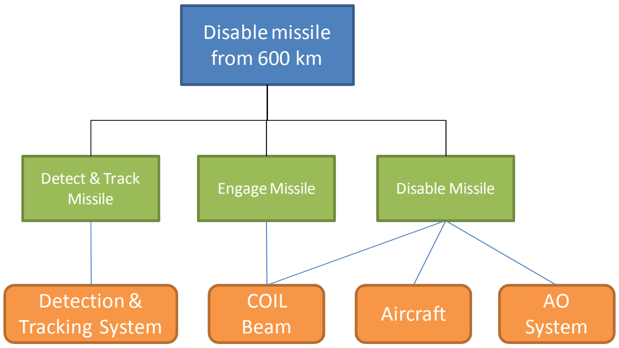

Figure 3. Assumed Capability Composition of ABL

The capability of the ABL is, therefore, a function of the performance levels of each of its constituent systems (Table 2).

Table 2. Performance Goals of ABL Systems

Constituent System	Performance Metric	Performance Level (units)
Detection & Tracking	Detection time, T_d	10 (sec)
Aircraft	Payload capacity	250,000 (lbs)
COIL beam	Beam power, P	5 (MW)
Adaptive Optics	Beam quality, b_q	1.2 (n/a)

The detection time, T_d, is the time that the D&T system requires to acquire a target and generate a track. This is an important performance parameter because it will dictate the time available to the laser to engage and disable the target during the boost phase. Based on the report by Barton et al. (2004), an acceptable dwell time (the amount of time that the laser must deliver its energy) for a liquid-propelled missile is on the order of 4 to 5 seconds. This means that for a given raid size, the D&T system has a limited time to acquire the target and generate tracks. We assume that in order for the ABL to disable up to 12 simultaneously launched liquid fuel missiles (with a boost phase of 170 seconds), the ideal detection time is 10 seconds (based on a dwell time, t_e, of 4.2 seconds; Equation 2).

$$T_d = \frac{\text{boost time}}{\text{raid size}} + t_e \qquad (2)$$

The COIL beam is the centerpiece of the ABL system. The beam power, P, determines the amount of energy that will be delivered to the missile. Again, based on the extensive report by Barton et al. (2004), a reasonable power performance for the COIL beam is around 5 MW. The capability of the ABL will be a function of this performance parameter as well as the performance of the other constituent systems.

The aircraft hosts the other constituent systems of the ABL and provides the necessary mobility characteristics of this weapon. However, we assume that from a capability point of view (to disable a missile from 600 km), it can fulfill the necessary requirements to host the constituent systems of the ABL and is thus not a part of the capability trade space. Note that this is a simplifying assumption in this study but one that can be included in more detailed studies.

Finally, atmospheric disturbance must be accounted for, since it plays a significant role on the laser performance. Development of the ABL system includes the development of an advanced Adaptive Optics System that can account for the atmospheric disturbances and increase the energy delivered to the missile. The performance of these optics is typically described by the Strehl ratio. The Strehl ratio is a measure of the quality of optics that compares the peak intensity at the detection point with a theoretical maximum intensity. While various factors contributed to the quantification of the Strehl ratio, Barton et al. (2004) provide the simplified description:

$$S_R = \frac{1}{b_q^2} \tag{3}$$

where b_q is the beam quality diffraction limit and can be used as a performance benchmark for adaptive optics. Barton et al. (2004) state that a beam quality value of 1.2 represents a reasonable goal.

The amount of energy required to disable a missile varies according to the missile construction and the type of fuel it utilizes (fuel tanks are the most vulnerable part of the missile). Barton et al. (2004) offer a simplified relationship between the performance parameters of its constituent systems and the capability of the ABL to disable a missile from a distance R. In this relationship, the force required to disable a missile, F_c, is expressed as follows:

$$F_c = \frac{\pi}{4}\left(\frac{D}{\lambda}\right)^2 \frac{1}{R^2}(P \cdot t_e)S_R \tag{4}$$

where D and λ are the diameter and wavelength of the COIL beam, respectively; R is the slant range (e.g., the distance between the ABL and the target missile); P is the COIL beam power in Watts; t_e is the laser dwell time (e.g., the time that the laser delivers its energy to the target); and S_R is the Strehl ratio of the Adaptive Optics System. Solving this relationship for the slant range, R, describes the capability of the ABL as a function of the performance parameters of its constituent systems.

$$R = \sqrt{\frac{\pi}{4}\left(\frac{D}{\lambda}\right)^2 (P \cdot t_e)S_R \cdot F_c} \tag{5}$$

The capability contributed by the COIL beam is represented by the COIL beam power, P, (and fixed values of D = 1.5 m and λ = 1.315 μm); the capability contributed by the AOS is represented by the S_R value; and the capability contributed by the D&T system is represented by the available dwell time, t_e. We assume that the capability of the ABL will be measured in terms of its ability to disable a liquid-fueled ICBM, which requires a force of 32 MJ, F_c = 32 MJ/m^2 (Barton et al., 2004). The capability of the ABL will be computed by using this relationship for different combinations of constituent systems that can offer various levels of system-specific performance and will be compared to their estimated development.

ABL Development

The Air Force and the Missile Defense Agency (MDA) have been experimenting with the simultaneous development, testing, and integration of the component systems of the ABL. Because of this, development of these systems is interdependent. For instance, the aircraft developer needs the stability requirements and dimensional specifications of the Adaptive Optics System and the COIL beam system to determine the proper mountings and fuselage dimensions of the aircraft; or, development of the aircraft requires knowledge of the heat dissipated by the COIL beam to determine the amount of heat protection to include in the aircraft airframe and/or subsystems. Depending on the performance of the COIL beam—i.e., its maximum power output—the adaptive optics must provide a certain level of performance in order to deliver the required amount of energy to the target. Similarly, depending on the capability of the D&T system, the adaptive optics must be able to effectively compensate for the atmospheric disturbances of the detection range. Development of the AOS is, therefore, dependent on the development of the COIL beam and the D&T system. A representation of the interdependencies in this example problem and its layered network structure is presented by Figure 4.

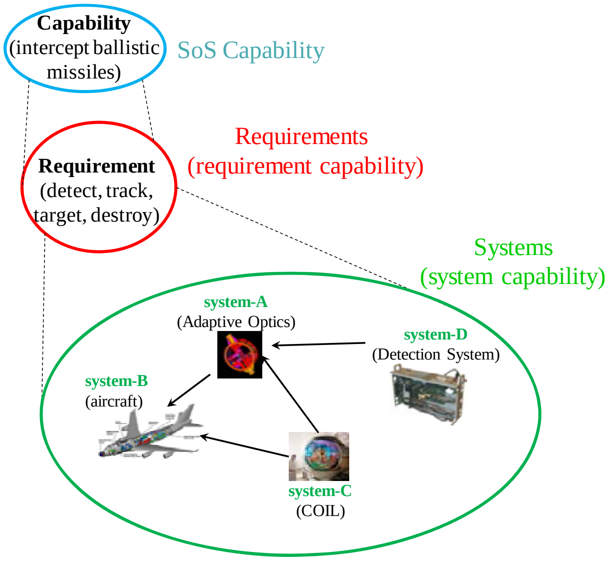

Figure 4. Assumed System Interdependencies in ABL Example

While more interdependencies may be present in the development of the ABL systems, for the purpose of this demonstration, we assume that the topology presented in Figure 4 represents the development interdependencies of the ABL system *and remains fixed during the analysis of alternatives*. The goal is to present a sample utilization of the CEM to perform analysis of alternatives and capability and development risk trade-off. The CEM will utilize these interdependency characteristics and other necessary parameters to estimate the development time of the ABL when alternative constituent systems (e.g., systems with varying levels of capability) are considered.

Results

For the proof of concept application presented here, the desired capability is the ability to engage and disable missiles from a range of 600 km. This capability is a function of the constituent, interdependent systems. Here, we assume that the designer has the option to select different constituent systems to satisfy this ABL requirement. The Boeing B747-400 is currently being used as the aerial platform that hosts the ABL system. The MDA stated in a 2007 report that an alternative to the current ABL platform is the utilization of Unmanned Aerial Vehicles (UAVs), which can offer longer endurance and eliminate the risk to crew members. Similarly, Davey (2000) reports that alternate systems to the currently used detection and tracking system could be considered to partially fulfill the ABL requirement (e.g., UAV or Space Tracking and Surveillance System [STSS]). Additionally, Barton et al. (2004) indicated that the ideal performance of the Adaptive Optics System and the COIL beam is still questionable, and sub-optimal “solutions” will be utilized following a spiral development strategy that will enable incremental improvement of these systems’ capabilities.

Three alternative aerial platforms and three detection and tracking systems are considered to fulfill the ABL requirement, while three levels of performance of the AOS and the COIL beam with different levels of initial readiness-level are considered. Table 3 presents these assumed values for alternatives for the aircraft system.

Table 3. Assumed Values for Alternative Systems for Aerial Platform

Aircraft Alternative	Max Payload [lbs]	TRL	Initial Readiness-Level [$m^o(i,r)$]	Implementation Pace [$p_{imp}(i)$]
new aircraft	TBD	5	0.56	0.04
KC-135A	105,821	6	0.67	0.04
B747-400	248,000	8	0.89	0.04

All alternatives are assumed to have an implementation pace of 0.04; this means that at every time-step during the CEM simulation, the completeness-level increases by an increment of 0.04, until a completeness-level of 1.0 is reached. The Boeing NKC-135A is included here as an alternate aerial host platform because it was the primary aircraft in the Airborne Laser Laboratory (ALL) —a precursor to today's Airborne Laser program—during the 1980s (Duffner, 1997). The purpose of this program was to perform tests and determine whether or not a laser mounted on an aircraft could actually shoot down an airborne target. The Boeing 747-400 is the aircraft that currently hosts the constituent systems of the ABL and has a payload capacity of 248,000 lbs (*Jane's All the World's Aircraft*, 2010). A GAO report (2002) stated that the present laser with six modules weighs 180,000 lbs and the laser design calls for a laser with 14 modules; while the actual power output of the laser is not known, we assume a linear relationship between the weight of the laser and its power output, and, therefore, a larger payload capacity is required for the aircraft to host the sub-systems of the COIL beam. The new aircraft alternative is assumed to provide this required payload capability.

Furthermore, because modifications are necessary to host the other component systems of the ABL, we assume that the KC-135A, the B747-400, and the new aircraft have a TRL of 6, 8, and 5, respectively. We utilize the TRL as an indicator of the risk associated with the development of a given system; the approach followed here normalizes the TRL value (by dividing by the maximum possible TRL, 9) and uses this value as the initial readiness-level of the system (m^0). The new aircraft alternative has the lowest TRL because it is a brand new system; however, it does not have a TRL of 0 because we assume that existing technologies can be utilized to meet its requirements.

The options to the designer for the detection and tracking system of the ABL are to design a brand new system or use legacy systems like the Space Tracking and Surveillance System (STSS) or UAVs. Table 4 presents the alternate systems and assumed capabilities along with their initial readiness-levels.

Table 4. Assumed Values for Alternative Systems for Detection System

Detection Alternative	Detection Time [sec]	TRL Level	Initial Readiness-Level [$m^o(i,r)$]	Implementation Pace [$p_{imp}(i)$]
New System	10	6	0.67	0.04
UAV	11	8	0.89	0.04
STSS	12	9	1.00	0.04

One option that the MDA has considered for the early detection and targeting of missiles is the utilization of UAVs (Buttler, 2009). However, because current concepts of operations involve the UAV accepting a cue from satellites about the threat missile, we assume that the detection time for such a system is of 11 seconds. Recall that detection time impacts the available laser dwell time (e.g., longer detection time reduces the available time to disable the missile during the boost phase). Furthermore, because UAVs are currently used to perform reconnaissance missions, we assume that utilizing UAVs for detection and tracking has a TRL level of 8. Another option for detecting and tracking the missile is the use of the Space Tracking and Surveillance System (STSS). As of 2003, the MDA has decided to fund the design but not the production of a competitive sensor for use aboard the satellites (Smith, 2003). We assume that the STSS has a TRL level of 9 and can achieve a detection time of 12 seconds if it is used as the detection and tracking system of the ABL. Finally, we consider the development of a new system to provide the D&T capability for the ABL system. Based on the GAO report (2002), the D&T system under development has a TRL level of 6. Because this is a custom system designed specifically for use in the ABL system, we assume that it can achieve a detection time of 10 seconds, which would enable the detection of up to 12 simultaneously launched missiles before the end of the boost phase, assuming a 170-second boost phase and a dwell time of 4.2 seconds.

While alternative systems for the aerial platform and the D&T system exist, the COIL beam and the Adaptive Optics System are new technologies for which alternatives do not exist. Because the level of performance of these systems is still uncertain, we assume that different levels of beam quality and power output for the AOS and COIL beam, respectively, can be achieved given the different TRL levels. Table 5 and Table 6 present these assumed values.

Table 5. Assumed Values for Alternative Systems for Adaptive Optics System

Detection Alternative	Beam Quality Diffraction Limited	TRL Level	Initial Readiness-Level [$m^o(i,r)$]	Implementation Pace [$p_{imp}(i)$]
Alternative 1	1.2	2	0.22	0.02
Alternative 2	1.3	3	0.33	0.02
Alternative 3	1.4	5	0.56	0.02

Table 6. Assumed Values for Alternative Systems for COIL beam System

COIL Beam Alternative	Power [MW]	TRL Level	Initial Readiness-Level [$m^o(i,r)$]	Implementation Pace [$p_{imp}(i)$]
Alternative 1	3	4	0.44	0.03
Alternative 2	4	3	0.33	0.03
Alternative 3	5	1	0.11	0.03

The GAO-02-631 report (2002) provides the TRLs for Alternative 1 for both the AO and the COIL beam systems, and assumed TRL and capability values are used for the other alternatives, as well as implementation paces. The systems engineer would like to know which combination of constituent systems results in a (ABL) system with lowest estimated completion time and provides the largest capability potential. We assume that all alternatives have a maximum probability of disruption of 0.2 ($\alpha_i = 0.2$), which decreases as the completeness-level of a system increases. This implies that alternatives with a larger initial readiness-level will have a smaller probability of disruption than systems with a smaller initial readiness-level.

In the present study, the interdependency strengths between systems are varied for each potential ABL architecture, based on the initial readiness-level of the candidate constituent system. We assume that the initial readiness-level of a given system indicates the interdependency strength between that system and all the systems that depend on it and that the interdependency strength is the complement of the initial readiness-level. For instance, if one of the alternatives for the COIL beam has an initial readiness-level of 0.33, then the strength of the dependency of the aircraft system on the COIL beam system is 0.77 (1-0.33).

Based on the alternative systems in Table 3, Table 4, Table 5, and Table 6, there are 81 possible combinations of D&T, aircraft, COIL beam, and Adaptive Optics Systems that could satisfy the requirement of the ABL, albeit at a different capability level. For the purpose of this study, these describe the design space for the analysis of alternatives. The goal is to quantify the trade-off between the ABL capability (in terms of the engagement range) and the estimated development time. To simplify, we assume that the interdependencies between the systems will not change in the scenarios where the alternative systems are utilized (i.e., the system interdependencies presented in Figure 4 will be invariant).

CEM simulates the development process and estimates the completion time of the entire program and uses system-specific capabilities to compute the ABL capability. Recall that the initial readiness level determines the maximum risk of the initial stages of the development process. The estimated completion time, therefore, reflects the impact that risk (both inherent and due to interdependencies) has on the completion time of the ABL program for the different alternative systems, their combinations, and implementation strategies. Figure 5 presents the expected completion time of the ABL project, as estimated by the computational model and the potential capability for the 81 combinations of alternative systems.

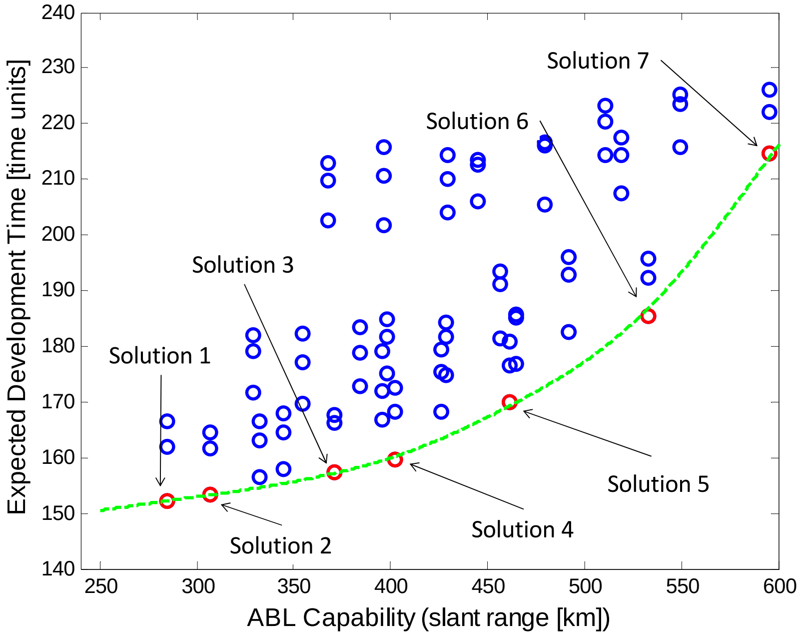

Figure 5. Tradeoff Between Expected Completion Time and Potential Capability of ABL

The seven solutions called out in Figure 5 represent the seven combinations of these alternative systems that yield promising combinations of capability and expected completion time. They are the non-dominated solutions of this trade-off study and, as such, define a Pareto Frontier. Essentially, by choosing any of these seven solutions, it is impossible to improve the expected completion time without giving up capability. Table 7 lists the systems that comprise each of these seven solutions, the resulting potential capability, and expected completion time.

Table 7. Description of Non-Dominated Solutions

Solution	D&T System	Aircraft System	COIL Beam System	AO System	ABL Capability [slant range, km]	Expected Completion Time [time units]
1	STSS	new system	Alternative-1	Alternative-3	285	152
2	STSS	new system	Alternative-1	Alternative-2	307	153
3	UAV	new system	Alternative-1	Alternative-2	371	157
4	UAV	new system	Alternative-1	Alternative-1	402	160
5	new system	new system	Alternative-1	Alternative-1	461	170
6	new system	new system	Alternative-2	Alternative-1	533	185
7	new system	new system	Alternative-3	Alternative-1	596	215

As expected, developing brand new systems for the D&T and aircraft system, combined with high capability COIL beam and AO system alternatives, produces the maximum possible capability (assuming that requirements will not change) but also the highest development time. Systems that provide the highest level of performance also have the lowest initial readiness-levels, which, in turn, means high development risk. Conversely, utilizing legacy systems with a relatively high readiness-level (e.g., STSS, alternative-1 for the COIL beam system, and alternative-3 for the AOS) results in the shortest development time but also the lowest capability-level. The model results, at these extremes, are verified with our intuition.

A new aircraft system is always preferred. Recall that the aircraft does not impact the ABL capability here but contributes to the development time. Furthermore, for the first five non-dominated solutions, the COIL beam system that has the lowest capability (e.g., 3 MW of power output) is selected. This means that the expected development time to be incurred to achieve higher power output is not worth the increase in the ABL capability (for the assumed risk values used here). Conversely, the Adaptive Optics System selected for the last four solutions (4–7) is the alternative that provides the highest capability. This means that the expected higher development time of this system justifies the potential capability that it can provide to the ABL. These results align with the observations of Barton et al. (2004), who showed in their sensitivity studies of the ABL capabilities that improvements in the COIL beam power output are not as critical as the ability of the Adaptive Optics System to correct for the atmospheric disruptions and deliver the required energy to the target.

Although the capability and initial readiness-level values of the candidate systems in this study were assumed, the trade-off study represents a very real decision-making situation for system engineers doing AOA in pre-milestone B portions of the acquisition process. The approach could be improved by using physics-based modeling tools for technical capacity and initial readiness-level estimation, as well as process modeling for the impact of disruptions under different system implementation strategies. The CEM enables this type of investigation by considering the relatively explicit inherent development risk of component systems as well as the implicit risk due to system interdependencies.

Conclusions

The development of complex systems (and SoS) is beset by risk. Risk analyses of individual systems can explain the threats and opportunities of systems but do not capture the impact that disruptions to individual systems have at the enterprise level, where multiple systems—explicitly or implicitly interdependent—collaborate to achieve various capabilities. The presence of interdependencies in layered networks of development systems often result in increased risk and higher order disruptions that are not always visible or predictable. The network structure behind the collaboration can contribute both negatively and positively to the successful achievement of SoS capabilities and, even earlier, to the developmental success. Collaboration via interdependence may increase capability potentials, but it also contains concealed risk in the development and acquisition phases.

This paper considered the Airborne Laser system under development by the Missile Defense Agency to present the CEM, its parameters, and example trade-off studies between estimated completion time of the program and its potential capability. Results of the analysis of this simplified system revealed that a Pareto Frontier exists when the completion time of a project is compared to the potential capability that it can provide. In this example, only seven of the 81 combinations of alternative systems for the aircraft and detection and tracking systems were non-dominated solutions. The highest capability (and highest completion time) was achieved when all component systems were developed from scratch and, conversely, the lowest capability (and lowest completion time) was a result of utilizing mature legacy systems that require minimal modifications.

The Computational Exploratory Model presented here is an ongoing research effort that aims to provide a framework for the aggregation of the system-specific risk to the enterprise level. The extensions to the model presented here via a proof-of-concept application point to the ability of such a framework to quantitatively perform analysis of alternatives and enable knowledge-based acquisition. It is our goal to improve/facilitate the decision-making process of systems engineers and system integration by providing the means to model risk in the system development process and quantify the cascading effect of risk for families of systems, or SoS, as well as enable quantitative analysis of alternatives. Analytical models in pursuit of the same goals are also under development; one version of an analytical approach was presented at the 2010 Annual Symposium.

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