SYSTEM INTEGRATION AND RISK PROPAGATION IN AERONAUTICAL SYSTEMS-OF-SYSTEMS

Muharrem Mane*, Daniel DeLaurentis*
***Purdue University, West Lafayette, IN 47907-2023**

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Abstract

The capability-based acquisition approach emphasizes required operational capabilities (rather than individual system performance) and thus directly leads to the simultaneous development of systems that must eventually interact within a system-of-systems. As a result, system interdependencies in the development and acquisition processes increase complexity and risk as well as complicate the tradeoff between risk and capability. The authors' prior work has developed a Computational Exploratory Model to simulate the development processes of interdependent systems intended for a system-of-systems capability. The progress documented in this paper focuses on the impact of network topologies on the propagation of disruption and achievement of target capabilities. The enhanced model differentiates the effectiveness of alternate configurations of constituent systems and quantifies the impact of varying levels of interdependencies on the timely completion of a project that aims to achieve a target capability. A proof-of-concept application problem examining options for missile defense detection and tracking is presented, including the identification of non-dominated solutions that offer a balance of development time and capability level.

1 Introduction

Over the past decade major defense organizations have shifted acquisition strategy from a system/platform-based philosophy to a capability-based one. According to Charles and Turner [1], the motivation behind this shift is to acquire a set of new capabilities instead of acquiring a family of threat-based, service-specific systems each with individually tuned performance requirements. The goal is a more efficient utilization of both human and engineered assets.

In their ultimate operational settings, then, these systems are increasingly required to interoperate along several dimensions which characterizes them as systems-of-systems (SoS) [2]. An SoS most often consists of multiple, heterogeneous, distributed systems that can (and do) operate independently but can also assemble in networks and collaborate to achieve a goal. Examples of aeronautical systems-of-systems include civil air transportation [3,4], battlefield ISR [5], and missile defense [6]. High-profile programs in these arenas have struggled with complexities in both program management and engineering design (e.g. NASA's Constellation Program [7], U.S. Army's Future Combat System [8], and the FAA's NextGen [9]). According to Maier [2], the distinctive traits of operational and managerial independence are key to making the collaboration work. The structure of the networks of component systems, however, can contribute both negatively and positively to the successful achievement of SoS capabilities and developmental success. Collaboration via interdependence may increase capability potentials; however, it also increases risk and complexity during development and acquisition. The tradeoff between risk and capability is, therefore, non-trivial and increased decision-support tools tailored to this setting are needed. In particular, these tools must directly treat specific sources of complexity.

Rouse [10] summarizes the complexity of a system (or model of a system) as related to the intentions with which one addresses the systems, 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. The work presented here specifically targets complexities stemming from system development risk, the interdependencies among systems, and the span-of-control of the systems engineers or system-of-systems managers and/or architects.

The objective of the research summarized in this paper is to analyze system interdependency complexities and capability potentials in an aeronautical proof-of-concept application using a computational exploratory modeling approach. The approach can be used both by aerospace systems engineers and systems-of-systems architects to quantify the impact of development risk of constituent systems on the SoS and its propagation through the SoS network, to quantify the potential capability of a family of systems at the enterprise level, and ultimately, quantify the tradeoff between risk and targeted capability.

2 Exploratory Model Structure

The evolving Computational Exploratory Model (CEM) summarized here has been described in [11], [12]. The CEM is based on the 16 basic technical management and technical system-engineering processes outlined in the Defense Acquisition Guidebook [13], and modified by the Systems Engineering Guide for System-of-Systems (SoS-SE) [14] to address the changes due to 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). Constituent elements at each level are a network representation of the level below (Figure 1).

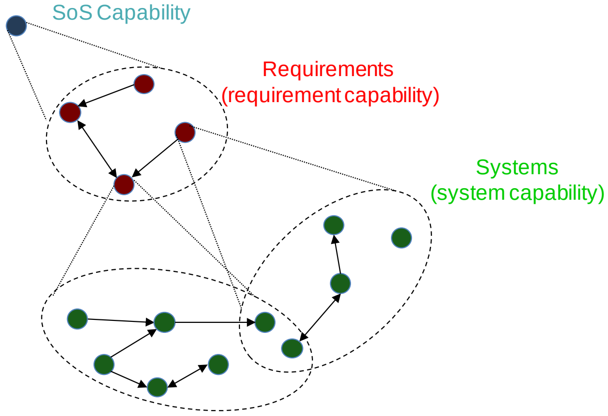

Figure 1. Layered network abstraction of computational exploratory model

The SoS Capability 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) is achieved a number of possibly interdependent systems (L3). 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. The next section will present an application problem, followed by a description of the model dynamics that make possible the study of these complexities and will explore the design space of the SoS architect and tradeoffs between development risk and capability for the proof of concept application.

3 Proof of Concept Application

The Airborne Laser (ABL) program serves as the proof-of-concept problem for demonstrating the CEM of system development and acquisition process. 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 [15]. 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. The ABL program may not be considered a system-of-systems operationally, but developmentally it has all of the traits required of an SoS, described by Maier [2]. 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 is undertaken by three companies (Northrop Grumman, Lockheed Martin, and Boeing), who operate and manufacture their respective pieces of the ABL across the country.

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 constituent systems of the ABL are grouped into three core systems: the aircraft system, the detection and tracking (D&T) system, and the targeting and firing (T&F) system. Development of these three systems and their integration results in the ABL capability of detecting, tracking and destroying theatre ballistic missiles in their boost phase.

The Air Force and the Missile Defense Agency (MDA) have been experimenting with the simultaneous development, testing, and integration of the constituent systems of the ABL, which makes the development of these systems interdependent. For instance, the aircraft developer needs the stability requirements and dimensional specifications of the D&T system and the T&F 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. This makes the aircraft development process dependent on the development of the D&T and T&F systems. A notional representation of the interdependencies in this example problem and its layered network structure is presented by Figure 2.

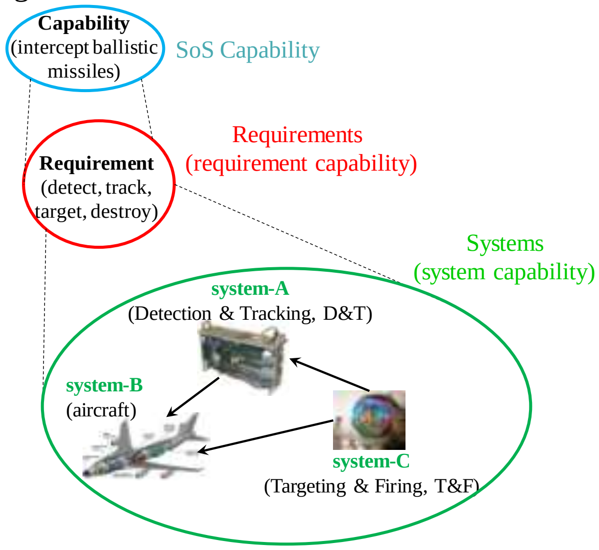

Figure 2. Assumed system interdependencies in ABL example

In this example, the systems engineer would like to know and analyze how the development risk of each constituent system and system interdependencies impact the timely and successful development of the program capabilities. Furthermore, the tradeoff between the potential capability of the ABL and its completion time when different constituent systems are considered as alternatives to the current ones is of interest. The CEM provides a platform to simulate the development process and enable tradeoff studies between development time of the ABL and its potential capability for different alternatives of constituent system.

4 Detailed Model Dynamics

The CEM operates as a discrete event simulator of the development process. Disruptions occur at various stages of development and are governed by the risk associated with individual systems. The CEM models risk associated with the implementation and integration of each constituent system as well as the risk due to system interdependencies. The *Implementation Phase* simulates the development of each system based on a pre-determined development pace and risk profile. The *Integration Phase* simulates the integration of constituent systems with each other based on the operational and/or development architecture.

4.1 Model Input Parameters

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 CEM

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 of disruptions in *Requirement Development Phase*
System Level (L3)		
System dependencies	D_{sys}	Adjacency matrix 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*	Sequential/simultaneous development
System readiness-level	$m(i,r)$	Readiness-level of system i to satisfy requirement r
System risk profile	$R_{sys}(i,r)$	Probability of disruptions in system i when satisfying requirement r
Impact of disruptions	$I_{sys}(i)$	Reduction in readiness-level when disruptions hit system i
Implementation pace	$p_{imp}(i)$	Increase in readiness-level of system i at each time step during implementation
Integration pace	$p_{int}(i)$	Increase in completeness-level of system i at each time step during integration
Implementation start	$l_{imp}(i,j)$	Readiness-level of system j when *Implementation* of system i begins
Strength of dependency	$S(i,j)$	Strength of dependency of system i on system j

The input parameters listed here enable the description of the development process in terms of requirement and system interdependencies, system development pace, and probability of disruptions. The CEM uses these inputs to simulate the development process of the entire SoS (project) and each constituent system.

4.2 Implementation Phase Dynamics

The nature of candidate systems may range from legacy systems to off-the-shelf, plug-and-play products to custom-built, new systems. Development of a ‘brand new’ SoS has been and will remain a rare occurrence. In their 2005 study on SoS, the United States Air Force Scientific Advisory Board [16] stated that one of the challenges in building an SoS is accounting for contributions and constraints of legacy assets. Similarly, the regular utilization of off-the-shelf component systems in both defense and civil programs contribute to cost and time savings but also introduce a different type of risk to the system development process [17]. These legacy systems may be used ‘as-is’ or may need re-engineering to fulfill needs of the new program.

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 the required 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. [18], is a metric that incorporates the maturity levels of critical components and the interoperability of the entire system by also considering the system architecture (i.e. integration requirements of technologies). This is an extension of the widely used Technology Readiness Level (TRL) [19]. While similar in spirit to the SRL metric proposed by Saucer et al. [18], readiness-level is defined and used differently here. We define 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. An initial readiness-level of 0 indicates a brand new system yet to be designed, 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. The dynamic model starts the development of a system from the initial readiness-level, $m^o(i,r)$, and simulates its development until it reaches 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.

For the purpose of this study, the ABL aerial platform (i.e. B747-400) has an initial readiness-level of 0.8 and 20% further development is required to host the other constituent systems of the ABL. Additionally, we assume that analysis of the detection and tracking, D&T, system indicates an initial readiness-level of 0.5, based on results of tests with similar systems, albeit in a different application. The T&F system, on the other hand, is a brand new system – the COIL beam is a new technology still under development – thus it has an initial-readiness level of 0.0. Note, however, that for the ABL program the constituent systems have a different initial readiness-level as of the publication of this paper than they did at the time of the program's inception (as published in [15]), which is represented herein.

The CEM simulates system development 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 and disruption propagation on the development process. Hence, more accurate modeling of the development process would increase the accuracy of the model for a particular application but it would not change the nature of the observed results.

4.3 Risk and Capability

4.3.1 Representation of Risk

The risk associated with the development of a system can be a complex function of funding, technology, time, and many other factors. Furthermore, disruptions in the development of systems can occur because of the inherent system risk and because of the risk due to interdependencies, when present. Inherent risk is the probability of disruptions during system development solely due to the development characteristics of the system, e. g. technology readiness-level, funding, politics, etc. Risk due to interdependencies, on the other hand, is the probability of disruptions during development due to disruption in the development of 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, $m(i,r)$. Therefore, risk changes as the readiness-level of a system increases. Equation 1 introduces the relationship between a system's readiness-level and its risk (probability of disruption) as used here.

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

In this relationship, α_i (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.

When systems are interdependent, systems that otherwise have a low inherent risk can be greatly impacted by disturbances because of the transmission of disturbances 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.

4.3.2 Representation of Capability

The potential capability that a system can provide to the SoS capability can be a function of its readiness-level, adaptability to satisfy new requirements, and other system specific performance measures. Potential capability is an indicator of the quality with which a system satisfies a requirement. For instance, if a requirement calls for the ability of the D&T system (in the ABL project) to detect and track all intruders within a 600 km radius of the aircraft's location, a system with a potential capability of 1.0 will be a system that satisfies this requirement. If, on the other hand, another system is able to detect all intruders within a 100 km radius of the aircraft's location its potential capability is less than 1.0. This study assumes that the potential capability of a candidate system i, $C_{sys}(i)$, for the ABL application is known (with a value between 0 and 1) and the total capability of the ABL, C, is the weighted sum of the component-systems capabilities:

$$C = \sum_{i=1}^{N} \frac{1}{N} C_{sys}(i) \qquad (2)$$

where N is the number of systems that comprise the program. While a simplified definition of capability, future research will generate a more detailed capability model that will be incorporated in the CEM.

5 Comparison of Alternatives

In design of integrated systems, or systems-of-systems, trades between capability and risk and new versus legacy systems are essential. Legacy assets can provide a certain level of capability with relatively low risk. Some legacy assets, however, may require substantial modifications in order to provide a needed capability, which may not result in time and/or cost savings. Similarly, other legacy assets may be limited in the potential capability that they provide because of some specific characteristic or inherent rigidity to adapt. These features create a tradeoff between development risk and capability potential of a system.

The MDA in a report in 2007 [20] states that an alternative to the current ABL platform (B747-400) are Unmanned Aerial Vehicles (UAVs), which can offer longer endurance and eliminate the risk to crew members, while Ref. [15] reports that alternate systems to the currently used D&T system could be considered to partially fulfill the ABL requirement (e.g. to detect and track the ballistic missile in its boost phase). We consider the analysis of alternatives of the ABL system in satisfying its requirement to center on three different aerial platforms and three D&T systems, while the T&F system is a unique system yet to be developed. Therefore, the T&F system has initial readiness-level, $m(i,r)$, of 0 and potential capability, $C_{sys}(i)$, of 1; we also assume that it has an implementation pace of 0.02; recall that the implementation pace indicates the gain in readiness-level at each time-step. Table 2 presents these assumed alternatives for the aerial platform.

Table 2. Assumed alternative systems for aerial platform

Aircraft Alternative	Range [nmi]	Max Payload [lbs]	Initial Readiness-Level [$m^o(i,r)$]	Potential Capability [$C_{sys}(i)$]	Implementation Pace [$p_{imp}(i)$]
new aircraft	TBD	TBD	0.0	1.0	0.03
KC-135A	4,000	105,821	0.9	0.6	0.04
B787-8	8,500	100,000	0.6	0.9	0.05

The Boeing NKC-135A was the primary aircraft in the Airborne Laser Laboratory (ALL) – a precursor to today's Airborne Laser program – during the 1980s [21]. 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. Because this aircraft has a smaller payload capacity than the currently used B747-400 (248,000 lbs [22]), we assume that it has a potential capability of 0.6. Furthermore, because modifications are necessary to host the other component systems of the ABL, we assume that this aircraft has an initial-readiness level of 0.9 and implementation pace of 0.04. An alternative aircraft considered is the Boeing B787-8. Because its payload capacity is less than the currently used B747- 400 we assume that this aircraft has a potential capability of 0.9; similarly, because the B787-9 is a relatively new aircraft and potential operational issues have not come to light we assume an initial readiness-level of 0.6.

The options to the SoS architect for the D&T 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 3 presents these systems and assumed initial readiness-levels and potential capability-levels. The utilization of UAVs is one option that the MDA has considered for the early detection and targeting of missiles [23], hence our assumptions as an alternative for the detection and tracking system in the ABL. Because current scenarios of operation and testing involve the UAV accepting a cue from satellites about the location of the missile and that tracking of the missile is done manually, by military personnel [23], we assume that the initial readiness-level of UAVs in the ABL application is of 0.6. Furthermore, because the ability to achieve these goals is unknown, we assume that utilizing UAVs for detection and tracking has a maximum potential capability of 0.9. Finally, another option for detecting and tracking the missile is the use of satellites, and more precisely the Space Tracking and Surveillance System (STSS). As of 2003 the MDA had decided to fund the design but not the production of a competitive sensor for use aboard the satellites [24]. Because of this and because of the technical and funding issues facing the program we assume that the STSS has an initial readiness-level of 0.8 and a potential capability of 0.7 if used as the D&T system of the ABL.

Based on the alternative systems in Table 2 and Table 3, there are nine (9) possible combinations of aircraft, D&T, and T&F systems that could satisfy the requirement of the ABL, albeit at a different capability level. The SoS architect would like to know which combination of constituent systems results in a (ABL) system with lowest estimated completion time and that provides the largest capability potential. Additionally, he/she wants to consider two alternative implementation strategies: simultaneous or sequential. A simultaneous strategy ($l_{imp}(i,j)$=0) implies that all systems start implementation at the same time; in a sequential strategy ($l_{imp}(i,j)$=1), implementation of dependent systems begins when the independent systems reach a

Table 3. Assumed alternative systems for detection and tracking system

Detection & Tracking Alternative	Initial Readiness-Level [$m^o(i,r)$]	Potential Capability [$C_{sys}(i)$]	Implementation Pace [$p_{imp}(i)$]
New System	0.0	1.0	0.02
STSS	0.8	0.7	0.03
UAV	0.6	0.9	0.05

readiness-level of 1. Each strategy, however, implies a different risk-level and a different disruption impact. Table 4 presents the parameters for this study.

Table 4. Assumed risk and disruption impacts

	System	Simultaneous Implementation Maximum Risk [α_i]	Simultaneous Implementation Disruption Impact [$I_{sys}(i)$]	Sequential Implementation Maximum Risk [α_i]	Sequential Implementation Disruption Impact [$I_{sys}(i)$]
D&T Alternative	new aircraft system	0.2	0.06	0.1	0.02
	KC-130A	0.2	0.08	0.1	0.03
	B787-8	0.2	0.07	0.1	0.04
Aircraft Alternative	new D&T system	0.2	0.04	0.1	0.02
	STSS	0.2	0.06	0.1	0.02
	UAV	0.2	0.07	0.1	0.02

While we assume that the dependencies between constituent systems are invariant (e.g. are the same as the interdependencies in Figure 2) for all nine combinations, we also assume that the dependency strengths, $S(i,j)$, vary. This means that depending on the type of constituent systems selected for each ABL configuration, different interdependencies exist and the nine networks that represent the design space of the SoS architect have a different topology. This is a reasonable assumption because depending on the type of systems selected for the aerial platform, D&T system, and T&F system, the level of development interdependencies will be different. For instance, a system with a high initial readiness-level may be less dependent on another constituent system and therefore have lower dependency strength than a system with initial readiness-level of zero. Here we assume that this strength of dependency is a uniformly random value between 0 and 1 (e.g. the probability of a disruption propagating to a dependent system is a random number between 0 and 1).

Estimating the expected completion time of any combination of alternative systems and the two strategies requires the CEM to quantify the tradeoff between development time and capability. We use the initial readiness-levels of these systems to begin the simulation of the development process and estimate the completion time of the entire program, which reflects the impact that risk (both inherent and due to interdependencies) has on the completion time of the ABL program for the different combinations of alternative systems and implementation strategies.

Figure 3 presents the expected completion time of the ABL project as estimated by the computational model and the potential capability for the nine combinations of alternative systems for the aircraft and D&T systems for both implementation strategies.

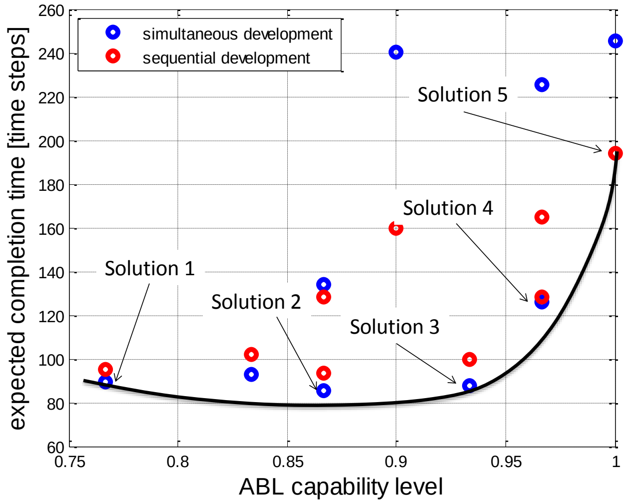

Figure 3. Tradeoff between expected completion time and potential capability of ABL

The five solutions called out in the figure represent the five combinations of the alternative systems that yield the maximum potential capability for the minimum expected completion time. They are the non-dominated solutions and, as such, define a Pareto Frontier. Table 5 lists the systems that comprise each of these five solutions along with the resulting potential capability of the ABL, its expected completion time, the implementation strategy, and a description of the dependency strength of the ABL topology. Note that the dependency strength reported here is a network-level metric that is the sum of dependency strengths between all systems in the network.

Table 5. Description of non-dominated solutions

Solution	Aircraft System	D&T System	Implementation Strategy	ABL Capability-Level [*C*]	Dependency Strength Metric	Expected Completion Time [time steps]
1	KC-135A	STSS	simultaneous	0.77	1.48	89.6
2	KC-135A	UAV	simultaneous	0.87	1.73	85.2
3	B787-8	UAV	simultaneous	0.93	1.28	87.7
4	new system	UAV	simultaneous	0.97	1.36	126.2
5	new system	new system	sequential	1.00	1.80	194.0

As expected, developing brand new systems results in the maximum possible capability (assuming that requirements will not change) but also in the highest development time because systems must be developed from anew, which in turn means high development risk. Furthermore, a sequential implementation strategy results in the highest expected completion time. Conversely, (simultaneous) development of legacy systems with a relatively high readiness-level (0.9 for the KC-135A and 0.8 for the STSS) results in the shortest development time but also a low capability-level. Despite the assumed capability and initial readiness-level values of the candidate systems and the changes in the impact of disruptions for the different implementation strategies, the tradeoff study represents a very real decision-making situation for many designers and system architects. 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 of the development process presented here, however, enables this type of tradeoff by considering the relatively explicit inherent development risk of component systems as well as the implicit risk due to system interdependencies.

5 Summary and Conclusions

Capability-based acquisition has the potential to improve the utilization of resources but it also introduces new complexities to the development process of large families of systems that stem from the numerous interdependencies between constituent systems. Because of these interdependencies, risk can propagate through the related systems during development. This paper considered the ABL system under development by the MDA to present the CEM of the development process and tradeoff studies between estimated development time of the program and its potential capability. Results of the analysis of 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 five of the nine combinations of alternative systems for the aircraft and detection and tracking systems were non-dominated solutions. The highest capability was achieved when all component systems were developed from scratch and, conversely, the lowest capability was a result of utilizing mature legacy systems that require minimal modifications.

The work presented here focuses on the development of a platform for investigating acquisition strategies and performing analysis of alternatives of potential constituent systems of SoS that can achieve target capabilities and reduce development time. It is our goal to facilitate the decision making process of systems engineers and system integration of aerospace systems 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, when conducting analysis of alternatives.

References

[1] Charles, P. and Turner, P., “Capabilities Based Acquisition…From Theory to Reality”, CHIPS magazine, Summer 2004, [online database]: http://www.chips.navy.mil/archives/04_summer/web_pages/GEMINII.htm [accessed 21 January, 2010].

[2] Maier, M. “Architecting Principles for System-of-Systems”, *Systems Engineering* Vol. 1, No. 4, 1998, pp. 267-284.

[3] DeLaurentis, D., Han, E-P., Kotegawa, T., "Network-Theoretic Approach for Analyzing Connectivity in Air Transportation Networks," *AIAA Journal of Aircraft*, Vol.45, No.5, 2008, pp. 1669-1679.

[4] DeLaurentis, D., Fry, D., "Understanding the Implications for Airports of Distributed Air Transportation Using a System-of-Systems Approach," *Transportation Planning and Technology*, Vol. 31, Issue 1, Feb. 2008 , pp. 69-92 .

[5] Butler, J. T., "UAVs and ISR Sensor Technology", Research Report for Air Command and Staff College, Air University, AU/ACSC/033/2001-04, April 2001, [online source]: https://research .maxwell.af.mil/papers/ay2001/acsc/01-033.pdf [accessed 26 January 2010].

[6] Francis, P. "Defense Acquisitions: Missile Defense Agency's Flexibility Reduces Transparency of Program Cost", Government Accountability Office's Testimony before the Subcommittee on Defense, Committee on Appropriations, U.S. House of Representatives, 30 April 2007, [online source]: www.gao.gov/ new.items/d07799t.pdf *[accessed 27 January 2010]*.

[7] Committee on Systems Integration for Project Constellation, "Systems Integration for Project Constellation", The National Academies, 2004, [online source] http://nap.edu/html/proj-constella tion/ltr-rep.pdf [accessed 15 January 2009].

[8] US Department of Defense, "Future Combat System (FCS) Program Transitions to Army Brigade Combat Team Modernization," No. 451-09, June 2009, [online database], http://www.defense.gov/ Releases/Release.aspx? ReleaseID=12763 [retrieved 3 March 2010].

[9] NextGen Integration and Implementation Office. *NextGen Implementation Plan 2009*. Federal Aviation Administration, [online database] http://www.faa.gov/about/initiatives/nextgen/media/ NGIP_ 0130.pdf [accessed 25 September 2009].

[10] Rouse, W., "Complex Engineered, Organizational and Natural Systems", *Systems Engineering* Vol. 10 No. 3, 2001, pp. 260-271.

[11] Mane, M. and DeLaurentis, D.A., "Acquisition Management for Systems-of-Systems: Exploratory Model Development and Experimentation", 6th Naval Postgraduate School Symposium, Monterey California, May 13-14, 2009

[12] Mane, M. and DeLaurentis, D.A., "System Development and Risk Propagation in Systems of Systems", 7th Naval Postgraduate School Symposium, Monterey California, May 11-13, 2010

[13] U.S. Department of Defense. Defense Acquisition Guidebook. [online database]: https://akss.dau.mil/ dag/ [accessed 4 April 2008].

[14] U.S. Department of Defense, "Systems Engineering Guide for System-of-systems", [online database]: http://www.acq.osd.mil/sse/ssa/initiat_sos-se.html\ [accessed 2 March 2008].

[15] Davey, M. E., "The Airborne Laser Anti-Missile Program", Congressional Research Service Report RL30185, 2000, [online database]: http://wikileaks.org/wiki/CRS-30185, [retrieved 30 December 2009] .

[16] Saunders, T.et al. "Report on System-of-Systems Engineering for Air Force Capability Development". *USAF Scientific Advisory Board*, SAB-TR-05-04, 2005.

[17] Constantine, J. and Solak, S., "SysML Modeling of Off-the-Shelf-Option Acquisition for Risk Mitigation in Military Programs", *Systems Engineering*, Vol. 13, No. 1, 2010, pp 80–94 .

[18] Sauser, B., Verna, D., Ramirez-Marquez, J., and Gove, R., "From TRL to SRL: The concept of Systems Readiness Levels", Proceedings of the Conference on Systems Engineering Research, CSER, Los Angeles, CA, 2006.

[19] Department of Defense Directive 5000.2, "Chapter 4: Systems Engineering", Washington DC, 2005.

[20] Bolkcom, C., and Hildreth, S.A., "Airborne Laser (ABL): Issues for Congress", Congressional Research Service Report RL32123, 2007 [online database]: www.fas.org/sgp/**crs**/weapons/ **RL32123**.pdf *[accessed 05 January, 2010]*.

[21] Duffner, R.W., "Airborne Laser: Bullets of Light", Plenum Publishers, New York, NY, 1997.

[22] *Jane's All the World's Aircraft*, Jane's Information Group Inc., Surrey, UK, [online database], http://jawa.janes. com/public/jawa/index.shtml [accessed January 2010] .

[23] Butler, A., "Reaper Tracking: U.S. refining concepts for using UAS to track ballistic missiles during boost phase", AviationWeek & Space Technology, 4 January, 2009, pp. 52-53.

[24] Smith, M. S., "Military Space Programs: Issues Concerning DoD's SBIRS and STSS Programs", CRS Report for Congress, RS21148, 3 November 2003, [online source]: http://www.au.af.mil /au/awc/awcgate/crs/rs21148.pdf [accessed 18 January 2009].

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