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Acquisition Management for System-of-Systems: Requirement Evolution and Acquisition Strategy Planning

Seung Yeob Han, Zhemei Fang, and Daniel DeLaurentis
Purdue University

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

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Preface & Acknowledgements

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

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

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

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

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

- Office of the Under Secretary of Defense (Acquisition, Technology, & Logistics)
- Director, Acquisition Career Management, ASN (RD&A)
- Program Executive Officer, SHIPS
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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 7. Predicting Performance and Interdependencies in Complex Systems Development

Wednesday, May 16, 2012	
1:45 p.m. – 3:15 p.m.	Chair: Mark Krzysko, Deputy Director, Enterprise Information and Office of the Secretary of Defense Studies, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics <i>Facilitating Decision Choices With Cascading Consequences in Interdependent Networks</i> Anita Raja, Mohammad Rashedul Hasan, and Mary Maureen Brown <i>University of North Carolina at Charlotte</i> <i>Applications of Lexical Link Analysis Web Service for Large-Scale Automation, Validation, Discovery, Visualization, and Real-Time Program-Awareness</i> Ying Zhao, Shelley Gallup, Douglas MacKinnon <i>Naval Postgraduate School</i> <i>Acquisition Management for System-of-Systems: Requirement Evolution and Acquisition Strategy Planning</i> Seung Yeob Han, Zhemei Fang, and Daniel DeLaurentis <i>Purdue University</i>

Mark Krzysko—Mr. Krzysko serves as the deputy director of the Enterprise Information and Office of the Secretary of Defense Studies. In this senior leadership position, he oversees Federally Funded Research and Development Centers and directs data governance, technical transformation, and shared services efforts to make timely, authoritative acquisition information available to support oversight of the Department of Defense's major programs—a portfolio totaling more than \$1.6 trillion of investment funds over the life cycle of the programs.

Preceding his current position, Mr. Krzysko served as ADUSD for business transformation, providing strategic guidance for re-engineering the Department's business system investment decision-making processes. He also served as ADUSD for strategic sourcing & acquisition processes and as director of the Supply Chain Systems Transformation Directorate, championing and facilitating innovative uses of information technologies to improve and streamline the supply chain process for the Department of Defense. As the focal point for supply chain systems, he was responsible for transformation, implementation, and oversight of enterprise capabilities for the acquisition, logistics, and procurement communities. In addition, Mr. Krzysko served as advisor to the deputy under secretary of defense for business transformation on supply chain matters and as the functional process proponent to the Department's business transformation efforts, resulting in the establishment of the Business Transformation Agency.

In March 2002, Mr. Krzysko joined the Defense Procurement and Acquisition Policy office as deputy director of e-business. As the focal point for the acquisition domain, he was responsible for oversight and transformation of the acquisition community into a strategic business enterprise. This included driving the adoption of e-business practices across the Department, leading the move to modernize processes and systems, and managing the investment review process and portfolio of business systems. Mr. Krzysko served as the division director of Electronic Commerce Solutions for the Naval Air Systems Command from June 2000 to March 2002. From April 1991 until March 2000,



Mr. Krzysko served in various senior-level acquisition positions at the Naval Air Systems Command, including contracting officer of F/A-18 foreign military sales, F/A-18 developmental programs, and the F-14. In addition, he served as program manager of Partnering, the Acquisition Business Process Re-engineering Effort, and as acquisition program manager for the Program Executive Office for Tactical Aircraft.

Mr. Krzysko began his career in the private sector in various executive and managerial positions, including assistant managing director for Lord & Taylor Department Stores and operations administrator for Woodward & Lothrop Department Stores. Mr. Krzysko holds a Bachelor of Science degree in finance from the University of Maryland University College, College Park, MD, and a Master of General Administration degree in financial management from the same institution.



Acquisition Management for System-of-Systems: Requirement Evolution and Acquisition Strategy Planning

Seung Yeob Han—Han is a graduate research assistant in the School of Aeronautics and Astronautics Engineering, Purdue University. He received his MS from Purdue University in Aerospace Engineering in 2009. His current research interests are in risk and interdependency analyses in complex systems (or system-of-systems), resilient system modeling under uncertainty, system-of-systems architecture design, and network modeling and analysis. He currently works in the System-of-Systems Laboratory led by Dr. DeLaurentis. [simonhan@purdue.edu]

Zhemei Fang—Fang is a graduate research assistant in the School of Aeronautics and Astronautics Engineering, Purdue University. She received her BE and MS degrees in control science and engineering from Huazhong University of Science and Technology in China in 2008 and 2011, respectively. Her current research interests are in system-of-systems architecture, interdependent system analysis, and network modeling and analysis. She currently works in the System-of-Systems Laboratory led by Dr. DeLaurentis. [fang59@purdue.edu]

Daniel DeLaurentis—DeLaurentis is an associate professor in Purdue's School of Aeronautics & Astronautics in West Lafayette, IN. He joined the faculty in 2004. DeLaurentis is the director of the Center for Integrated Systems in Aerospace, which is home to over 15 additional faculty and staff, and leads the System-of-Systems Laboratory (SoSL), which includes graduate and undergraduate students as well as professional research staff. His primary research interests are in the areas of problem formulation, modeling, and system analysis methods for aerospace systems and systems-of-systems (SoS), with particular focus on network analysis and agent-driven models. [ddelaure@purdue.edu]

Abstract

The complex interdependencies between systems organized for a system-of-systems (SoS) capability pose a challenge to effective acquisition management of SoS assets. In general, methodologies to assess risk that cascades through interdependencies are critical to effectively analyzing alternatives in a capability-based acquisition strategy. A particular problem occurs in cases where requirements on systems are evolving. In this paper, a Bayesian Network (BN) method is presented, which models requirement evolution in the midst of system interdependencies. The method analyzes the cascading effects of requirement and systems interdependencies on risk. A primary output of the approach is the identification of both critical systems and requirements. A synthetic problem is solved to demonstrate the proposed method.

Introduction

Acquisition management continues to struggle with complex dependencies between systems in both technical and programmatic dimensions in the face of requirements that evolve during the development process. The Government Accountability Office (GAO) studies have identified the evolution of requirements as a source of program cost and schedule overruns (Sullivan, 2011). Therefore, an adequate assessment of the cascading effects of risk among interdependent systems in the presence of evolving requirements has the potential to reduce cost and schedule overruns. The research in this paper aims to provide a methodology that supports pre- and post-milestone B activities by analyzing the impact of requirement changes and system development failures during the generation of a system-of-systems capability.

According to Maier (1998), a system-of-systems (SoS) refers to a collection of geographically distributed, heterogeneous, collaborative systems that demonstrate operational and managerial independences. The collaboration can be represented via networks that define interactions required to achieve a unique capability. Further, in a



capability-based acquisition setting, requirements are expressed in terms of capabilities, and interdependencies between requirements add another dimension of complexity to system development. Complexity is further aggravated by the many stakeholders who influence requirements and may even have conflicting requirements for the same SoS. An example of this is the development of the Joint Strike Fighter (JSF), or F-35, which continues to face schedule and cost overruns (Wilson, 2011), partially due to a development climate that includes three different services and many potential international buyers, each of which has differing requirements and requirement hierarchies. Documented case studies in the development of computer-based systems have shown that requirement interdependencies are real and that they tend to evolve over time (Anderson & Felici, 2001).

Interdependent systems are directly and indirectly impacted by the associated networks of interdependent requirements, resulting in hierarchical networks. Figure 1 is a simplified adaptation from current literature on SoS artifacts and their employment in the engineering of SoS capability architectures using a wave model structure (Lane, Dahmann, Rebovich, & Lowry, 2012). The model is adapted here to include hierarchy and time scale that range from the broad, overarching objectives that are strategic in nature (γ -level) to the tactical aspects of individual system (and subsystem) acquisition (α -level). This paper focuses on interdependency analysis (i.e., α -level process in Figure 1) with requirement evolution from above (perhaps due to shifts in portfolio management) occurring during the development process.

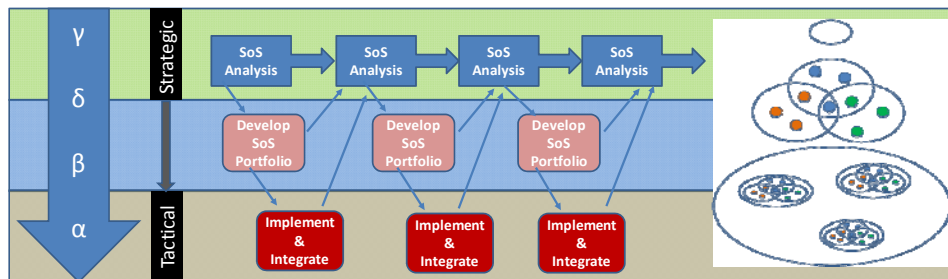


Figure 1. System-of-Systems Acquisition Hierarchy

Research reported in this paper follows from methods and tools targeting improved decision-support for SoS capabilities developed under prior grants sponsored by the NPS Acquisition Research Program and reported in papers at the 2008 (Ghose & DeLaurentis, 2008), 2009 (Mane & DeLaurentis, 2009a), 2010 (Mane & DeLaurentis, 2010), and 2011 (Mane & DeLaurentis, 2011) NPS Acquisition Research Symposiums. Research conducted during the first year centered on the computational exploratory model (CEM) based on the 16 basic technical management and technical system-engineering processes outlined in the *Systems Engineering Guide for System-of-Systems* (SoS-SE) (Department of Defense [DoD], 2008) and *Defense Acquisition Guidebook* (DoD, 2012). Research efforts during the second year entered on improvements to allow for modeling of scenarios that illustrate the underlying dynamics that produce schedule delays and, ultimately, cost overruns. The third year of research focused on the addition of system development-risk detail that enables the analysis of the impact of system maturity on the development process when the higher-order effects of interdependencies are captured. The fourth year of research added a capability module based on Markov analysis to the CEM that aggregate the network interdependency characteristics and compare alternatives with respect to the time required to arrest the propagation of development delays in a network. The current research is focused on tools suitable to analyzing uncertainties in systems and the interdependencies

between systems and possibly evolving requirements. The rationale is that such analysis can reduce risk to program success.

A Bayesian Network (BN) is used to represent interdependencies between systems and between requirements in an SoS capability development context. BNs are explored due to their strength in representing causal relationships between systems involving uncertainty. Uncertainty is addressed in a BN using a continuous density distribution, allowing an increase in the robustness of model outcomes. The BN is exercised on a synthetic problem to compute time impacts due to both requirements evolution and the impact of interdependencies between component systems.

The Analytical Approach

A Hierarchical Network Representation of System-of-Systems

To achieve a wide range of objectives, each system operates independently, but each must also interact effectively with other systems to meet the specified SoS capability. Thus, it is necessary to understand the interdependencies between component systems to obtain high confidence in achieving capability levels. As mentioned, components in an SoS assemble in networks and present interdependencies within a level and between levels in a hierarchy. Figure 2 shows the multi-level network in more detail that includes three levels: capability, requirements, and systems levels (Mane & DeLaurentis, 2011). At the requirement level, each node represents a requirement, while each link represents the interdependency between requirements. Likewise, at the system level, each node represents a system, and each link represents the interdependency between systems (Mane & DeLaurentis, 2009b). Interdependent systems are grouped to fulfill a requirement, while interdependent requirements are expected to achieve a capability. The interdependencies contribute to increasing capability but also may lead to failure through concealed risks (Mane & DeLaurentis, 2011). Hence, evaluating the impact of interdependencies is a critical task.

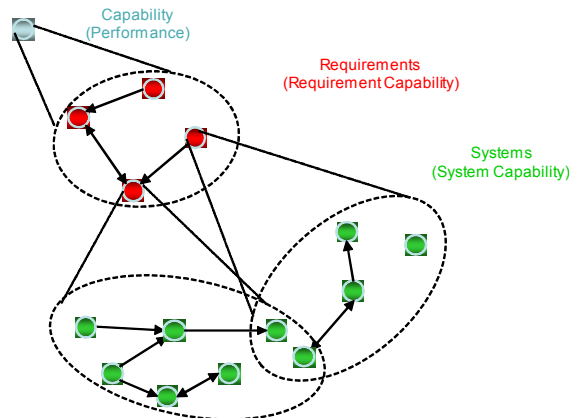


Figure 2. Hierarchical Multi-Level Representation of a System-of-Systems Capability

An Interdependency Analysis of System-of-Systems Using a Bayesian Network

In this paper, a BN is adopted to analyze uncertain interdependencies between systems. The BN can graphically represent interactions among multiple components and provide the basic structure for analyzing and visualizing the capacity-based acquisition model. The BN is a probabilistic tool that evaluates networks of systems with respect to disruption propagation in developing systems for an SoS. The evaluation not only identifies

critical components from a risk perspective while considering requirement revolution, but also it can determine component requirement flexibilities given expected development time of the SoS capability.

A Bayesian Network

A BN is a directed acyclic graph (DAG) whose nodes are the random variables and whose edges directly influence one another. Local probabilities represent the nature of the dependence of each variable (node) on its parents. Probability information in a BN model is defined through these local distributions. A node with no parent node in the BN model denotes a random variable and its associated probability distribution. A node with its parent node(s) can be represented as a conditional probability distribution (CPD).

Uncertainty with Beta Distribution

Probability information in a BN is collected through experiment tests, measured data, or expert opinions. Many errors can occur in developing this information. It is important to account for uncertainty in the model in order to generate reliable results. In this paper, which treats a synthetic proof-of-concept example, beta distributions are used for node probability information to address uncertainties. Beta distributions are a family of continuous probability distributions defined on the interval between 0 and 1 parameterized by two positive shape parameters (α and β). There are several reasons to use a beta distribution. First, a beta family is rich in shapes, allowing representation of various types of probability information (Reese, Johnson, Hama, & Wilson, 2005). Figure 3 presents various shapes of beta distributions according to two positive shape parameters. Second, when there is no available probability information, the beta family is the best choice for use in determining the most conservative probability information.

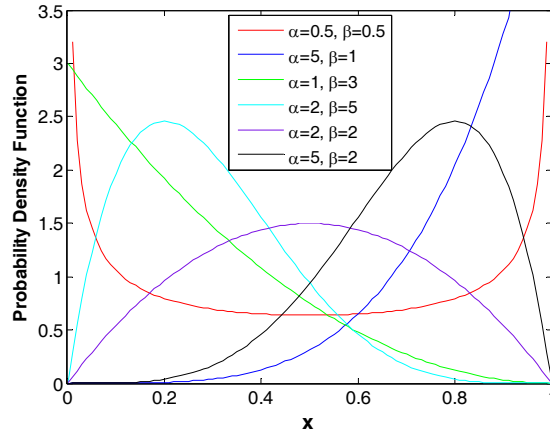


Figure 3. Various Shapes of Beta Distributions

Propagating System Failures Through Interdependencies

There are two sources of system failure in an SoS context: heritage and propagating. If a system fails on its own, then it is called a heritage failure. However, if a system failure is caused by propagating effects from interdependent systems, it is then called a propagating failure. It is therefore important to fuse all failure information, heritage and propagated.

Figure 4 shows a simple BN where the node Y has N parent nodes. This paper focuses on binomial failures for a node. For example, each node in the BN can only take either 0 or 1 to represent the status of the component, “failure” or “working,” respectively. This is a limiting factor of the approach that we revisit at the conclusion.

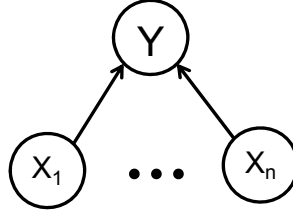


Figure 4. A Bayesian Network Representation

Consider that each node has its own heritage failure rate defined by a beta distribution and that node Y has n parents, $X_1 \dots X_n$. A beta distribution is parameterized by two positive shape parameters, denoted by s_n+1 and s_n+n_n+1 . These two positive parameters are interpreted as the number of failures and survivors, respectively, when s_n and n_n are integers (Spring & Thompson, 1966). Let $PA(Y)$ denote the set of the parents of the node Y (i.e., $\{X_1 \dots X_n\}$). According to the law of total probability, the propagating failure rate of node Y is

$$p(Y=0) = \sum_k CPD_k p(PA(Y)=k) \quad (1)$$

where $CPD_k \equiv p(Y=0|PA(Y)=k)$, k is all combination of parent node values. For example, if $PA(Y)$ includes two parent nodes (X_1 and X_2), then $k = \{\{0,0\}, \{0,1\}, \{1,0\}, \{1,1\}\}$. Therefore, a node with two parent nodes has four CPD_k values. CPD_k values here indicate the dependency strength of a failure propagating to a dependent system. For instance, if node X_1 (or X_2) fails, then node Y has a 30% (or 20%) chance to fail by a propagating effect of the node X_1 (or X_2) failure. In this case, all CPD_k values are determined: $p(Y=0|X_1=1, X_2=0) = 0.3$, $p(Y=0|X_1=0, X_2=1) = 0.2$, $p(Y=0|X_1=0, X_2=0) = 0$, and $p(Y=0|X_1=1, X_2=1) = 0.5$. Analytical solution $p(Y=0)$ for the propagating failure rate of node Y is very likely to be non-parametric due to its complicated functional form. For computational convenience, we use the approach in reference (Thompson & Haynes, 1980; Liu, Li, & Kim, 2011) to approximate the propagating failure rate with a beta distribution having the same first two moments. Let $\text{beta}(b,c)$ denote the beta distribution of the propagating failure rate of node Y. Then, the first two moments of this distribution are

$$M_1 = E(Y) = \frac{b}{b+c}, \text{ and } M_2 = E(Y^2) = \frac{b+1}{b+c+1} E(Y) \quad (2)$$

The first moment of $p(Y=0)$ is the mean:

$$M_1 = E(p(Y=0)) = E\left(\sum_k CPD_k p(PA(Y)=k)\right) = \sum_k CPD_k \prod_i E[p(PA_i(Y)=j)] \quad (3)$$

where j is the value for $PA_i(Y)$ in the set of k . For computational ease, Equation 3 can be further written as follows:

$$M_1 = E(p(Y=0)) = \sum_k CPD_k \prod_i \left\{ j_i - E[p(PA_i(Y)=0)] \right\} = \sum_k CPD_k \prod_i \left\{ j_i - \frac{s_i+1}{n_i+2} \right\} \quad (4)$$

The second moment of $p(Y=0)$ is the mean of $p(Y=0)^2$:

$$M_2 = E(p(Y=0)^2) = \sum_k CPD_k \prod_i \left\{ j_i^2 - 2j_i \frac{s_i+1}{n_i+2} + \frac{(s_i+1)(s_i+2)}{(n_i+2)(n_i+3)} \right\} \quad (5)$$

Finally, we can define two parameters, b and c , for a beta distribution of $p(Y=0)$ as

$$b = \frac{M_1(M_1 - M_2)}{(M_2 - M_1^2)}, \quad c = \frac{(1 - M_1)(M_1 - M_2)}{(M_2 - M_1^2)} \quad (6)$$

Now, node Y has two different beta distributions, one for heritage failure rate and one for propagating failure rates encapsulated in Equation 6. These two beta distributions are integrated to get the new failure rate distribution of node Y, including both failure information: heritage and propagating. This task can be easily completed using the same process for obtaining fusion of all propagating failure information mentioned above with different CPDs indicating 100% propagating effects. After applying these two fusion processes (the first is fusion of propagating effects from dependent systems for the propagating failure rate, and the second is fusion of both heritage and propagating failure rates for the new integrated failure rate) to all nodes in a network, we can obtain the beta distributions of the new failure rate information, including propagating effects for all nodes. This result can be used to determine the critical component indicating the vulnerable component and expected development time for a whole SoS.

A Representation of Requirement Evolution with Technology Readiness Level

Requirement evolution refers to changes that take place in a set of system requirements after the initial requirement analysis (Anderson & Felici, 2001). In the SoS capability context, requirement evolution seems inevitable. For instance, an initial performance goal for payload capacity of an aircraft is 250,000 lbs, while in the future, customers might ask for 300,000 lbs. Or decision-makers may decide to reduce the payload capacity to 200,000 lbs due to the considerable delay and cost. Along with requirements evolving, failure rates of components related to requirement evolution may change as well.

Technology readiness levels (TRLs) are a systematic metric/measurement NASA invented that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology (Mankins, 1995). In other words, TRLs represent the current highest available technology level, which is also a time-dependent variable. Thus, both requirement evolution and TRLs can impact component system failure rates. Take the previous aircraft payload capacity for example. In the former case, although we require a higher requirement capability, if TRL is increasing, meaning that the technology has been continuously proven for an application, at the same time failure rates might decrease, keep the same, or still increase. Similarly, in the latter case, TRL may influence failure rates by reducing a certain amount of its value. Additionally, TRLs could effect requirement evolutions. For example, policy makers may consider technology readiness levels and current development state together to decide whether necessary to reduce requirement capability.

The critical connection between requirement evolution, TRL, and component failure rates plays an essential part in the development of the SoS capability. In the synthetic problem presented in the Research Result section, we assume TRL to be constant for all component systems. Therefore, if a requirement evolves to a higher level, system failure rates always increase.

Research Result: A Synthetic Demonstration Problem

A simple synthetic problem is formulated and solved to demonstrate the proposed BN approach. Figure 5 shows the representation of a five-system network where, for example, the development of system 1, here denoted by S_1 , depends on the development of systems 2 and 4. This implies that information from one system development process affects the development of dependent systems. For system 1, information flows from system 2 and system 4 to system 1 to fuse all information from dependent systems. The T values indicate the dependency strength and correspond to the conditional probability of a failure



propagating to a dependent system. For instance, if system 4 fails, then system 1 has a 30% chance to fail by a propagating effect of the system 4 failure. The table in Figure 5 summarizes heritage failure rates for all systems in terms of beta distributions, means, and standard deviations.

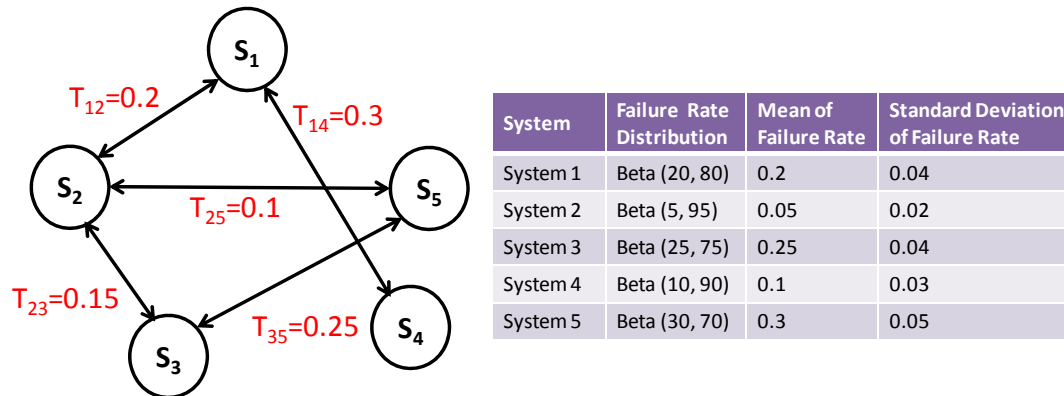


Figure 5. A Five-System Development Network and Heritage Failure Rate Information

Consider the information fusion of failure rates of systems 2 and 3 with system 5 (see Figure 6). System 5 is connected to two dependent systems, 2 and 3, with interdependency strength of 0.1 and 0.25, respectively. Systems 2 and 3 have their own heritage failure rates, with beta distributions shown in Figure 6a. The propagating failure rate on system 5 is easily calculated through the proposed approach in this paper, based on the given information about heritage failure rates and conditional probability for propagating effects. In Figure 6, blue lines denote the heritage failure rate distributions for systems, and red lines denote the propagating failure rate on system 5, respectively. The green line in Figure 6b represents the integrated failure rate for system 5. The mean of the system 5 integrated failure rate represents an increase of 0.07 over its heritage rate value due to the propagating effects from dependent system failures. Figure 7 shows the mean values of propagating effects for all systems. These values depend on the number of dependent systems and the failure rates of dependent systems. System 2 has the highest propagating effects, indicating strong dependencies with numerous other systems. It also has a higher probability to be disrupted by other system failures during the development process. Because it is hard to control this kind of failure, the design team for system 2 should consider these propagating effects when scheduling for the development time.

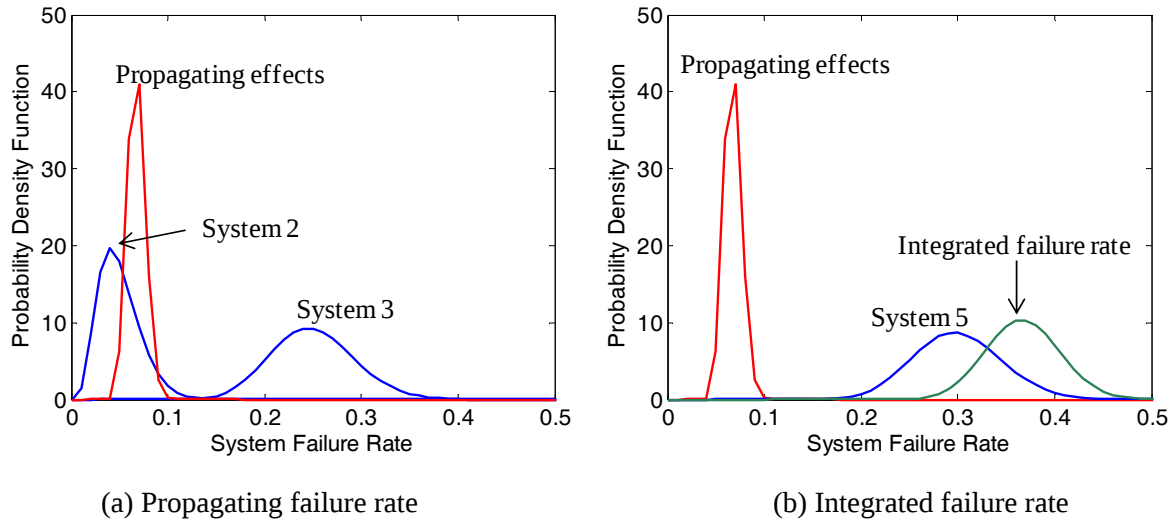


Figure 6. Information Fusion of Failure Rates of Systems 2 and 3 with System 5

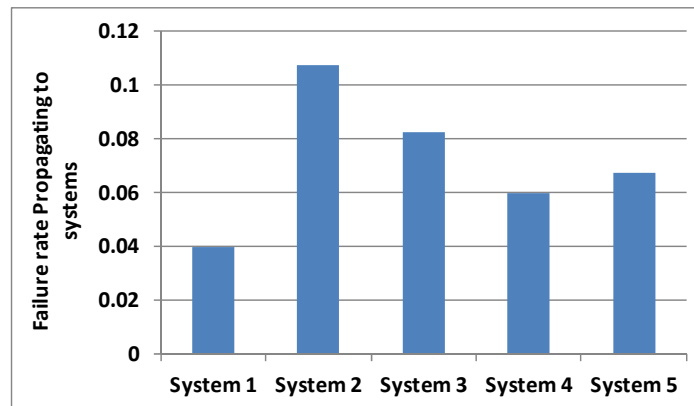


Figure 7. Mean Values for Failure Rates Propagating to Systems

The same synthetic problem is now considered with the requirement evolution modeled via modified heritage failure rates. The rationale is that, when a system's requirements become more stringent in efforts to reach a new capability goal, an increase of heritage failure rate follows. The total expected development time is adopted to measure development time of an SoS capability. We assumed that the expected development time for each system is 1, indicating that if there is no failure, each system can be done in one time unit. Every system also has development delay time due to its failure rate, calculated as the product of failure rate and the expected development time. For instance, if a system's failure rate is 0.6 and expected development time for the system is 1, then the design team of this system needs 1.6 more times than normal to complete it. Therefore, the total expected development time can be formulated as the follows:

$$\text{Total expected development time} = \sum_i (1 + \text{failure rate}_i \times \text{expected development time}_i) \quad (7)$$

We increase the heritage failure rate of each system, one at a time, from 0 to 0.5. The resulting expected time to develop the systems to meet the SoS capability in each case is shown in Figure 8. System 1 has the steepest slope, indicating that it is most critical in terms of impact on total expected development time. The total expected development time

for all systems evolves linearly, a result of the model assumption of constant interdependent strengths.

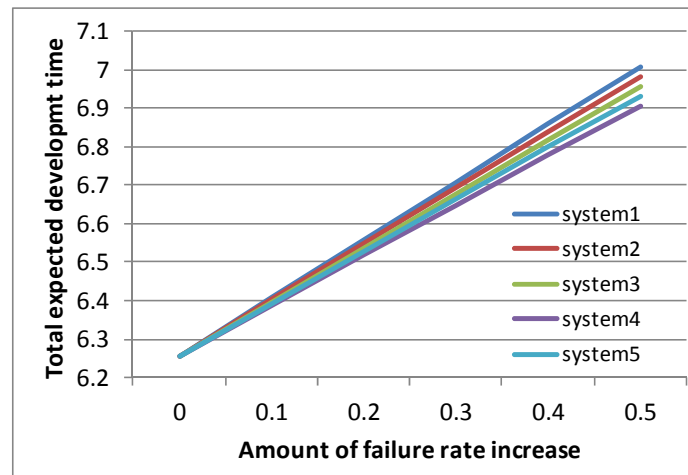


Figure 8. Evolution of Total Expected Development With Respect to Failure Rate Increases

However, if decision-makers knew how much requirement change could be tolerated within the budgeted total development time, then they could make more informed choices. In the present method, this is done using a system upgrade capacity diagram. Figure 9 shows the system upgrade capacity diagram for the synthetic problem. The total expected development time is set to a limit of 7, and the maximum increase of failure rate for each system is computed. System 4's upgrade capacity is higher than others, meaning that it can be substituted with an alternative system, which has higher failure rates. However, system 1 has the lowest upgrade capacity because it was the most critical system in the synthetic problem, according to Figure 8.

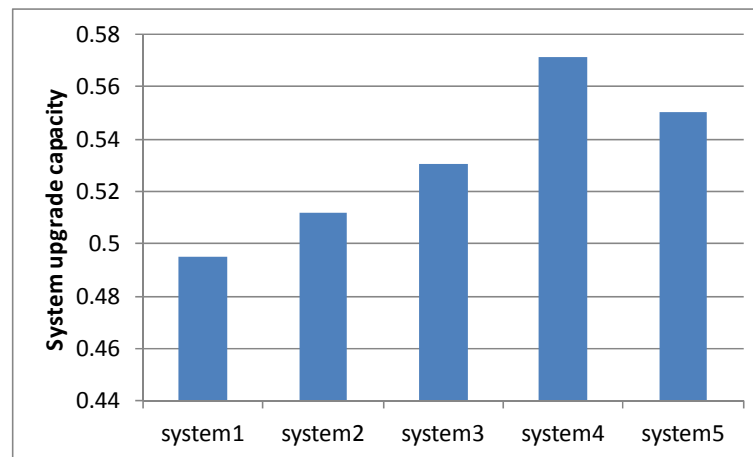


Figure 9. System Upgrade Capacity for Requirement Evolutions

Conclusion

The development process of an SoS capability is often affected by risks from interdependencies between constituent systems and the requirement evolution during the development life cycle. This paper adopts a BN approach to analyze interdependencies by measuring component failure rates and total expected development time for a whole SoS. Propagating failure rates are calculated to describe interdependencies, with heritage failure

rates being evaluated for individual systems. By the integration of these two failure rates, both currently expressed in beta distributions, a new failure rate distribution is achieved that more completely represents the true risk and more faithfully determines the critical components.

A simple, synthetic five-system SoS problem demonstrates the proposed BN approach. Results illustrate that the integrated failure rate for individual systems increases due to the propagating effects of interdependencies. The comparison of integrated failure rates among all systems is useful in identifying the most critical system. Meanwhile, given a development time constraint, upgrade capacity for each system when requirements evolves were computed.

The specific BN formulation approach in this paper rests on two basic assumptions. First, the failure rates (selected based on TRL) are assumed constant. Second, the interdependency strengths between systems are assumed constant. Hence, future work will address the relaxation of the assumptions. More generally, two additional challenges must be addressed. First, a BN approach can use only 0 or 1 to represent two discrete states, like “working” or “failure”; thus, continuous variables, such as development percentage, cannot be expressed directly. The second challenge is the collection of input failure rates, which were simply generated arbitrarily in this paper. Such rates may be inferred from analyses of historical data on TRL levels as they related to eventual development success.

References

- Anderson, S., & Felici, M. (2001). Requirements evolution: From process to product oriented management. In *Proceedings of 3rd International Conference on Product Focused Software Process Improvement* (pp. 27–41). Kaiserslautern, Germany.
- Charles, P., & Turner, P. (2004). Capabilities based acquisition: From theory to reality. *CHIPS Magazine*. Retrieved from http://www.chips.navy.mil/archives/04_summer/web_pages/GEMINI.htm
- DoD. (2008). *Systems engineering guide for system-of-systems*. Retrieved from http://www.acq.osd.mil/sse/ssa/initiat_sos-se.html
- DoD. (2012). *Defense acquisition guidebook*. Retrieved from <http://at.dod.mil/docs/DefenseAcquisitionGuidebook.pdf>
- Ghose, S., & DeLaurentis, D. (2008). Defense acquisition management for system-of-systems. In *Proceedings of the Fifth Annual Acquisition Research Symposium*. Monterey, CA: Naval Postgraduate School.
- Lane, J. A., Dahmann, J., Rebovich, G., & Lowry, R. (2012). Key system of systems engineering artifacts to guide engineering activities. Presented at the NDIA SE Conference, San Diego, CA. Retrieved from http://www.dtic.mil/ndia/2010systemengr/WednesdayTrack3_10806Lane.pdf
- Liu, J., Li, J., & Kim, B. U. (2011). Bayesian reliability modeling of multi-level system with interdependent subsystems and components. In *IEEE International Conference on Intelligence and Security Informatics* (pp. 252–257). Beijing, China.
- Maier, M. W. (1998). Architecting principles for system-of-systems. *Systems Engineering*, 1(4), 267–284.
- Mane, M., & DeLaurentis, D. A. (2009a). Acquisition management for systems-of-systems: Exploratory model development and experimentation. In *Proceedings of the Sixth Annual Acquisition Research Program Symposium*. Monterey, CA: Naval Postgraduate School.
- Mane, M., & DeLaurentis, D. A. (2009b). Impact of programmatic system interdependencies on system-of-systems development. In *4th International Conference on System of Systems Engineering*. Albuquerque, NM.



- Mane, M., & DeLaurentis, D. A. (2010). System development and risk propagation in systems of systems. In *Proceedings of the Seventh Annual Acquisition Research Program Symposium*. Monterey, CA: Naval Postgraduate School.
- Mane, M., & DeLaurentis, D. A. (2011). Capability and development time tradeoff analysis in systems-of-systems. In *Proceedings of the Eighth Annual Acquisition Research Program Symposium*. Monterey, CA: Naval Postgraduate School.
- Mankins, J. C. (1995). Technology readiness levels: A white paper. *Advance Concepts Office, Office of Space Access and Technology*. NASA.
- Reese, C. S., Johnson, V. E., Hama, M., & Wilson, A. (2005). *A hierarchical model for the reliability of an anti-aircraft missile system* (UT MD Anderson Cancer Center Department of Biostatistics Working Paper Series).
- Spacy, W. L., II (2004). Capability-based acquisition in the Missile Defense Agency. *Journal of Contract Management*, 10–19.
- Springer, M. D., & Thompson, W. E. (1966). The distribution of products of independent random variables. *SIAM Journal on Applied Mathematics*, 14, 511–526.
- Stark, G., Oman, P., Skillicorn, A., & Ameele, R. (1999). An examination of the effects of requirements changes on software maintenance releases. *Journal of Software Maintenance Research and Practice*, 11, 293–309.
- Sullivan, M. (2011). *An assessment of acquisition outcomes and impact of reforms & initiatives*. Paper presented at the Eighth Annual Acquisition Research Symposium, Monterey, CA. Retrieved from http://www.acquisitionresearch.net/_beta/files/FY2011/NPS-AM-11-C8P14Z01-123.pdf
- Thompson, W. E., & Haynes, R. D. (1980). On the reliability, availability, and bayes confidence intervals for multi-component systems. *Naval Research Logistics Quarterly*, 27, 345–358.
- Wilson, J. R. (2011). *F-35 a time of trial*. Retrieved from http://www.aerospaceamerica.org/Documents/Aerospace_America_PDFs_2011/June_2011/F-35_A_Time_of_Trial_Feature_June2011.pdf
- Xu, N., Donohue, G., Laskey, K. B., & Chen, C. H. (2005). Estimation of delay propagation in aviation system using Bayesian Network. In *6th USA-EUROPE ATM Seminar*. Baltimore, MD.





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