NPS-AM-12-C9P07R03-058

EXCERPT FROM THE

PROCEEDINGS

OF THE

NINTH ANNUAL ACQUISITION RESEARCH SYMPOSIUM WEDNESDAY SESSIONS VOLUME I

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

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Published April 30, 2012

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 APR 2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**

4. TITLE AND SUBTITLE **Acquisition Management for System-of-Systems: Requirement Evolution and Acquisition Strategy Planning**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Purdue University,School of Aeronautics and Astronautics Engineering,West Lafayette,IN,47907**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. 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.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**53**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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

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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 Kryzsko,** Deputy Director, Enterprise Information and Office of the Secretary of Defense Studies, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics ***Facilitating Decision Choices With Cascading Consequences in Interdependent Networks*** Anita Raja, Mohammad Rashedul Hasan, and Mary Maureen Brown *University of North Carolina at Charlotte* ***Applications of Lexical Link Analysis Web Service for Large-Scale Automation, Validation, Discovery, Visualization, and Real-Time Program-Awareness*** Ying Zhao, Shelley Gallup, Douglas MacKinnon *Naval Postgraduate School* ***Acquisition Management for System-of-Systems: Requirement Evolution and Acquisition Strategy Planning*** Seung Yeob Han, Zhemei Fang, and Daniel DeLaurentis *Purdue University*

Mark Kryzsko—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

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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.

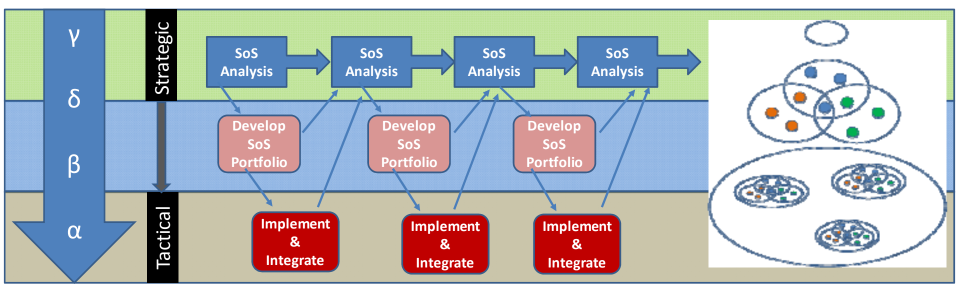


Figure 1. System–of-Systems Acquisition Hierarchy

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 & DeLarentis, 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.

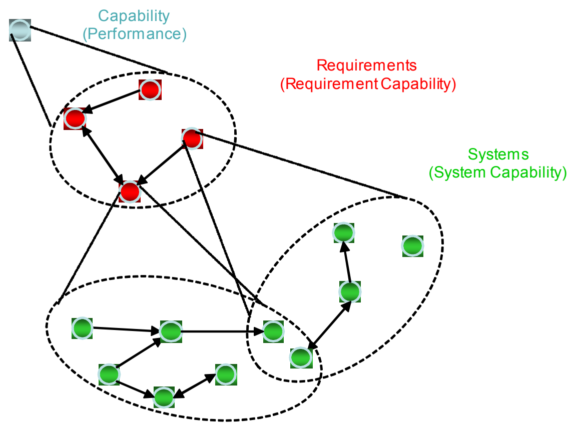


Figure 2. Hierarchical Multi-Level Representation of a System-of-Systems Capability

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.

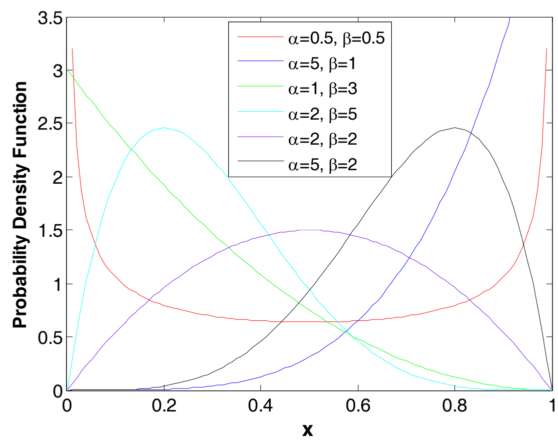


Figure 3. Various Shapes of Beta Distributions

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.

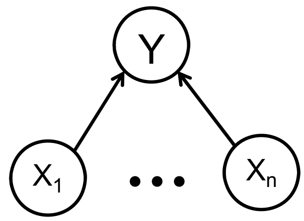


Figure 4. A Bayesian Network Representation

Consider that each node has its own heritage failure rate defined by a beta distribution and that node Y has n parents, $X_1 \ldots X_n$. 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.,{ $X_1 \ldots X_n$ }). According to the law of total probability, the propagating failure rate of node Y is

$$p(Y=0)=\sum_k CPD_k \, p(PA(Y)=k) \tag{1}$$

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 beta(b,c) denote the beta distribution of the propagating failure rate of node Y. Then, the first two moments of this distribution are

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

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

$$M_1=E(p(Y=0))=E(\sum_k CPD_k \, p(PA(Y)=k))=\sum_k CPD_k \prod_i E[p(PA_i(Y)=j)] \tag{3}$$

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:

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

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

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

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

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

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

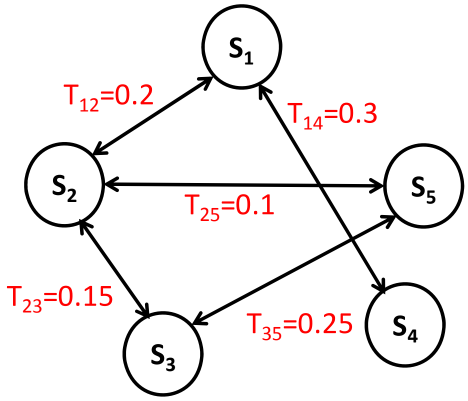
Requirement evolution refers to changes that take place in a set of system requirements after the initial requirement analysis (Anderson & Felici, 2001). In the SoS capability context, requirement evolution seems inevitable. For instance, an initial performance goal for payload capacity of an aircraft 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

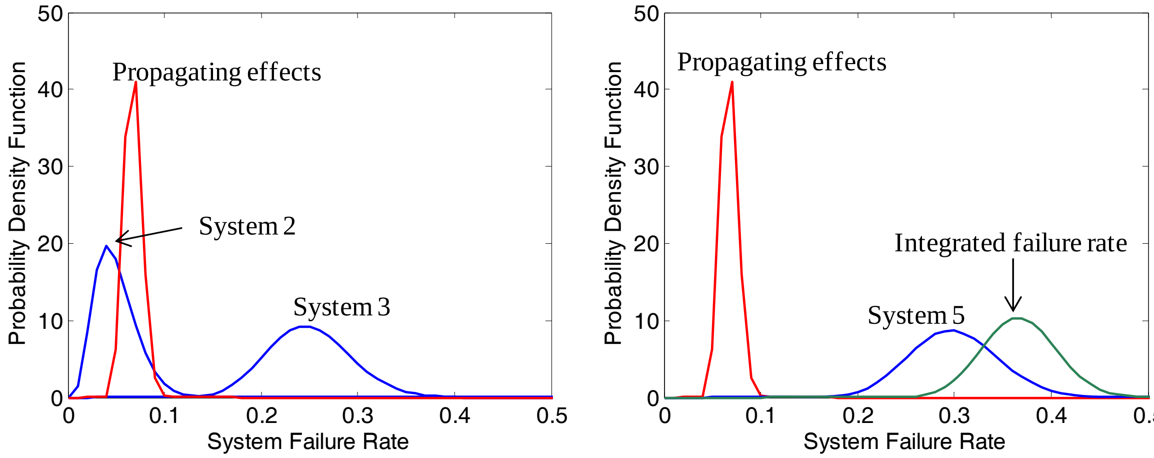
A simple synthetic problem is formulated and solved to demonstrate the proposed BN approach. Figure 5 shows the representation of a five-system network where, for example, the development of system 1, here denoted by S_1, depends on the development of systems 2 and 4. This implies that information from 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.



System	Failure Rate Distribution	Mean of Failure Rate	Standard Deviation of Failure Rate
System 1	Beta (20, 80)	0.2	0.04
System 2	Beta (5, 95)	0.05	0.02
System 3	Beta (25, 75)	0.25	0.04
System 4	Beta (10, 90)	0.1	0.03
System 5	Beta (30, 70)	0.3	0.05

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.



(a) Propagating failure rate (b) Integrated failure rate

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

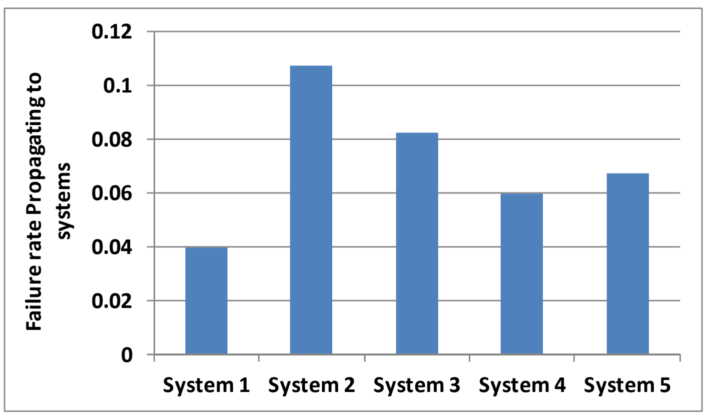


Figure 7. Mean Values for Failure Rates Propagating to Systems

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.

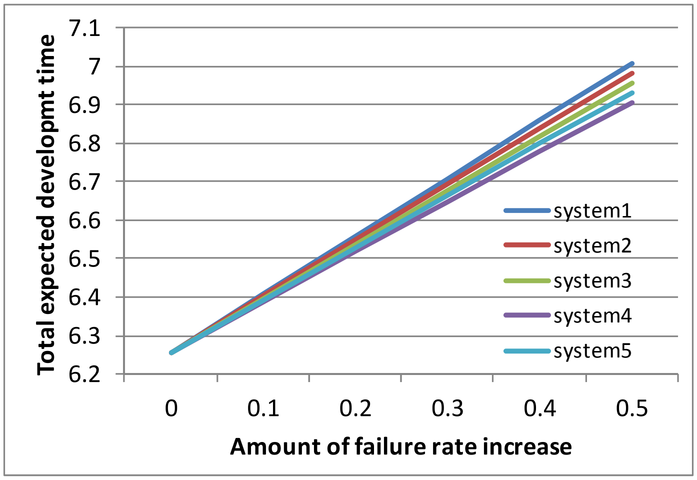


Figure 8. Evolution of Total Expected Development With Respect to Failure Rate Increases

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.

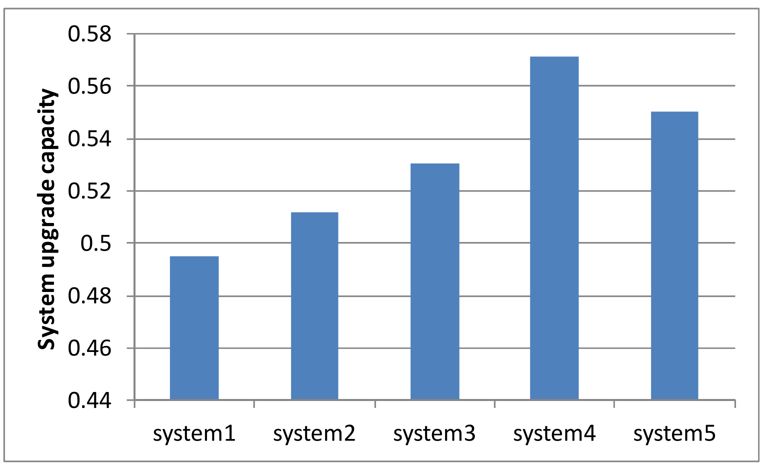


Figure 9. System Upgrade Capacity for Requirement Evolutions

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.

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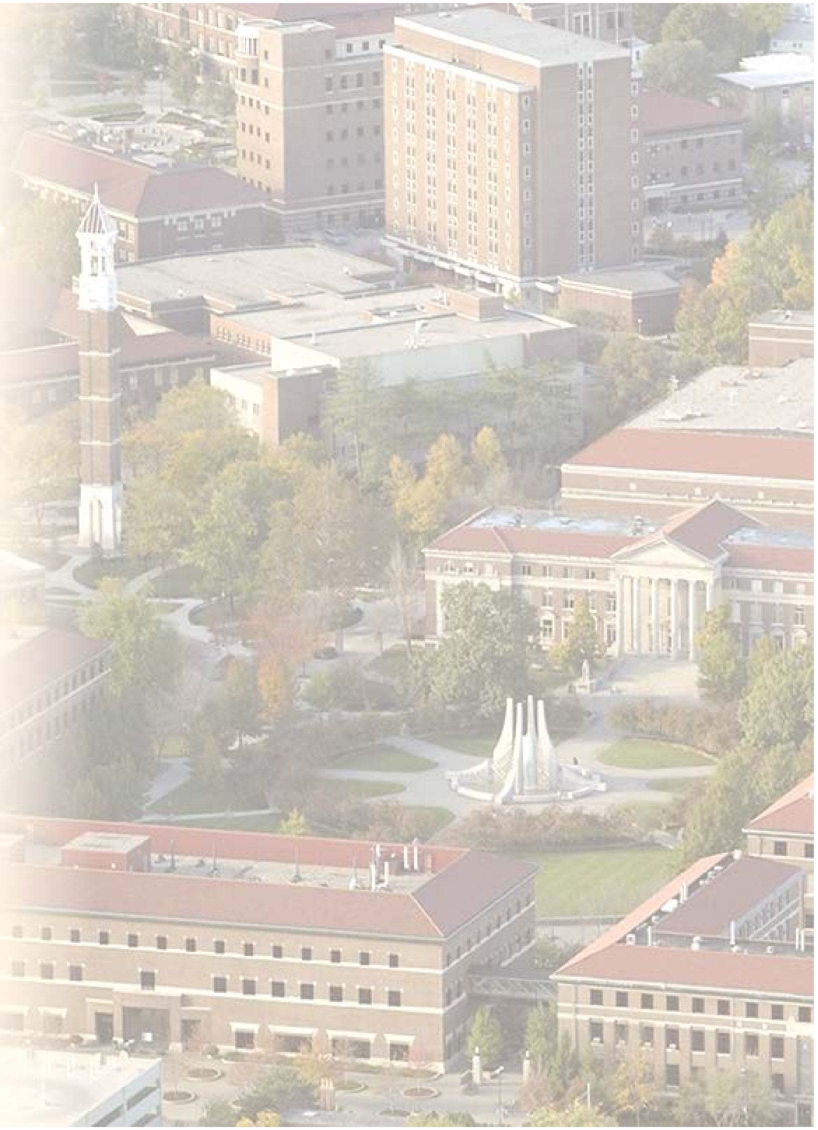
Acquisition Management for System-of-Systems: Requirement Evolution and Acquisition Strategy Planning

NPS Acquisition Research Symposium
May 16th, 2012

Purdue University
Center for Integrated Systems in Aerospace (ISA)

Dr. Daniel DeLaurentis, *Associate Professor*
Simon Han, *Graduate Student*
Zhemei Fang, *Graduate Student*

Contact: ddelaure@purdue.edu



Motivation – Interdependency in SoS

- Interdependency between systems is a necessary characteristic to achieve a SoS capability
- Interdependency (expressed in developmental and operational architectures), however, brings possibility of risk, especially from cascading failures.

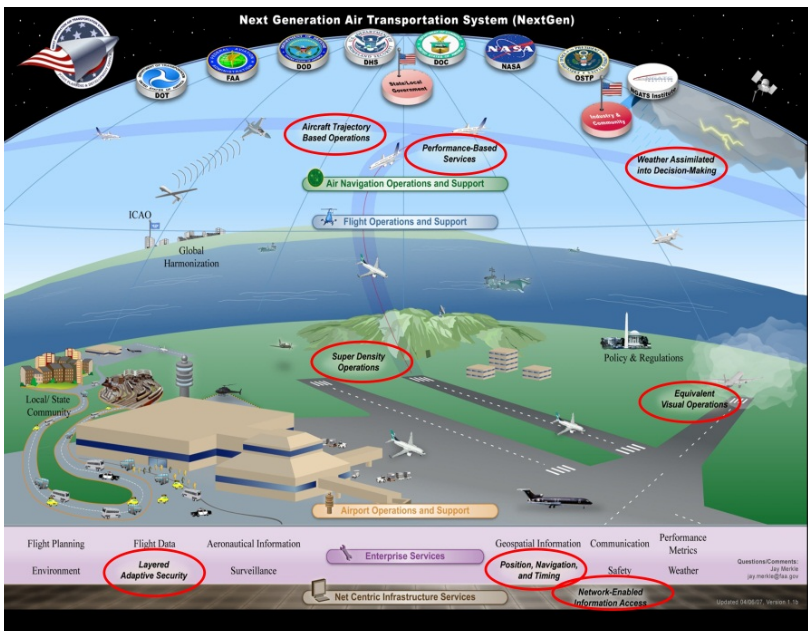


Image from: http://www.nws.noaa.gov/nextgen/ng101.shtml

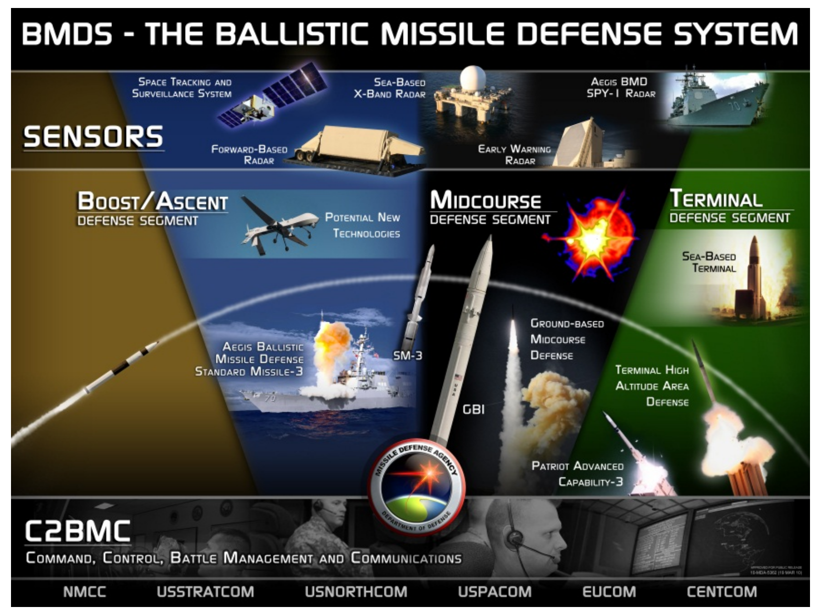
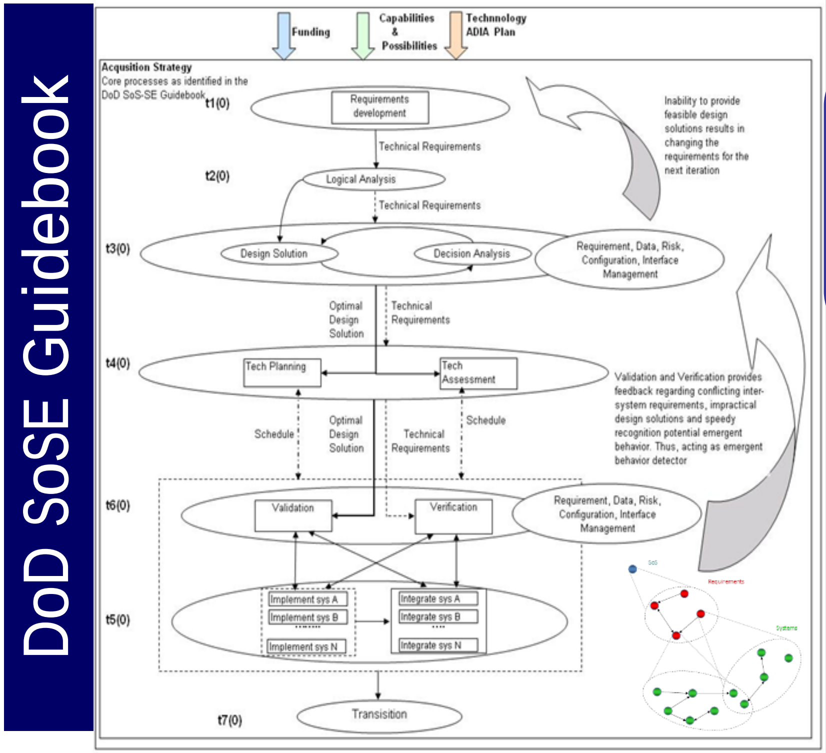


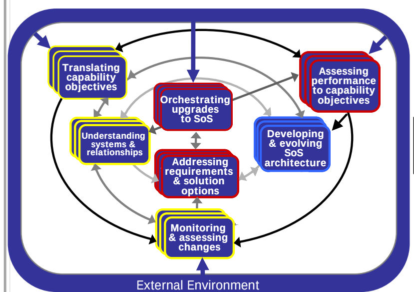
Image from: website of Missile defense agency
http://www.mda.mil/system/system.html

Brief History: Our* Methods Development in this Arena

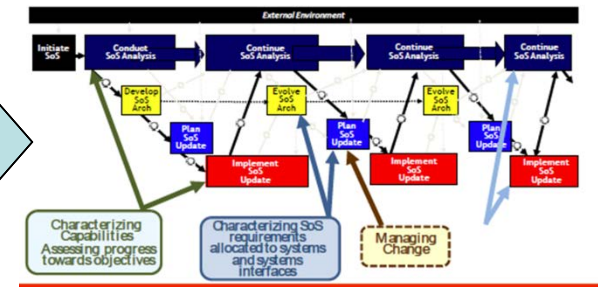
** Thanks to NPS ARP and now also DoD SERC*

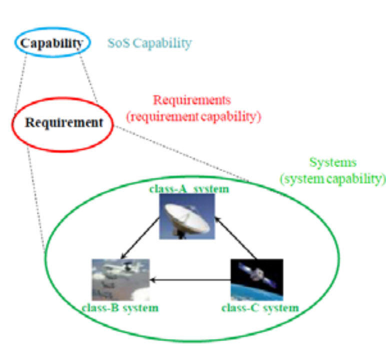


Trapeze

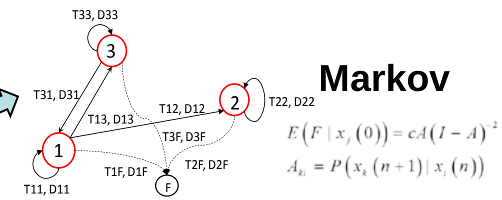


Wave Model





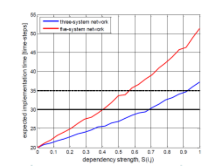
Markov

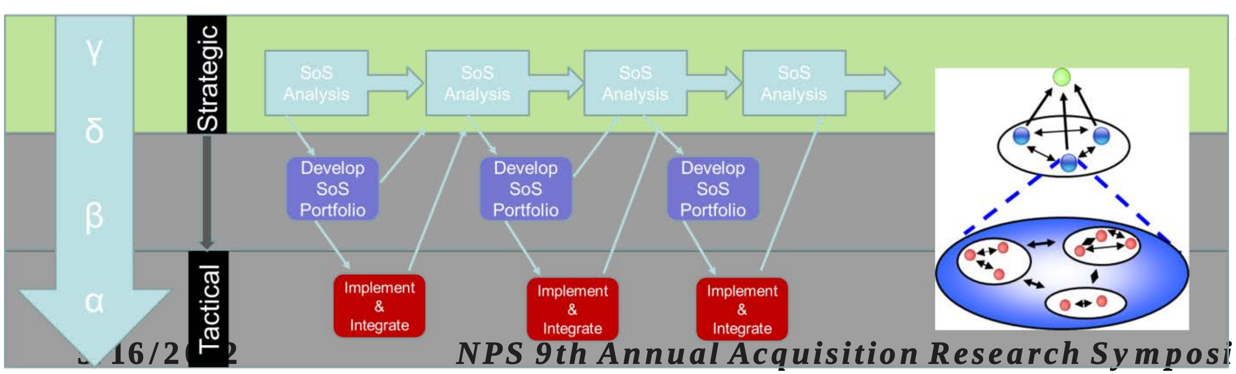


$$E\left(F \mid x_i(0)\right) = cA\left(I - A\right)^{-2} b$$

$$A_{ki} = P\left(x_k(n+1) \mid x_i(n)\right)$$

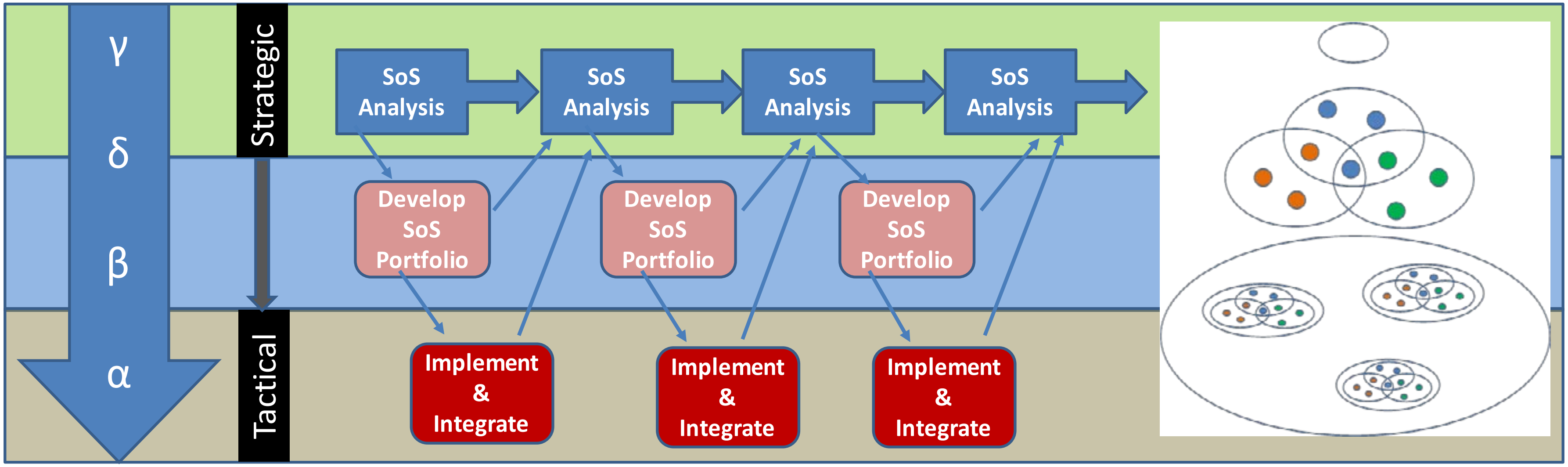
CEM





Methods	Nature	Inputs
CEM	Discrete Event Simulation	Probabilities, Connectivities
Markov	Probabilistic Graphical	Probabilities, Connectivities
Bayesian Network (BN)	Probabilistic Graphical	Conditional Distribution Connectivity
Portfolio Approach	Decision/Analysis based	Capabilities, Requirements, Connection rules

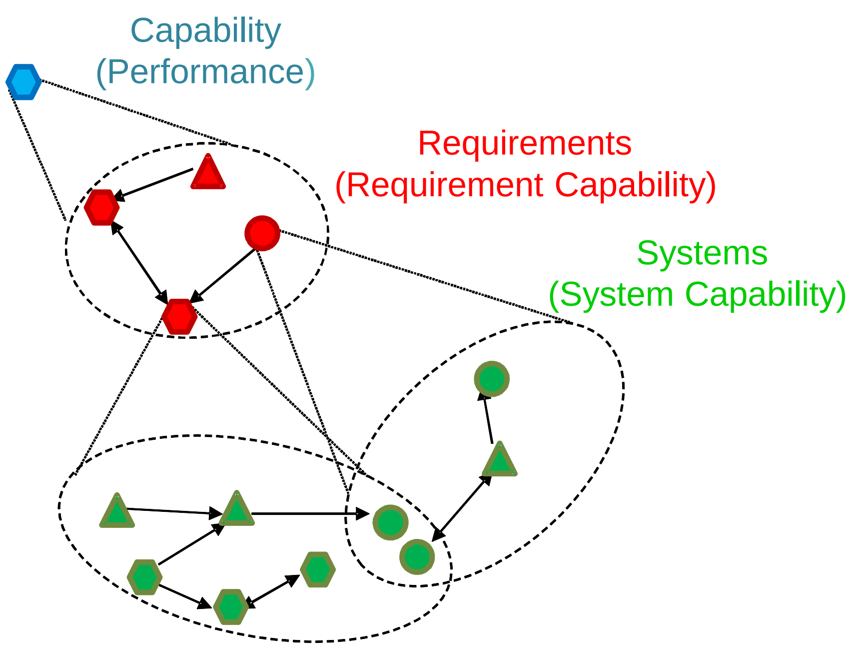
Aim– Tools for Better Acquisition



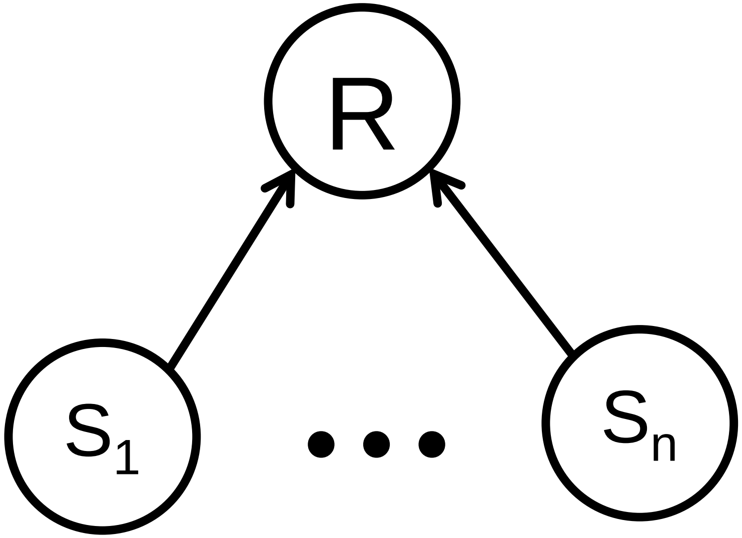
- Aim: Method that supports pre- and post- milestone A, B activities by analyzing the impact of requirement changes and system development failure during generation of a SoS capability.
    - uncertainties in systems and requirement interdependencies
- Evidence: DoD, GAO and others identify requirement evolution & technology uncertainty as critical issue

A hierarchical representation of an SoS

- Interdependent systems are grouped to fulfill a requirement while interdependent requirements are expected to achieve a capability.
- Hierarchy in interdependencies contribute to increasing capability but also may lead to failure through concealed risks



Interdependency analysis via Bayesian Network (BN)



- In analyzing interdependencies, we need:
  - Inherent uncertainty of systems
  - Propagation of uncertainty
- BN is a directed acyclic graph.
- Node *R* has *n* parent nodes.
  - *R*: the requirement
  - S_i: the system that meet this requirement.
  - ***PA***(R_i) denote the set of parents of the node R_i, i.e. $\{S_1 \ldots S_n\}$
- Applying the law of total probability, the probability of achieving a particular requirement, node R_i *i*s:

$$p(R_i = 1) = \sum_{\boldsymbol{S}} p(R_i = 1 \mid PA(R_i) = \boldsymbol{S})\, p(PA(R_i) = \boldsymbol{S})$$

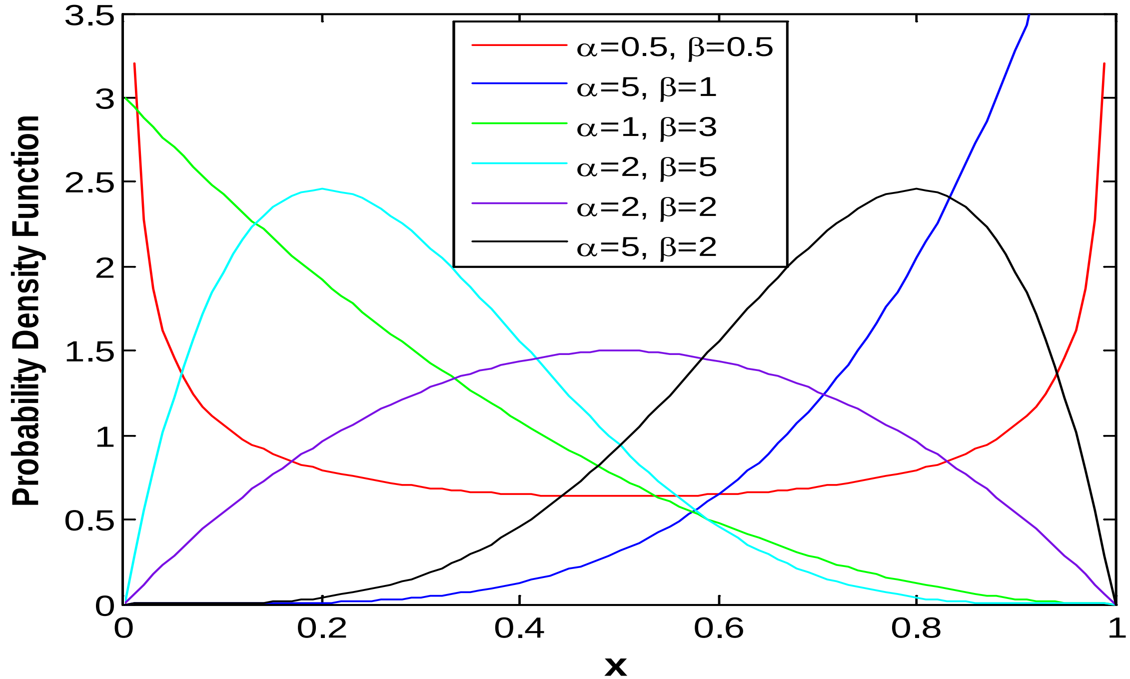
where ***S*** is the set of all the possible combinations of parent node values

- For example, if ***PA****(Ri)* includes two parent nodes S_1 and S_2,

then ***S*** = {(0, 0), (0, 1), (1, 0), (1, 1)}.

Uncertainty with Beta Distribution

- Beta distributions are often used as node failure 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)



Overview of interdependency analysis

- Each system has its own inherent information (e.g., failure rate or reliability).
- Integrated information (e.g., failure rate or reliability) can be obtained by combing inherent information and propagating effects from dependent systems.
- Process:
  1. Estimate propagating effects from dependent systems using a joint probability.
  2. Combine the inherent information and propagating effects.

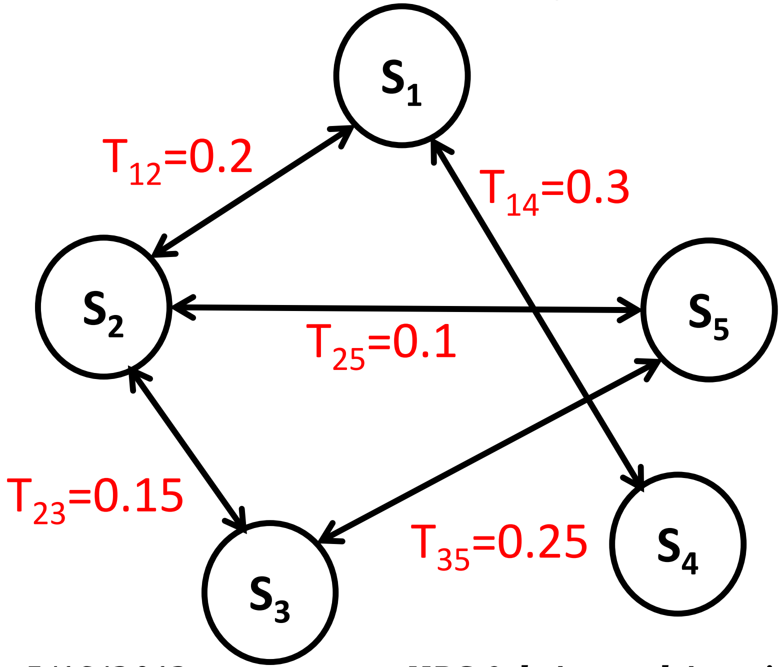
Requirement Evolution

- Both requirement evolution and Technology Readiness Levels (TRLs) can impact component system failure rates.
  - Requirement evolution refers to changes that take place in a set of system requirement after the initial requirement analysis [1].
  - TRLs are a systematic metric/measurement, invented by NASA that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology [2].
- In this study, we assume TRL to be constant for all component systems.
- Therefore, if a requirement evolves to a higher level, system failure rates will increase always.

[1] Anderson, S., & Felici, M. (2001). Requirements Evolution From Process to Product Oriented Management. *3rd International Conference on Product Focused Software Process Improvement* (pp. 27-41). Kaiserslautern, Germany.
[2] Mankins, J. C. (1995). Technology Readiness Levels: A white paper. *Advance Concepts Office, Office of Space Access and Technology*: NASA.

Synthetic Problem Demonstration

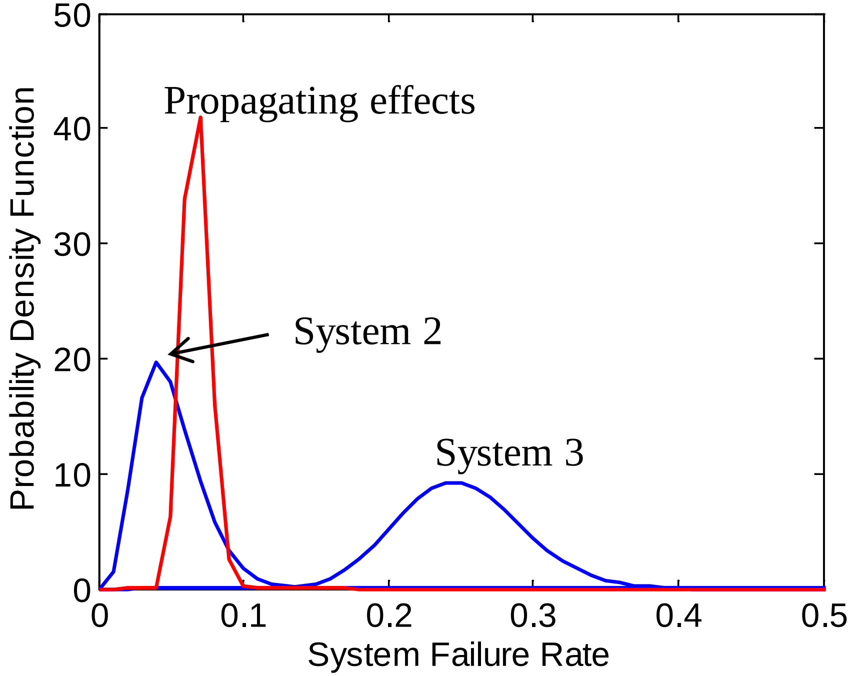
- In a five-system network, the development of system 1, here denoted by S_1, depends on the development of system 2 and 4.
- Table below summarizes inherent failure rates for all systems in terms of beta distributions, means, and standard deviations.
- T values indicate the dependency strength and correspond to the conditional probability of a failure propagating to a dependent system.

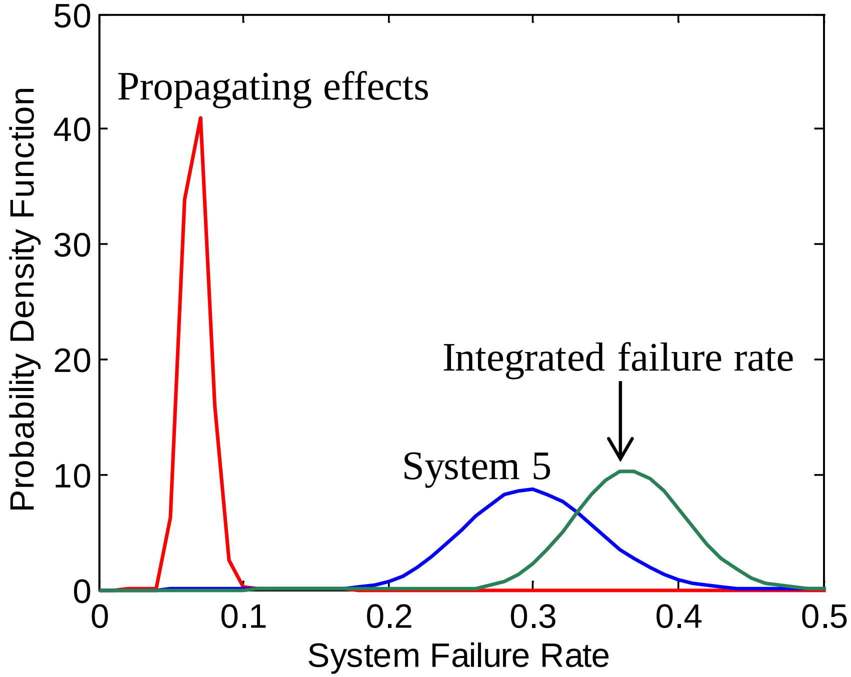


System	Failure Rate Distribution	Mean of Failure Rate	Standard Deviation of Failure Rate
System 1	Beta (20, 80)	0.2	0.04
System 2	Beta (5, 95)	0.05	0.02
System 3	Beta (25, 75)	0.25	0.04
System 4	Beta (10, 90)	0.1	0.03
System 5	Beta (30, 70)	0.3	0.05

Results – Fusion of failure rate information

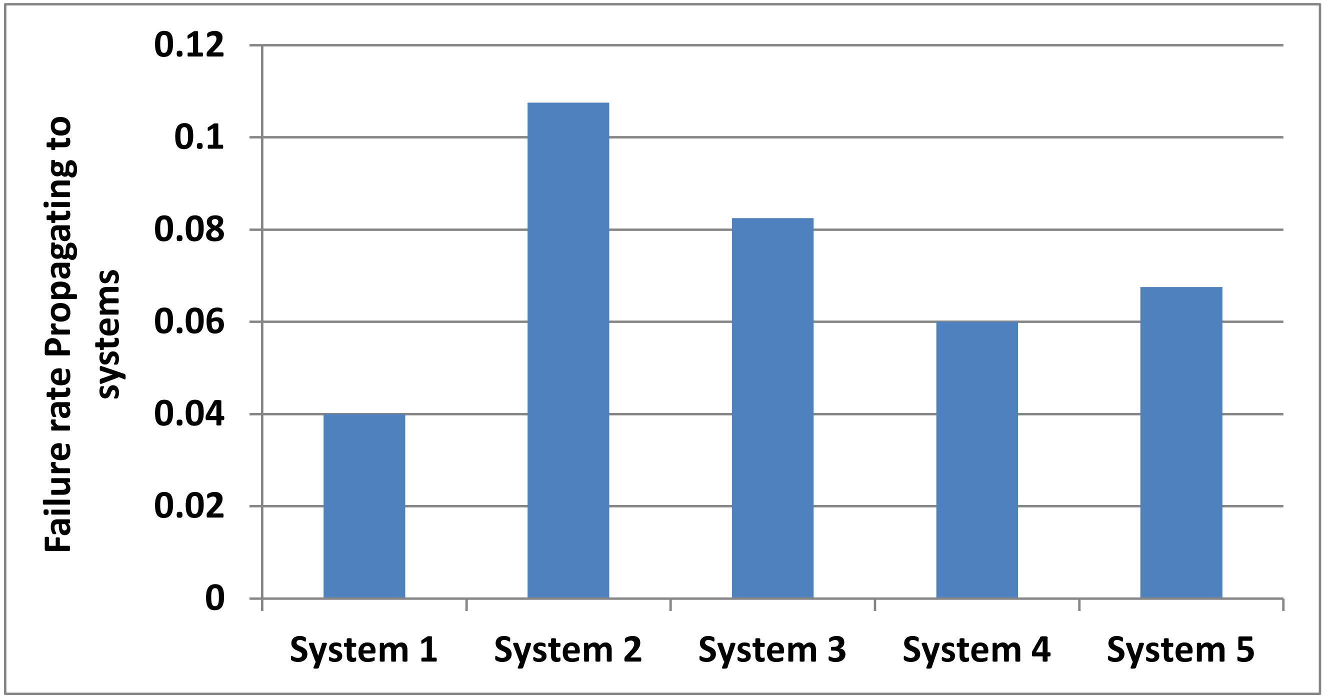
- Figure in left shows the fusion of inherent failure rates for calculate propagating effects.
- Figure in right shows the fusion of propagating effects with inherent failure rate of system 5.





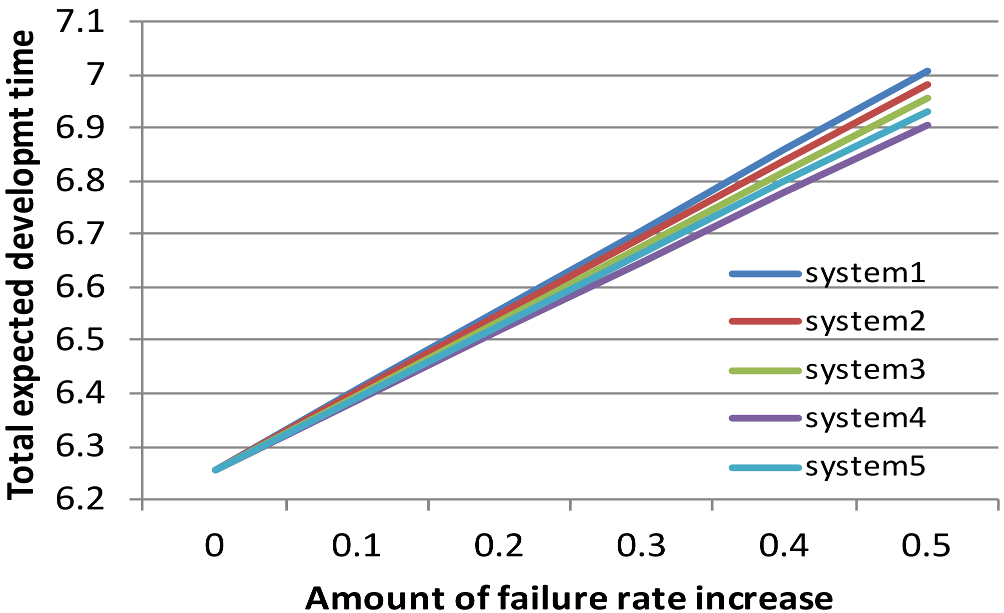
Results – Comparison of propagating effects

- Figure below shows the mean values of propagating effects for all 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.



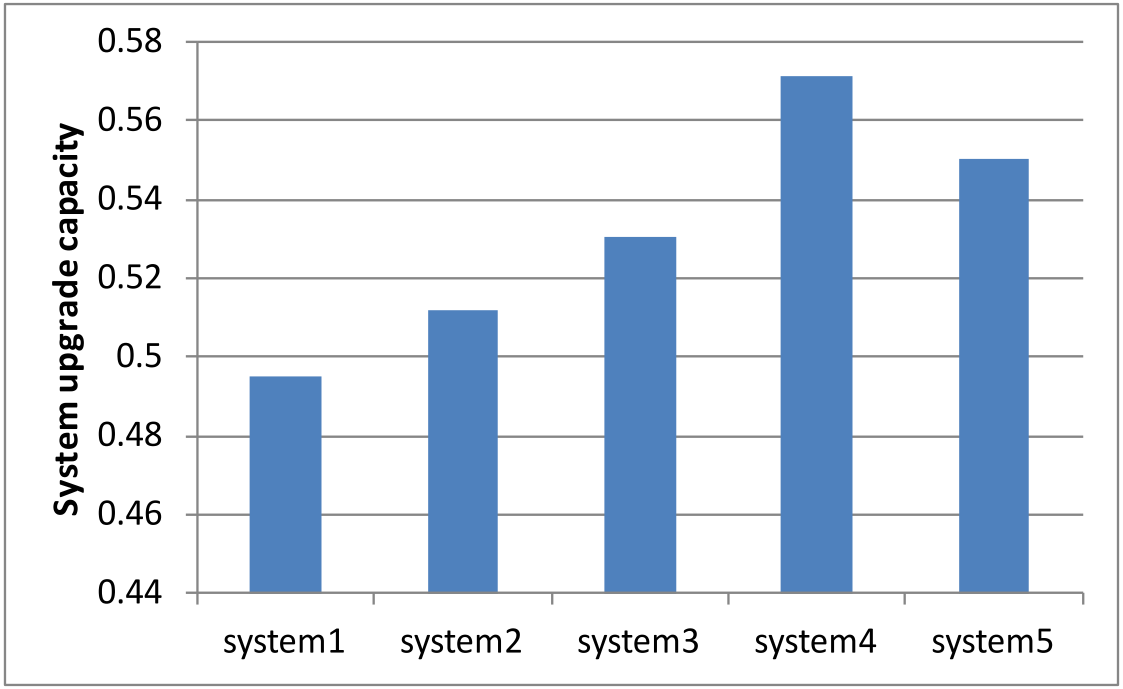
Results – Requirement Evolution Effects

- Figure below shows total expected development time of each system with inherent failure rates increasing from 0 to 0.5.
- System 1 has the steepest slope -- most critical in terms of impact on total expected development time.
- Linearity -- a result of the model assumption of constant interdependent strengths.



Results –Requirement Evolution Effects (Cont.)

- Figure below shows the system upgrade capacity diagram for the synthetic problem.
- System 4's upgrade capacity is higher than others -- it can be substituted with an alternative system which has higher failure rates.
- System 1 has the lowest upgrade capacity because it was the most critical system.



Implementation Example

- Littoral Combat Ship (LCS) systems is adopted as example for applying the proposed approach.
- LCS systems is designed to counter growing potential threats in the littoral area such as coastal mines, quiet diesel submarines and terrorists on small, fast, armed boats.

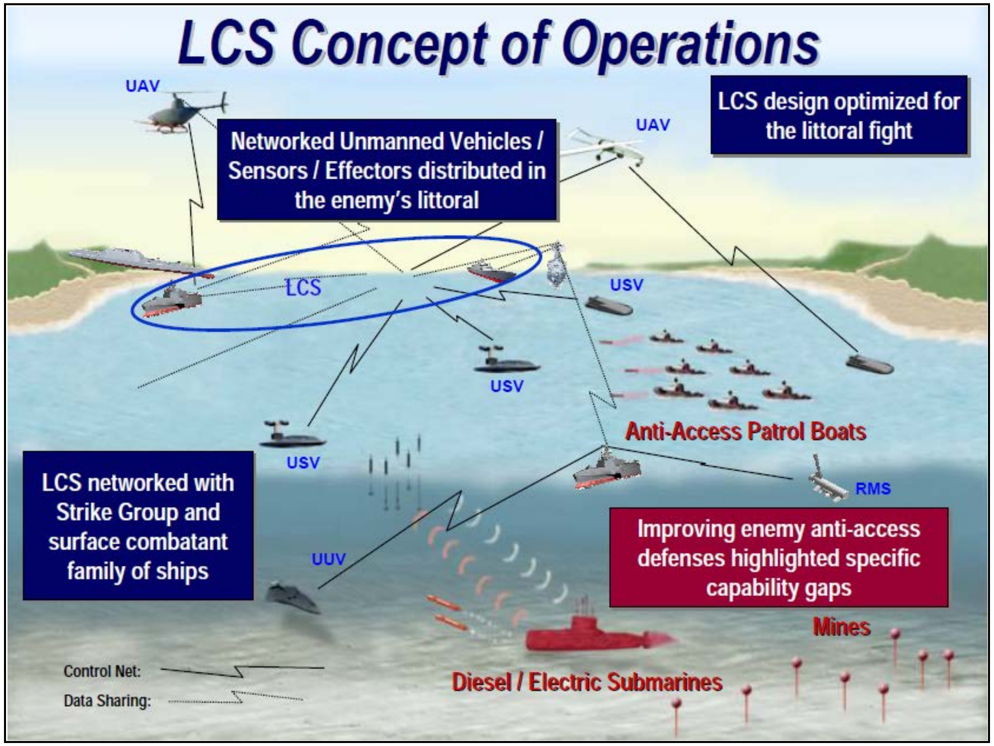
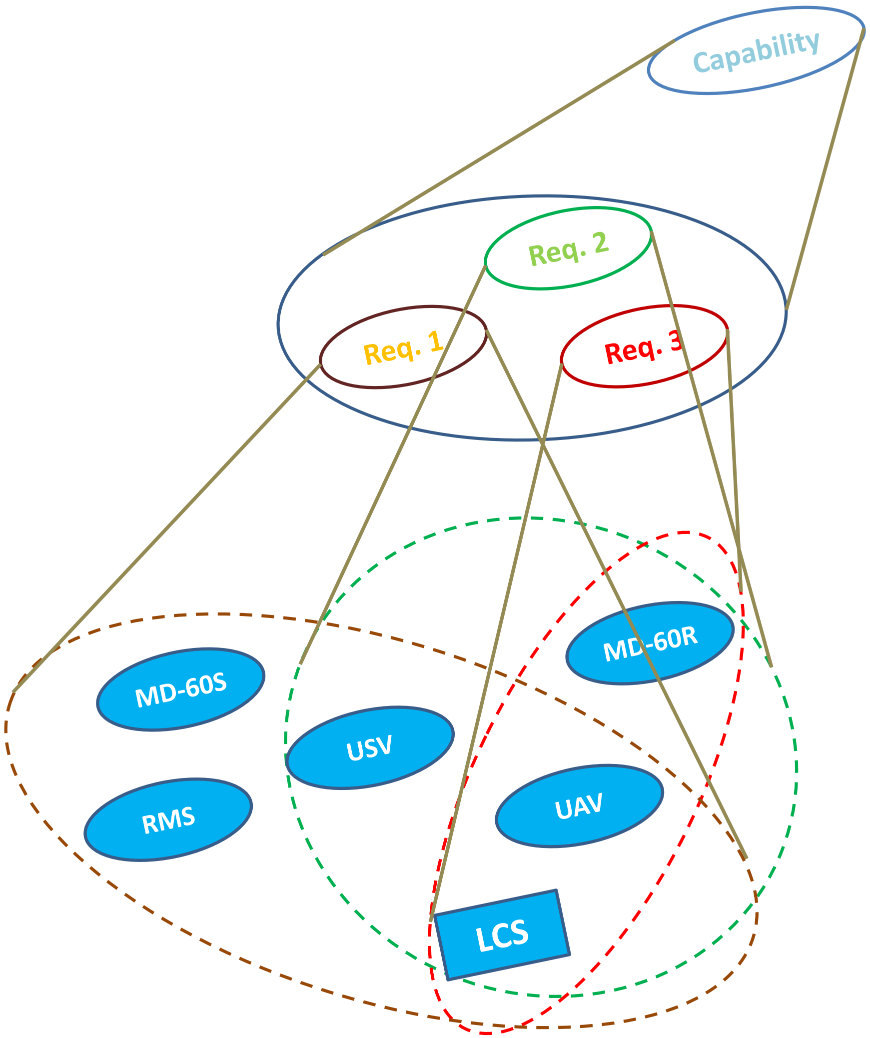
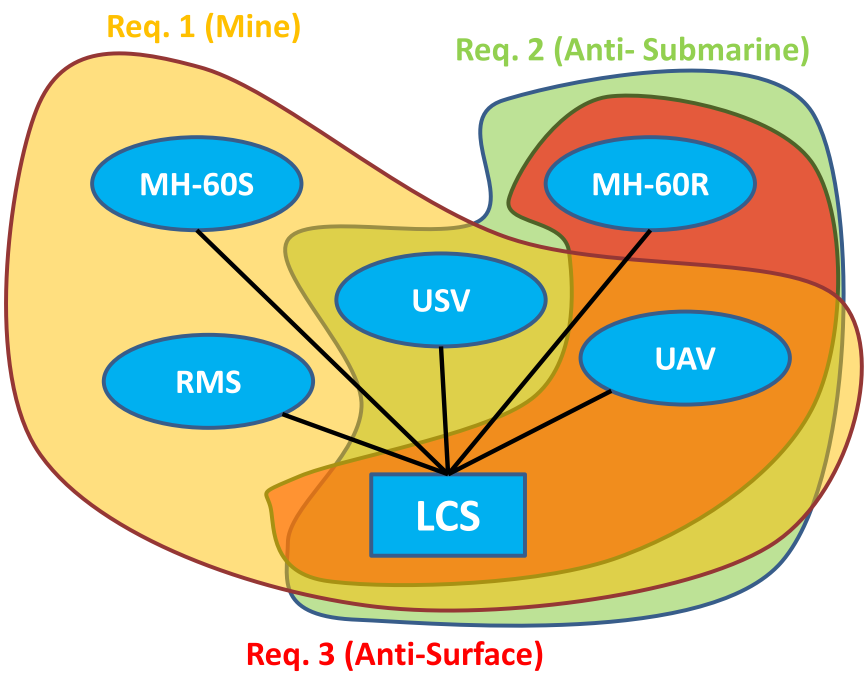


Image from: Presentation slides by RDML Vic Guillory of OPNAV at Mine Warfare Association Conference (titled "Littoral Combat Ship", 08-May-07)

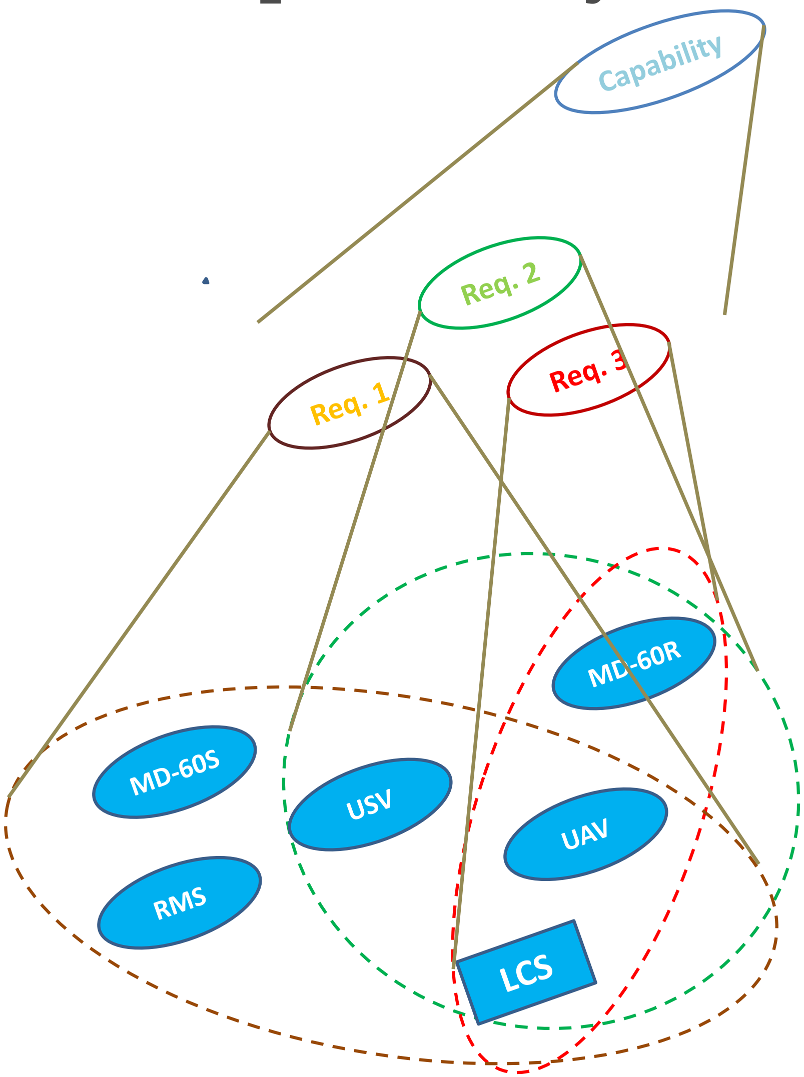
Hierarchical representation of Littoral Combat Ship



MH-60R: Armed Helicopter for Surveillance and Attack
MH-60S: Helicopter for Airborne Mine Counter-Measure
UAV: Unmanned Air Vehicle
USV: Unmanned Surface Vehicle
RMS: Remote Mine Hunting System
Torpedo, **Missile**, and the **LCS**



Interdependency analysis



Fusion all information from requirements

$$p(C=1)=\sum_{\boldsymbol{R}} p(C=1\,|\,PA(C)=\boldsymbol{R})\,p(PA(C)=\boldsymbol{R})$$

Fusion all information from systems

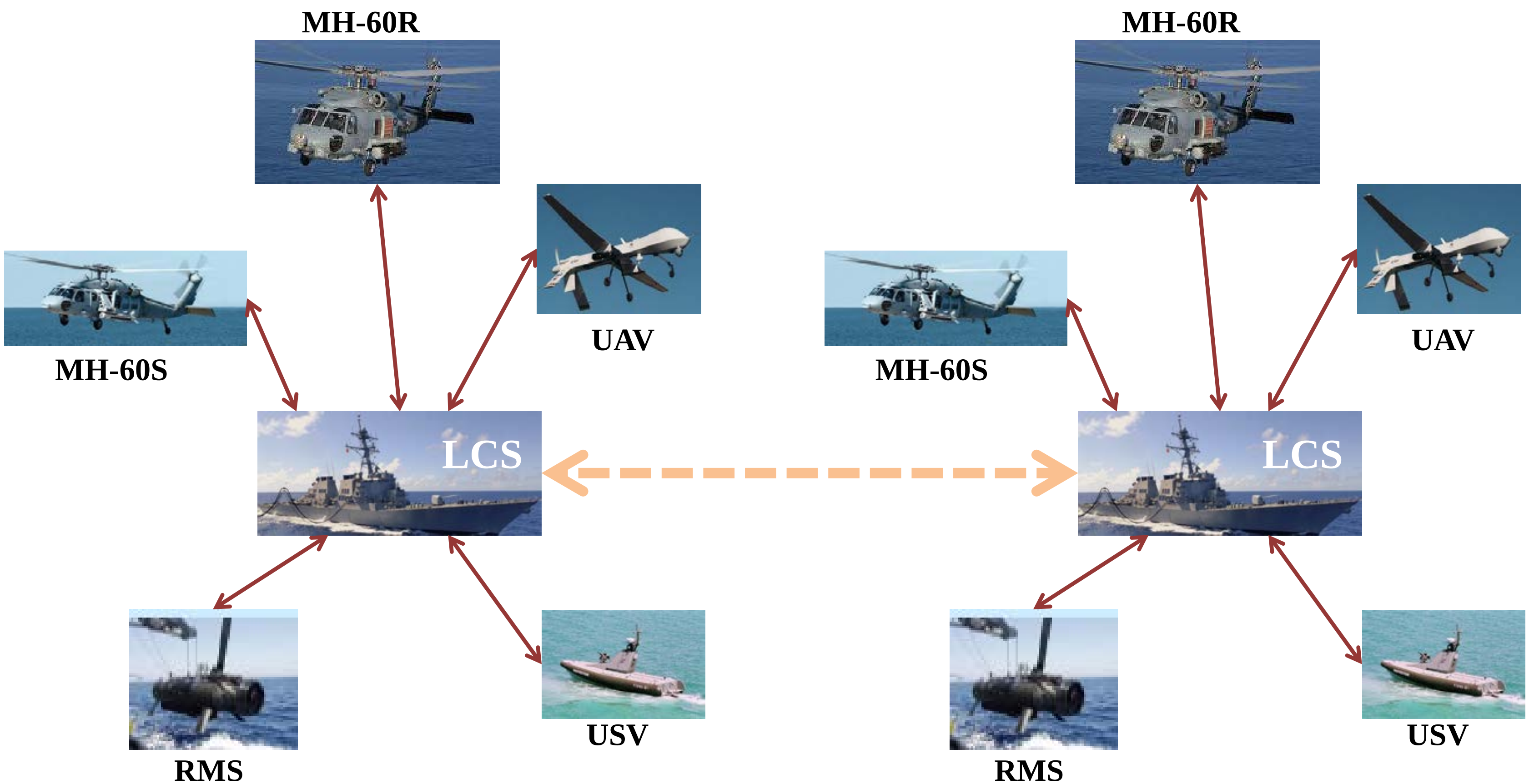
$$p(R_k=1)=\sum_{\boldsymbol{S}} p(R_k=1\,|\,PA(R_k)=\boldsymbol{S})\,p(PA(R_k)=\boldsymbol{S})$$

System failure rates

$$P(System_i = Failure) = 1 - e^{-\lambda_i t}$$

The performance of LCS systems is defined as the probability to complete the mission.

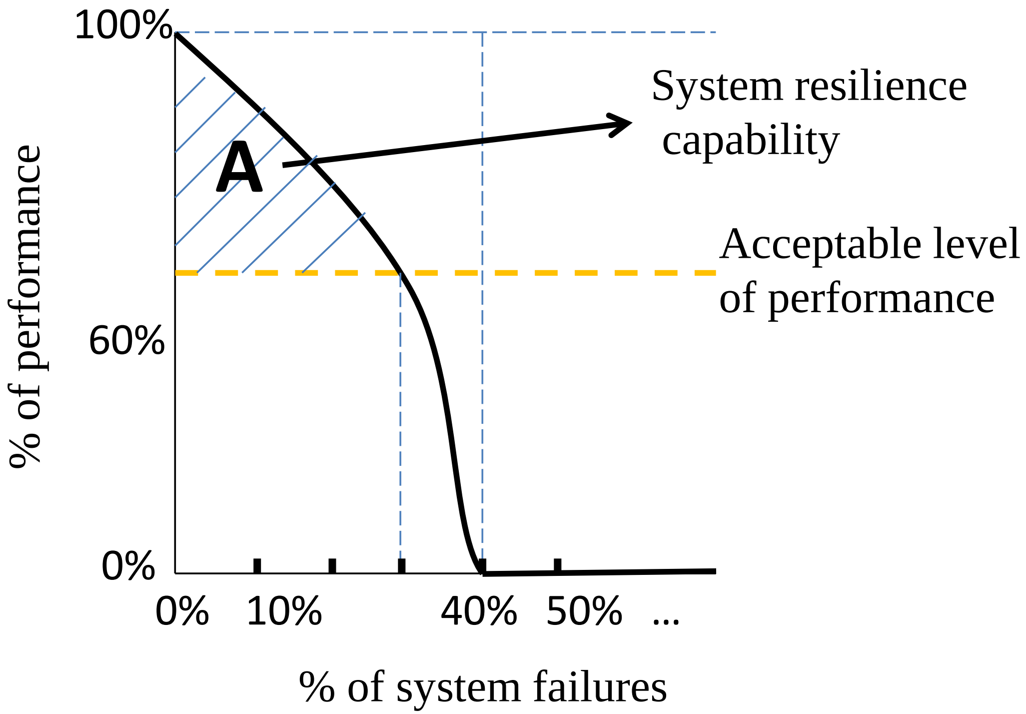
Two different architectures



- architecture 1 has NO communication between LCS command centers
- architecture 2 DOES have communication between LCS command centers

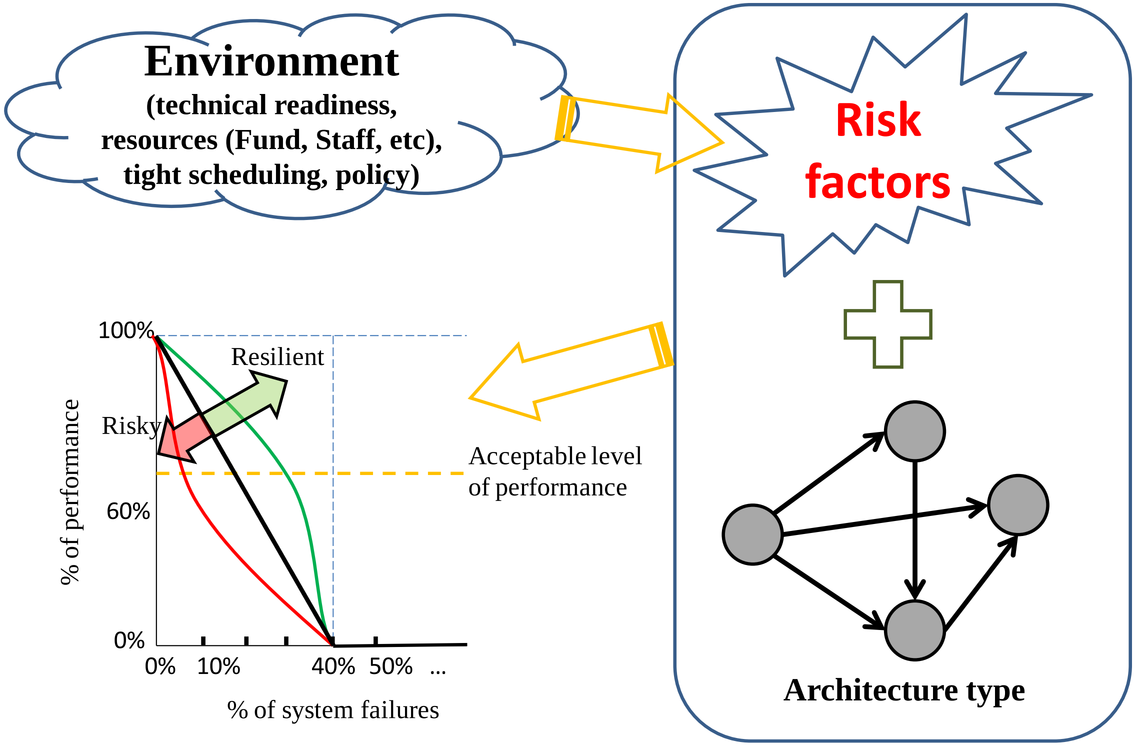
Resilience Metric

- Resilience pattern represents the relationship between performance (or capability) and the level of component failures in the entire domain.
- The yellow horizontal line represents the acceptable level of performance to meet a system requirement.
- The area of A, called system resilience capability, indicates the ability of the system to sustain the performance beyond a desired level in the face of failures.

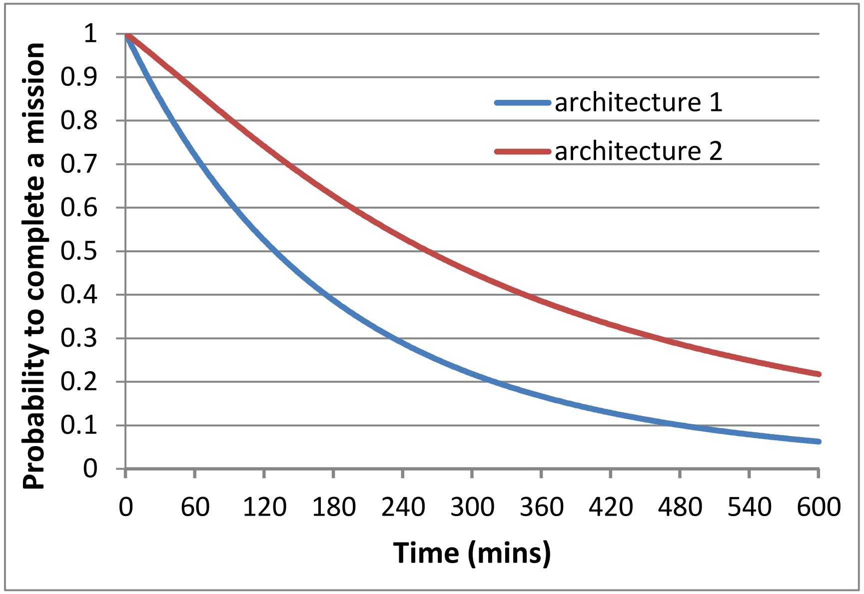


Two factors affecting resilience patterns

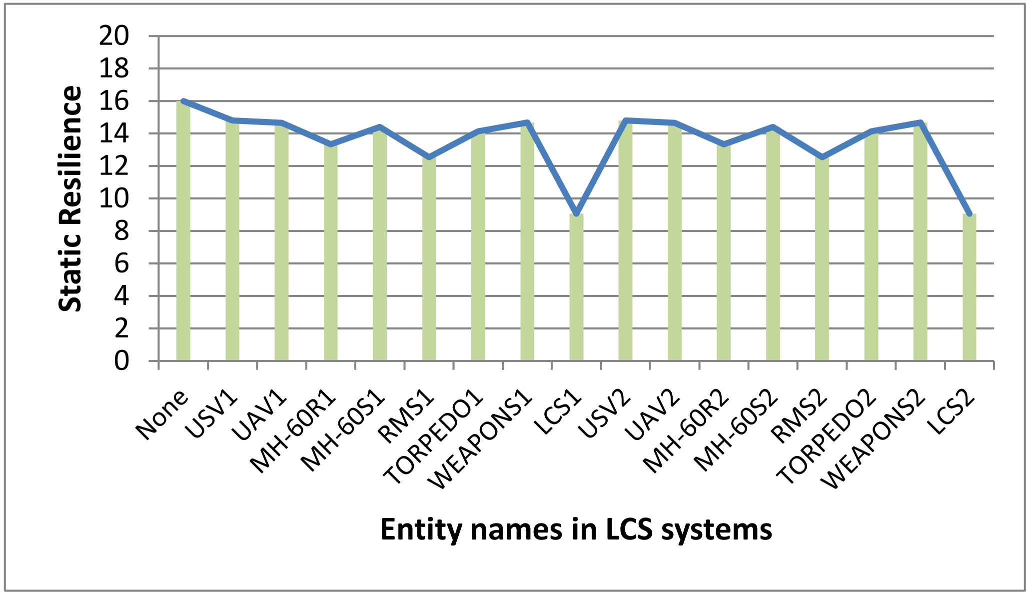
- Architecture type: the fundamental organization of an SoS embodied by its components and their relationships to each other (i.e., interdependencies).
- Risks to SoS: the sources and consequence of component failures.



Results of LCS systems case study



Evolution of system performance of both architectures for 600 mins

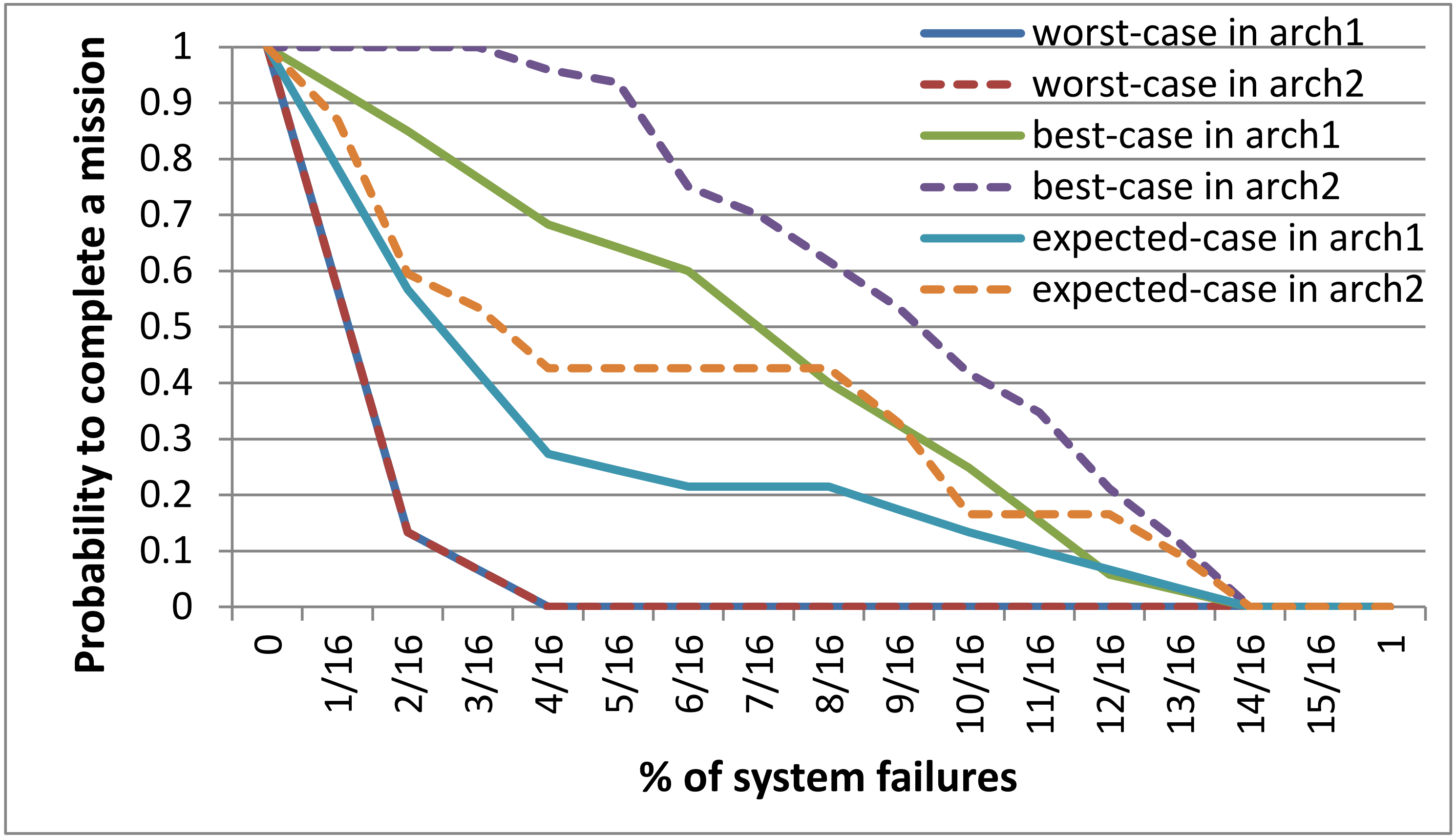


Static resilience with one entity failure in architecture 1

- The exponential distribution is a function of time: the failure rate of a system increases as time elapses.
- Arch2 has the better resilience pattern than Arch1.
- The systems with lower static resilience values are critical systems.
- The right figure indicates that LCS nodes are most critical.

Results of LCS systems case study

- Best-case: when critical systems fail last.
- Worst-case: when critical systems fail first.
- Expected-case: when system failures occur based on systems' own failure rates.



The two major factors, architecture type and failure rate of a system, affect system resilience.

Strengths and weaknesses of the BN

- Strengths
  - Can handle directed nets of interdependencies
  - Can easily represent the system structure and interactions
  - Can be automatically updated with new observations
  - Can be used constructively in sensitivity mode when very few or no data available, with some prior knowledge
- Weaknesses
  - Cannot handle cycles in network.
  - Require rich collection of data (failure and performance) to obtain conditional probability distribution connectivity and node information

Conclusion

- A Bayesian Network approach is adopted to analyze interdependencies by measuring component failure rates and total expected development time for a whole SoS.
- Integration of inherent failure rates and propagating failure rates is calculated to more completely represent the true risk and more faithfully determine the critical components.
- Upgrade capacity for each system can be obtained for decision makers when requirements evolve.

Future Work

- A Bayesian Network approach can only use 0 or 1 to represent two discrete states, like ‘working’ or ‘failure’; thus continuous variables such as development percentage cannot be expressed directly
- Collection of input failure rates -- may be inferred from analysis of historical data on TRL levels as they related to eventual development success.

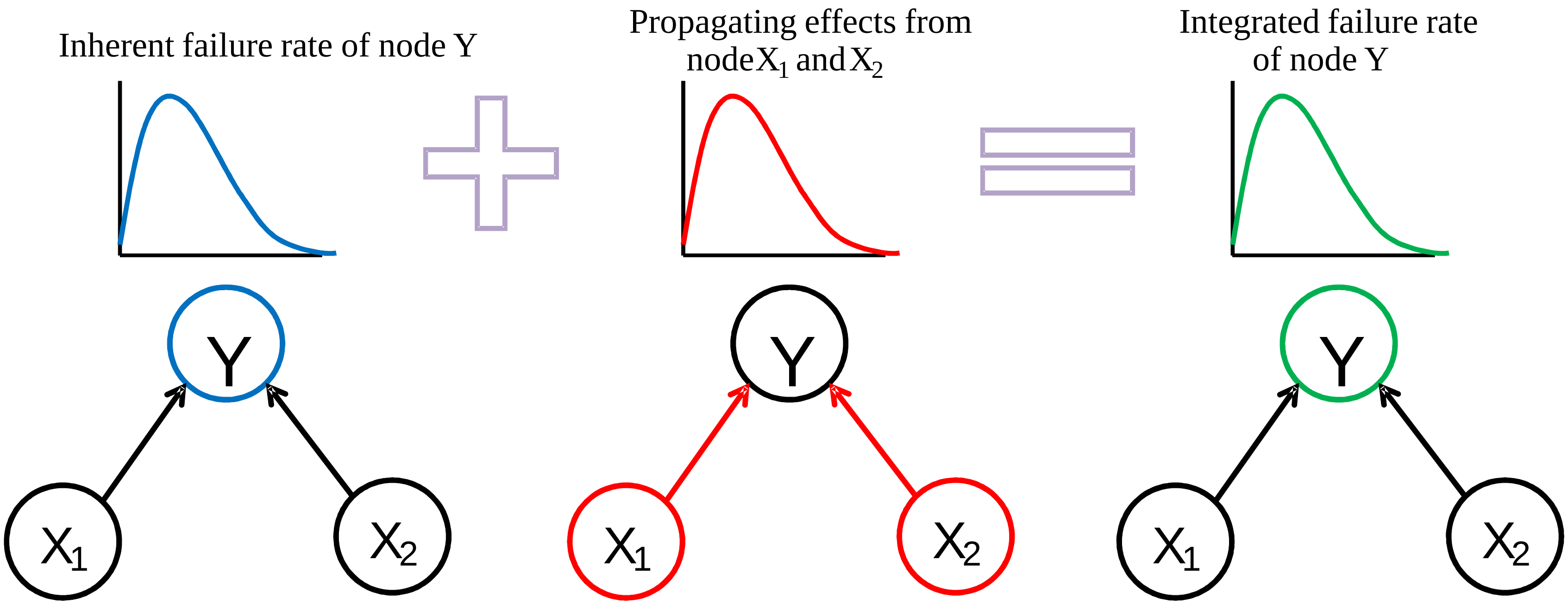
Thank you

Questions ?

BACKUP SLIDES

Overview of interdependency analysis

- Each system has its own inherent information (e.g., failure rate or reliability).
- Integrated information (e.g., failure rate or reliability) can be obtained by combing inherent information and propagating effects from dependent systems.



Previous Work

- **2008 --** Computational Exploratory Model (CEM) based on the 16 basic technical management and technical system-engineering processes.
- **2009 --** Improvements to allow for modeling of scenarios that illustrate the underlying dynamics that produce schedule delays and cost overruns.
- **2010 --** 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.
- **2011 --** 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.

Case study – Littoral Combat Ship (LCS) (Cont.)

- The failure rates are also given to all entities based on mission time limit of that entities using the exponential distribution.

$$p(X=0)=1-e^{-\lambda T} \qquad \lambda=\frac{1}{mission\ \ time\ \ limit}$$

- where T is the system exposure time and λ is the system's failure rate which can be written as a function of the mean time between failures (mission time limit).
- Expected reliability of LCS systems to finish the mission is calculated as the performance using Bayesian Network with two different architectures: unavailable (arch1)/available (arch2) communication between command centers of two Littoral Combat Ships.

Static resilience of a complex system

- Two metrics are defined to quantify system resilience in the multi-level system tester module.
- The static resilience can be thoughts of as a ‘specific’ performance measure – for a given number of component failures, how much performance is maintained.
- Static resilience is defined as the ratio of percentage of performance of a complex system (e.g., SoS) to percentage of component failures

$$\text{Static Resilience} = \frac{\%\text{ of performance (or capability) of a system}}{\%\text{ of component failures}}$$

Metric: System Resilience

- The general definition of resilience is the capacity of a system to survive, adapt and grow in the face of change and uncertainty[1].
- The concept of resilience has been used to analyze systems and solve problems in fields such as ecology, psychology, computer science, material science, and disaster management[2,3,4,5,6].
- See back-up slide for definition in different domains

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[3]Masten, A. S, "Ordinary Magic: Lessons from research on resilience in human development" (PDF). Education Canada 49 (3): 28–32, 2009

[4]Mohammad, A. J., Hutchison, D., Sterbenz, James P.G. "Poster: Towards Quantifying Metrics for Resilient and Survivable Networks", in 14th IEEE International Conference on Network Protocols (ICNP 2006), Santa Barbara, California, USA, November 2006

[5]From: Avallone, Eugene A., et al. eds. Marks' Standard Handbook for Mechanical Engineers, 11th ed., 2007

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Definitions of resilience in different domains

Domains	The definition of resilience
Ecology	The capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and recovering quickly. Such perturbations and disturbances can include stochastic events such as fires, flooding, windstorms, insect population explosions, and human activities such as deforestation and the introduction of exotic plant or animal species.
Psychology	The idea of an individual's tendency to cope with stress and adversity. This coping may result in the individual “bouncing back” to a previous state of normal functioning, or using the experience of exposure to adversity to produce a “steeling effect” and function better than expected.
Computer science	The ability to provide and maintain an acceptable level of service in the face of faults and challenges to normal operation.
Material science	The property of a material to absorb energy when it is deformed elastically and then, upon unloading to have this energy recovered. In other words, it is the maximum energy per unit volume that can be elastically stored.
Disaster application	The ability of countries, communities and households to manage change, by maintaining or transforming living standards in the face of shocks or stresses - such as earthquakes, drought or violent conflict – without compromising their long-term prospects.

Presentation Outline

- Motivation and Research Objectives
- Previous Work
- Analytical Approach
  - A hierarchical representation of System of Systems (SoS)
  - An interdependency analysis of an SoS using a Bayesian Network with beta distribution
- Synthetic Problem Demonstration
- Conclusion & Future Work

Research Objectives

- 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 failure during generation of a system-of-systems capability.
- In other words, this study is focused on tools suitable to analyze uncertainties in systems and the interdependencies between systems and possibly evolving requirements.

An interdependency analysis using a BN

- In analyzing interdependencies, we need to handle:
  - ➢ Inherent uncertainty of systems
  - ➢ Propagation of uncertainty
- A Bayesian Network (BN) can handle these.
- A Bayesian Network (BN) is a directed acyclic graph.
  - ➢ Nodes are the random variables and edges correspond to direct influence of one node on another.
  - ➢ Each variable in the BN model is associated with a conditional probability distribution.
- A BN facilitates the formation of a joint probability:

$$P(X_1, X_2, \ldots, X_n) = \prod_{i=1}^{n} P(X_i \mid P_a(X_i))$$

where $Pa(X_i)$ are the parents of X_i.