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Volume I:
Defense Acquisition in Transition

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

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www.researchsymposium.org

Preface and Acknowledgements

For the first time in recent memory, acquisition reform has emerged as a significant topic in Presidential discourse. While procurement surfaced occasionally as a second-tier issue in last fall's debates, its importance has increased considerably in the current economic crisis. The massive federal spending of recent months has highlighted the need for cost-savings elsewhere, and the President has announced acquisition reform as a priority of his Administration to help achieve those savings.

That our new President would use his "bully pulpit" to advance acquisition reform should be good news for the nation. Too often in the past, champions of reform have lacked the political standing necessary to bring about substantive and enduring change. If the President, with his own party in control of the Congress, is unable to successfully lead such an effort, we may rightfully despair that anyone can.

Of course, students of acquisition know only too well that such comprehensive change must be led by leaders who grasp and can address the complex interplay of interests and issues faced by the various institutions and organizations that make up the acquisition culture. Accordingly, the discourse of today's reform agenda must rise well above the "sound-bite" level of so-called "no-bid" contracts which seems to dominate the popular media. Rather, the reform agenda must reflect the experiences and judgments of the "best and the brightest" from government, industry, and academia, many of whom are convened at this Symposium. We sincerely hope that the Administration will be open to their voices.

Such "informed reform" is a primary goal of the Naval Postgraduate School's Acquisition Research Program (ARP). Established in 2003, the ARP provides leadership in innovation, creative problem solving and an on-going dialogue, contributing to the evolution of Department of Defense (DoD) acquisition strategies. The program continues to grow and mature with the number of projects, products, collaboration opportunities and faculty/graduate student participation continuing to increase substantially. Our goals remain the same as noted below:

- Position the ARP in a leadership role to continue to develop the body of knowledge in defense acquisition research
    - Over 300 published works since inception
    - Sponsoring an annual Acquisition Research Symposium, the first of which was held in May 2004, which draws the thought leaders of the DoD acquisition community.
- Establish acquisition research as an integral part of policy-making for DoD officials. Some processes informed by this research include:
    - Contract close out procedures;
    - The impact of spiral development in the acquisition process;
    - Cost estimating for new design Ballistic Missile Submarine
    - Termination liability clauses for Major Defense Acquisition Programs
    - Contractual language and context to incorporate Open Architecture in weapons system contracts

    - All completed research is published in full text on the ARP website, www.acquisitionresearch.net, allowing ready access by any and all parties interested in the DoD acquisition process.
- Create a stream of relevant information concerning the performance of DoD Acquisition policies with viable recommendations for continuous process improvement.
    - The body of knowledge on the DoD acquisition process has been greatly increased.
    - Faculty researchers routinely give multiple presentations, in both national and international fora, featuring their research work—thereby increasing exposure to a broader audience. Typical audiences include the London School of Economics, the Federal Reserve and the International Procurement Conference.
    - With the launch of the ARP's International Journal of Defense Acquisition Management (IJDAM), the '"reach" of our products has increased substantially. In addition, the IJDAM provides another forum in which acquisition scholars might publish and recognize the globalization that is occurring in the defense industry.
- Prepare the DoD workforce to participate in the continued evolution of the defense acquisition process.
    - The ARP plays a major role in providing a DoD-relevant graduate education program to future DoD officials. Synergy between research conducted and course content delivered enhances both the teaching and learning processes.
    - The number of students engaged in focused acquisition research for their MBA project continues to grow dramatically. These students have the benefit of being able to immediately apply their newly acquired acquisition skills to real-world issues.
- Collaboration among universities, think tanks, industry and government in acquisition research.
    - Over 50 universities/think tanks participated in the 5th annual Acquisition Research Symposium as a result of a focused effort to create a Virtual University Consortium.
    - Emerging collaborative research efforts continue to bring new scholar and practitioner thought to the business issues facing the DoD as was demonstrated by the large response to our second Broad Area Announcement (BAA) in support of the OSD-sponsored acquisition research program. As we write this, our third BAA is being prepared for release.
    - The International Journal of Defense Acquisition is attracting scholars from the United Kingdom, Canada, Nigeria, Singapore, The Netherlands and Australia.

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

- Office of the Under Secretary of Defense (Acquisition, Technology & Logistics)
- Program Executive Officer SHIPS
- Commander, Naval Sea Systems Command
- Army Contracting Command, U.S. Army Materiel Command
- Program Manager, Airborne, Maritime and Fixed Station Joint Tactical Radio System
- Program Executive Officer Integrated Warfare Systems
- Office of the Assistant Secretary of the Air Force (Acquisition)
- Office of the Assistant Secretary of the Army (Acquisition, Logistics, & Technology)
- Office of Naval Air Systems Command PMA-290
- Office of the Deputy Assistant Secretary of the Air Force (Management Policy & Program Integration)
- Deputy Assistant Secretary of the Navy (Acquisition & Logistics Management)
- Director, Strategic Systems Programs Office
- Deputy Director, Acquisition Career Management, US Army

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

James B. Greene, Jr.	Keith F. Snider, PhD
Rear Admiral, US Navy (Ret.)	Associate Professor

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The Acquisition Research Program Team

Rear Admiral James B. Greene, Jr. USN (Ret.)—Acquisition Chair, Naval Postgraduate School. RADM Greene develops, implements and oversees the Acquisition Research Program in the Graduate School of Business and Public Policy. He interfaces with DoD, industry and government leaders in acquisition, facilitates graduate student research and conducts guest lectures and seminars. Before serving at NPS, RADM Greene was an independent consultant focusing on Defense Industry business development strategy and execution (for both the public and private sectors), minimizing lifecycle costs through technology applications, alternative financing arrangements for capital-asset procurement, and "red-teaming" corporate proposals for major government procurements.

RADM Greene served as the Assistant Deputy Chief of Naval Operations (Logistics) in the Pentagon from 1991-1995. As Assistant Deputy, he provided oversight, direction and budget development for worldwide US Navy logistics operations. He facilitated depot maintenance, supply chain management, base/station management, environmental programs and logistic advice, and support to the Chief of Naval Operations. Some of his focuses during this time were leading Navy-wide efforts to digitize all technical data (and, therefore, reduce cycle-time) and to develop and implement strategy for procurement of eleven Sealift ships for the rapid deployment forces. He also served as the Senior Military Assistant to the Under Secretary of Defense (Acquisition) from 1987-1990; as such, he advised and counseled the Under Secretary in directing the DoD procurement process.

From 1984-1987, RADM Greene was the Project Manager for the AEGIS project. This was the DoD's largest acquisition project, with an annual budget in excess of $5 billion/year. The project provided oversight and management of research, development, design, production, fleet introduction and full lifecycle support of the entire fleet of AEGIS cruisers, destroyers, and weapons systems through more than 2500 industry contracts. From 1980-1984, RADM Greene served as Director, Committee Liaison, Office of Legislative Affairs followed by a tour as the Executive Assistant, to the Assistant Secretary of the Navy (Shipbuilding and Logistics). From 1964-1980, RADM Greene served as a Surface Warfare Officer in various duties, culminating in Command-at-Sea. His assignments included numerous wartime deployments to Vietnam, as well as the Indian Ocean and the Persian Gulf.

RADM Greene received a BS in Electrical Engineering from Brown University in 1964; he earned an MS in Electrical Engineering and an MS in Business Administration from the Naval Postgraduate School in 1973.

RADM Greene received the **2009 Richard W. Hamming Annual Faculty Award for Achievement in Interdisciplinary Activities.** The selection is based on his work in leading and administering the Naval Postgraduate School's Acquisition Research Program.

Dr. Keith F. Snider—Associate Professor of Public Administration and Management in the Graduate School of Business & Public Policy at the Naval Postgraduate School in Monterey, California, where he teaches courses related to defense acquisition management. He also serves as Principal Investigator for the NPS Acquisition Research Program and as Chair of the Acquisition Academic Area.

Snider has a PhD in Public Administration and Public Affairs from Virginia Polytechnic Institute and State University, a Master of Science degree in Operations Research from the Naval Postgraduate School, and a Bachelor of Science degree from the United States Military Academy at West Point. He served as a field artillery officer in the US

Army for twenty years, retiring at the rank of Lieutenant Colonel. He is a former member of the Army Acquisition Corps and a graduate of the Program Manager's Course at the Defense Systems Management College.

Professor Snider's recent publications appear in *American Review of Public Administration*, *Administration and Society*, *Administrative Theory & Praxis*, *Journal of Public Procurement*, *Acquisition Review Quarterly*, and *Project Management Journal.*

Dr. Snider received the **2009 Richard W. Hamming Annual Faculty Award for Achievement in Interdisciplinary Activities.** The selection is based on his work in leading and administering the Naval Postgraduate School's Acquisition Research Program.

Karey L. Shaffer—Program Manager, General Dynamics Information Technology, supporting the Acquisition Research Program at the Graduate School of Business & Public Policy, Naval Postgraduate School. As PM, Shaffer is responsible for operations and publications in conjunction with the Acquisition Chair and the Principal Investigator. She has also catalyzed, organized and managed the Acquisition Research Symposiums hosted by NPS.

Shaffer served as an independent Project Manager and Marketing Consultant on various projects. Her experiences as such were focused on creating marketing materials, initiating web development, assembling technical teams, managing project lifecycles, processes and cost-savings strategies. As a Resource Specialist at Watson Wyatt Worldwide in Minneapolis, Shaffer developed and implemented template plans to address continuity and functionality in corporate documents; in this same position, she introduced process improvements to increase efficiency in presentation and proposal production in order to reduce the instances of corruption and loss of vital technical information.

Shaffer has also served as the Project Manager for Imagicast, Inc., and as the Operations Manager for the Montana World Trade Center. At Imagicast, she was asked to take over the project management of four failing pilots for Levi Strauss in the San Francisco office. Within four months, the pilots were released; the project lifecycle was shortened; and the production process was refined. In this latter capacity at the MWTC, Shaffer developed operating procedures, policies and processes in compliance with state and federal grant law. Concurrently, she managed $1.25 million in federal appropriations, developed budgeting systems and helped secure a $400,000 federal technology grant. As the Operations Manager, she also launched the MWTC's Conference site, managed various marketing conferences, and taught student practicum programs and seminars.

Shaffer holds an MBA from San Francisco State University and earned her BA in Business Administration (focus on International Business, Marketing and Management) from the University of Montana.

A special thanks to our editors Jeri Larsen, Jessica Moon, Breanne Grover and Adrianne Malan for all that they have done to make this publication a success, to David Wood, Tera Yoder, Jordy Boom and Ian White for production, web and graphic support, and to the staff at the Graduate School of Business & Public Policy for their administrative support. Our program success is directly related to the combined efforts of many.

7TH ANNUAL
ACQUISITION RESEARCH SYMPOSIUM

May 12 - 13, 2010

Monterey, California

Announcement and Call for Proposals

The Graduate School of Business & Public Policy at the Naval Postgraduate School announces the **7th Annual Acquisition Research Symposium** to be held **May 12-13, 2010 in Monterey, California.**

This symposium serves as a forum for the presentation of acquisition research and the exchange of ideas among scholars and practitioners of public-sector acquisition. We seek a diverse audience of influential attendees from academe, government, and industry who are well placed to shape and promote future research in acquisition.

The Symposium Program Committee solicits proposals for panels and/or papers from academicians, practitioners, students and others with interests in the study of acquisition. The following list of topics is provided to indicate the range of potential research areas of interest for this symposium: **acquisition and procurement policy, supply chain management, public budgeting and finance, cost management, project management, logistics management, engineering management, outsourcing, performance measurement, and organization studies.**

Proposals must be submitted by **November 6, 2009**. The Program Committee will make notifications of accepted proposals by **December 4, 2009**. Final papers must be submitted by **April 2, 2010**.

Proposals for papers should include an abstract along with identification, affiliation, contact information and short bio for the author(s). Proposals for papers plan for a 20 minute presentation. Proposals for panels (plan for 90 minute duration) should include the same information as above as well as a description of the panel subject and format, along with participants' names, qualifications and the specific contributions each participant will make to the panel.

Submit paper and panel proposals to www.researchsymposium.org **.**

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NPS BAA-09

BROAD AGENCY ANNOUNCEMENT
Acquisition Research Program
Open until 4:00 pm PDST 30 June 2009

Primary objective is to attract outstanding researchers and scholars to investigate topics of interest to the defense acquisition community. The program solicits innovative proposals for defense acquisition management and policy research to be conducted during fiscal year (FY) 2010 (1 Oct 2009 - 30 Sep 2010).

Defense acquisition management and policy research refers to investigations in all disciplines, fields, and domains that (1) are involved in the acquisition of products and/or services for national defense, or (2) could potentially be brought to bear to improve defense acquisition. It includes but is not limited to economics, finance, financial management, information systems, organization theory, operations management, human resources management, and marketing, as well as the "traditional" acquisition areas such as contracting, program/project management, logistics, and systems engineering management.

This program is targeted in particular to U.S. universities (including U.S. government schools of higher education) or other research institutions outside the Department of Defense.

The Government anticipates making multiple awards up to $120,000 each for a basic research period of twelve months. NPS plans to complete proposal evaluations and notify awardees in early September 2008. The actual date of grant award will depend on availability of funds and the capabilities of the grants office. Prior year awards occurred in the November – January timeframe. Awardees may request approval of pre-award costs (up to three months), or they may request adjustments in the grant period of performance.

Full Text can be found at

http://www.nps.edu/Research/WorkingWithNPS.html

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Disclaimer: The views represented in this report are those of the authors and do not reflect the official policy position of the Navy, the Department of Defense, or the Federal Government.

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Table of Contents

Wednesday, May 14, 2008

Panel 1 - Plenary Panel - National Security Acquisition Agenda for the New Administration

Wednesday, May 13, 2009	Panel 1 - Plenary Panel - National Security Acquisition Agenda for the New Administration
9:30 a.m. – 11:00 a.m.	**Chair: Dr. Jacques S. Gansler**, Director, Center for Public Policy & Private Enterprise, University of Maryland; former Under Secretary of Defense (Acquisition, Technology & Logistics) **Discussants:** **Lieutenant General Ross Thompson, III, US Army**, Military Deputy, Assistant Secretary of the Army (Acquisition, Logistics & Technology) **Dr. Nancy Spruill**, Director, Acquisition Resources & Analysis, Office of the Under Secretary of Defense (Acquisition, Technology & Logistics) **Ms. Susan L. Coté**, Vice President, Corporate Contracts, Pricing & Supply Chain, Northrop Grumman Corporation

Chair: The Honorable Jacques S. Gansler, former Under Secretary of Defense for Acquisition, Technology, and Logistics, is a Professor and holds the Roger C. Lipitz Chair in Public Policy and Private Enterprise in the School of Public Policy at the University of Maryland. He is also the Director of both the Center for Public Policy and Private Enterprise and the Sloan Biotechnology Industry Center. As the third-ranking civilian at the Pentagon from 1997 to 2001, Gansler was responsible for all research and development, acquisition reform, logistics, advance technology, environmental security, defense industry, and numerous other security programs.

Before joining the Clinton Administration, Gansler held a variety of positions in government and the private sector, including Deputy Assistant Secretary of Defense (Material Acquisition), Assistant Director of Defense Research and Engineering (Electronics), Executive Vice President at TASC, Vice President of ITT, and engineering and management positions with Singer and Raytheon Corporations.

Throughout his career, Gansler has written, published, and taught on subjects related to his work. He recently served as the Chair of the Secretary of the Army's "Commission on Contracting and Program Management for Army Expeditionary Forces." He is also a member of the National Academy of Engineering and a Fellow of the National Academy of Public Administration. Additionally, he is the Glenn L. Martin Institute Fellow of Engineering at the A. James Clarke School of Engineering, an Affiliate Faculty member at the Robert H. Smith School of Business, and a Senior Fellow at the James MacGregor Burns Academy of Leadership (all at the University of Maryland). For 2003–2004, he served as Interim Dean of the School of Public Policy. For 2004–2006, Gansler served as the Vice President for Research at the University of Maryland.

Discussants:

Lieutenant General Ross Thompson, III, US Army, was assigned as Military Deputy, Assistant Secretary of the Army (Acquisition, Logistics and Technology) in November 2006. LTG Thompson previously served as the Director, Program Analysis and Evaluation Directorate, HQDA, G-8 from

October 2004 through November 2006. From 2001 to 2004, he served as the Commanding General of the US Army Tank-automotive and Armaments Command. Prior to his current assignment, he held a wide variety of command and staff assignments, including three years as the Military Deputy Director, Program Analysis and Evaluation Directorate, HQDA, G-8.

Thompson is a distinguished military graduate of the College of William and Mary. Initially assigned to the 82nd Airborne Division, he served as a Platoon Leader, Company Executive Officer and Company Commander from 1975 to 1979. After receiving a Master's degree in operations research from George Washington University, he attended the Ordnance Officer Advanced Course. From 1980 to 1983, he served in Germany in the 4th Brigade, 4th Infantry Division (Mechanized), as a Company Commander, assistant brigade S-3, and brigade S-4.

Thompson's staff assignments include tours as Operations Research Analyst in the Military Personnel Center and Strategic Defense Command from 1983 to 1986. After graduating from the College of Naval Command and Staff in 1987 with a Master's degree in national security and strategic studies, he was assigned to Korea as the Executive Officer of the 194th Maintenance Battalion. LTG Thompson then served on the Armor Anti-armor Task Force in the Office of the Chief of Staff; as the Materiel Development Team Chief in the Armored Systems Modernization Coordination Office, Office of the Deputy Chief of Staff for Operations and Plans; and as the coordinator for the Chief of Staff's weekly Requirements Review Council.

From 1991 to 1993, Thompson commanded the 27th Main Support Battalion, 1st Cavalry Division. He graduated from the Industrial College of the Armed Forces in 1994. For the next two years, he was the special assistant to the Commanding General, Army Materiel Command. From July 1996 to July 1998, he commanded the 45th Corps Support Group (Forward), Schofield Barracks, Hawaii.

LTG Thompson's awards and decorations include the Army Distinguished Service Medal, Legion of Merit with third oak leaf cluster, Meritorious Service Medal with fourth oak leaf cluster, Army Commendation Medal, Army Achievement Medal, Department of the Army Staff Identification Badge, senior parachutist badge, and ranger tab.

Dr. Nancy Spruill is a native of Takoma Park, MD. After receiving Bachelor of Science Degree in Mathematics from University of Maryland in 1971, she joined the Center for Naval Analyses (CNA). From 1971 to 1983, she held a variety of positions on the CNA staff, including Technical Staff Analyst, Professional Staff Analyst and Project Director. In 1975, she earned her Master of Arts in Mathematical Statistics from George Washington University followed by her Doctorate in 1980.

Spruill served on the staff of the Office of the Secretary of Defense from 1983 to 1993. Initially, she was the Senior Planning, Programming, and Budget Analyst in the Manpower, Reserve Affairs and Logistics Secretariat. Later, she served as the Director for Support and Liaison for the Assistant Secretary of Defense for Force Management and Personnel. Then, she served as the Senior Operations Research Analyst in the Office of the Assistant Secretary of Defense for Program Analysis and Evaluation.

In 1993, she joined the staff of the Defense Mapping Agency (DMA), serving as the Chief of Programs and Analysis Division for the DMA Comptroller. Subsequently, she served as Acting Deputy Comptroller and was a member of the Reinvention Task Force for the Vice President's National Performance Review.

In March 1995, she was selected as the Deputy Director for Acquisition Resources for the Under Secretary of Defense for Acquisition and Technology. In February 1999, she was appointed Director, Acquisition Resources & Analysis (ARA) for Under Secretary of Defense for Acquisition, Technology and Logistics (USD (AT&L)). In this capacity, she is responsible for all aspects of AT&L'S participation in the Planning, Programming and Budgeting System (PPBS), the Congressional process, and the Defense Acquisition System. She serves as the Executive Secretary to the Defense Acquisition Board and is responsible for the timely and accurate submission to Congress of Selected Acquisition Reports and Unit Cost Reports for Major Defense

Acquisition Programs. She manages the Defense Acquisition Execution Summary monthly review of programs, monitors cost and schedule status of high-interest programs, and conducts analyses of contract and program cost performance—including analysis of the effective use of Integrated Program Management principles through the use of Earned Value Management. Spruill performs systemic analysis to improve acquisition policy and education, and conducts special analyses for the Under Secretary. She leads the Department in developing plans to manage Property, Plant and Equipment, Inventory, Operating Materials and Supplies/Deferred Maintenance and Environmental Liabilities. She proposes modifications to, or acquisition of, new DoD feeder systems, in support of achieving an unqualified audit opinion on DoD Financial Statements as mandated by the Chief Financial Officers (CFO) Act. She also manages the studies program for OSD, oversees USD (AT&L)'s office automation system and manages its information system network, and conducts special analyses for the Under Secretary.

Spruill has been a member of the Senior Executive Service since 1995. She is a certified Acquisition Professional and an active member of the American Statistical Association. Her many honors and awards include the Department of Defense Medal for Distinguished Civilian Service, the Secretary of Defense Medal for Exceptional Civilian Service, the Secretary of Defense Medal for Meritorious Civilian Service, the Hammer Award, the Acker Skill in Communications Award and the Presidential Rank Award. She has contributed papers in publications of the statistics and defense analyses communities and authored articles in the general press on how politicians use—and abuse—statistics.

Susan L. Coté is Vice President of Corporate Contracts, Pricing and Supply Chain at Northrop Grumman Corporation. In this role, she is responsible for corporate business management functions including contracts, pricing, supply chain and government financial relations. Coté is responsible for maintaining an effective risk-review process, providing corporate-wide policy, direction, training and oversight of contracts and pricing matters and ensuring that all Northrop Grumman sectors meet acceptable performance standards in these areas. She serves as the principal interface with the Defense Corporate Executive regarding all governmental accounting, contract and pricing matters, government procurement policy and oversight. She also leads the corporate government financial relations function.

She develops and implements company-wide supply chain strategies and key processes. She is also responsible for enterprise socio-economic business planning, strategy and compliance relative to the organization's supply chain. She chairs the Supply Chain Leadership Council, which serves as the principal governance body for the supply chain function, comprised of sector supply chain vice presidents.

Previously, Coté was Vice President of Corporate Contracts and Pricing. Prior to that appointment, she was Sector Vice President of Contracts, Pricing and Programs Business Management at the Space Technology sector. She has worked on NASA, US Air Force, commercial and classified programs.

Prior to joining Northrop Grumman, Coté held various contracting positions within the United States Air Force. She served at HQ Space Division (Los Angeles AFB), HQ Air Force Systems Command (Andrews AFB), and HQ USAF (Pentagon). She entered government service through the Presidential Management Intern Program.

A graduate of Principia College, Illinois, Coté earned a Bachelor's degree in political science and a Master's degree in Public Administration from the University of Arizona. Coté is an active member of the National Contract Management Association and currently serves on its board of advisors. She also serves on the Defense Acquisition University board of visitors.

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Wednesday, May 13, 2009 11:15 a.m. – 12:45 p.m.	Panel 2 - Advances in Resource Decision-making
	Chair: Joseph L. Yakovac, Jr., LTG, USA, (Ret.), Naval Postgraduate School; former Military Deputy to the Assistant Secretary of the Army (Acquisition, Logistics & Technology) **Discussant: Paul L. Francis**, Managing Director, Acquisition and Sourcing Management, Government Accountability Office ***The Economic Evaluation of Alternatives (EEoA): Rethinking the application of Cost-effectiveness Analysis, Multi-criteria Decision-making (MCDM) and the Analysis of Alternatives (AoA) in Defense Procurement*** **Francois Melese**, Naval Postgraduate School ***Programmatic Complexity & Interdependence: New Predictive Indicators of Development Resource Demand*** **Robert Flowe**, Software Engineering and Systems Assurance, Office of the Deputy Under Secretary of Defense (Acquisition & Technology)

Chair: Joseph Yakovac spent the last 16 years of his active duty military career in the Army Acquisition Corps. His last assignment was as the "Military Deputy to the Assistant Secretary of the Army for Acquisition, Logistics, and Technology" in the grade of Lieutenant General.

Discussant: Paul Francis serves as the Managing Director, Acquisition and Sourcing Management, US Government Accountability Office. He has a Bachelor's degree in Accounting from the University of Scranton, a Master's degree in Public Administration from George Washington University and was a Senior Executive Fellow at the Kennedy School of Government. Francis has been with the GAO for over 32 years, with most of his work experience being in the area of major weapon acquisitions. He has been a member of the Senior Executive Service since 2002. He has conducted or been involved with reviews of many individual weapon programs, including Army helicopters, Future Combat Systems, unmanned aerial vehicles, tactical communications, shipbuilding programs, and missile defense. He has also conducted or been involved with cross-cutting reviews, several of which involved benchmarking with leading commercial firms and successful Department of Defense programs. These included acquisition culture, transition to production, technology maturation, requirements setting, supplier relationships, integrated product teams, requirements setting, training, test and evaluation, earned value management, milestone authorization, and affordability. He has also done work in the areas of wartime medical requirements and detection of landmines and unexploded ordnance. He has testified before congressional committees numerous times. Francis also spent one year with the House Science and Technology Committee early in his career.

The Economic Evaluation of Alternatives (EEoA): Rethinking the Application of Cost-effectiveness Analysis, Multi-criteria Decision-making (MCDM) and the Analysis of Alternatives (AoA) in Defense Procurement

Presenter: Dr. Francois Melese joined the Naval Postgraduate School in 1987 and today is Professor of Economics at the Defense Resources Management Institute (DRMI). He has consulted extensively, most recently with the Joint Staff and the OSD. In 2008, he helped edit the DoD's first *Strategic Management Plan*. He has published extensively on a variety of topics, including a co-authored paper entitled "A New Management Model for Government." Results in implementing that model for the Joint Staff were recently published in the *Armed Forces Comptroller*. At the request of NATO HQ, Melese has represented the US as an expert in defense management and public budgeting throughout Europe. He recently organized a major NATO meeting in Monterey on "Building Integrity and Defense Institution Building."

Abstract

Our primary goal is to improve public investment decisions by providing defense analysts and acquisition officials a comprehensive set of approaches to structure an "Economic Evaluation of Alternatives" (EEoA). This study identifies a significant weakness in the Multi-criteria Decision-making (MCDM) approach that currently underpins many contemporary AoAs. While MCDM techniques, and therefore most AoAs, correctly focus on lifecycle costs and operational effectiveness of alternatives, "Affordability" is often only implicitly addressed in the final stages of the analysis. In contrast, the adoption of EEoA encourages decision-makers to include affordability explicitly and up-front in the AoA. This requires working with vendors to build alternatives based on different funding (budget/affordability) scenarios. The key difference between the traditional MCDM approach to AoAs and the EEoA approach is that instead of modeling alternatives from competing vendors as points in cost-effectiveness space, EEoA models alternatives as functions of *optimistic*, *pessimistic*, and *most likely* funding (budget) scenarios. The Decision Map offered to practitioners to structure EEoAs provides a unique opportunity to achieve a significant defense acquisition reform—to coordinate the requirements generation system (JCIDS), Defense Acquisition System (DAS), and PPBE process, to lower the costs of defense investments, and improve performance and schedules.

Introduction to the Problem: Making the Case for "Affordability"

Our nation's security, billions of taxpayer dollars, and the survival of our soldiers can all hinge on an Analysis of Alternatives (AoA).[1] Routinely conducted by the US Department of Defense (DoD), the AoA is a key component of the defense acquisition process. Investment decisions supported by AoAs help shape future forces, influence defense spending, and occasionally transform the defense industry.

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[1] This study often uses the term "Analysis of Alternatives" (AoA) in its broad, generic sense. Although focused on defense acquisition, the results of the study apply to any public-sector procurement. It should be clear in context when the term AoAs references major defense acquisition programs (MDAPs) as opposed to the acquisition of major automated information systems (MAISs).

This study points to a significant weakness in the Multiple-criteria Decision-making (MCDM) approach that underpins many contemporary AoAs. The weakness is that while MCDM techniques, and therefore most AoAs, correctly focus on lifecycle costs and the operational effectiveness of individual alternatives, “Affordability” is an after-thought, often only implicitly addressed through a weight assigned to costs.

In contrast, the approach recommended in this study encourages analysts and decision-makers to include affordability explicitly in the AoA. This requires working with vendors to build alternatives based on different funding (budget/affordability) scenarios. Supported by a static, deterministic, multi-stage, constrained, optimization micro-economic production (procurement auction) model described in Section 3 (with the math relegated to the Mathematical Appendix available upon request), this “Economic Evaluation of Alternatives” (EEoA) explicitly addresses affordability up-front. The key difference between the MCDM approach to AoAs and the EEoA approach is that, instead of modeling decision alternatives from competing vendors as points in cost-effectiveness space, EEoA models alternatives as functions of *optimistic*, *pessimistic*, and *most likely* funding (resource/budget) scenarios. Given the current financial crisis and future public-spending challenges, affordability is a growing concern. As a consequence, it is imperative that the DoD gets the best value for every dollar it invests in major defense acquisition programs (MDAPs) or major automated information systems (MAISs).

A brief review of the DoD’s high-level, fiscally constrained budget development and acquisition systems highlights the key role that affordability needs to play up-front in any AoA. The Planning, Programming, Budgeting and Execution (PPBE) process is the principal decision support system used by the DoD to provide the best possible mix of forces, equipment, and support within fiscal constraints. Two other major decision support systems complement the PPBE process: a requirements generation system called the Joint Capabilities Integration and Development System (JCIDS) and the Defense Acquisition System (DAS).

Based on strategic-level guidance (the *National Security Strategy*, *National Military Strategy, Quadrennial Defense Review, Strategic Planning Guidance*, etc.), the requirements generation system reviews existing and proposed capabilities and identifies critical capability gaps. To fill those capability gaps, senior leadership examines the full range of “doctrine, organization, training, materiel, leadership and education, personnel and facilities” (DOTMLPF) (CJCS, 2007, p. A-1; USD (AT&L), 2008, p. 14).

Whenever a “materiel” solution is recommended, prospective military investments are identified that serve as the basis for AoAs that underpin the development of new acquisition programs in the Defense Acquisition System (DAS). The DAS provides principles and policies that govern major defense acquisition decisions and milestones. To ensure transparency and accountability, and to promote efficiency and effectiveness, various instructions (e.g., *FAR*, *DFARS, DoD Directive 5000.01, DoD Instruction 5000.02*, etc.) specify statutory and regulatory reports (e.g., AoAs) and other information requirements for each milestone and decision point.

The primary purpose of PPBE is to make hard choices among alternative military investments necessary for national security within fiscal constraints. As we identify alternative materiel investments that can fill current capability gaps, the requirements generation process (JCIDS) naturally fits into the Planning phase of PPBE.

The first step in any investment analysis is to identify the derived demand for a key capability, program, or project. This is accomplished through the DoD's requirements generation system (JCIDS). Ideally, user demands are expressed and refined in the Planning phase of the PPBE process. MDAP and MAIS proposals that emerge from JCIDS and the Planning process enter the Defense Acquisition System (DAS) and are incorporated in the Programming phase of PPBE.

The Planning phase of PPBE establishes fiscally constrained guidance and priorities for military forces, including readiness, sustainability and modernization. This guidance provides direction for DoD Components (military departments and defense agencies) to develop their individual program proposals or their Program Objective Memorandum (POM) in the Programming phase. The POM details resource-allocation decisions (funding, personnel, etc.) proposed by each Component for its programs, projected six years into the future. DAS data for major defense acquisitions generally includes lifecycle cost estimates that project well beyond the six years of the POM.

Senior leadership in the OSD and the Joint Staff subsequently review each Component POM to ensure it satisfies the Planning guidance, and that it can be integrated into effective and affordable overall defense programs. The Budgeting phase of PPBE occurs concurrently with the Programming phase.

The Budgeting phase converts the Programming phase's (output-oriented) view into the (input-oriented) format required by Congressional appropriation structures. While the DoD's biennial defense budget projects funding only two years into the future, it includes more financial detail than the POMs. The Under Secretary of Defense Comptroller and the Office of Management and Budget (OMB) are responsible for reviewing budget submissions to ensure programs are affordable, i.e., satisfy current fiscal constraints. The GAO recognizes the major challenges faced by the DoD to "achieve a balanced mix of weapon systems that are affordable" (GAO, 2009, p. 5).[2]

The primary focus of Multi-criteria Decision-making (MCDM), as traditionally applied in AoAs, is to evaluate the lifecycle costs and operational effectiveness of alternative defense investments. "An AoA is an analytical comparison of the operational effectiveness, suitability, and Life-Cycle Cost of alternatives that satisfy established Capability needs" (DoD, 2006, July 7, Section 3.3). This study emphasizes another key aspect—"Affordability."

In helping generate investment alternatives, and illuminating advantages and disadvantages of those alternatives, AoAs have the potential to contribute to requirements generation in the Planning phase of PPBE, and through DAS decision milestones, also in the Programming phase of PPBE. However, according to the GAO: "while JCIDS provides a framework for reviewing and validating needs […] the vast majority of capability proposals that enter the JCIDS process are validated or approved without accounting for resources

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[2] According to the Government Accountability Office (GAO), over the next 5 years, the DoD plans to spend more than $357 billion on development and procurement of major defense acquisition programs (GAO, 2009, p. 4).

[funding, budgets] […] that will be needed to acquire the desired capabilities" (GAO, 2009, p. 6).[3]

We believe the GAO's results reflect a weakness in the way AoAs have traditionally been structured. While AoAs provide a sharp focus on cost and effectiveness estimates of competing alternatives, the affordability (funding/budget realities) of the overall program is at best implicit, and usually conducted ex-post.[4] This is reflected in the GAO's concern that "at the program level, the key cause of poor outcomes is the approval of programs with business cases [e.g., AoAs] that contain inadequate knowledge about […] resources [funding] […] needed to execute them" (2009, p. 7).

Yet *DoD Directive 5000.01* explicitly states that, "All participants in the acquisition system shall recognize the reality of fiscal constraints […]. DoD components shall plan […] based on realistic projections of the dollars […] likely to be available […and] the user shall address affordability in establishing capability needs" (USD (AT&L), 2007, Enclosure 1, p. 5).

For all major (ACAT 1) defense acquisition programs, an AoA is required at key milestone decision points (i.e., A, B, C). Affordability assessments are required at Milestones B and C for major defense acquisition programs and automated information systems (USD (AT&L), 2008, Enclosure 4, p. 40).

According to the *Defense Acquisition Guidebook*, the purpose of an affordability assessment is to demonstrate that the program's projected funding requirements are realistic and achievable.[5] "In general, the assessment should address program funding over the six-year programming period, and several years beyond. The assessment should also show how the projected funding fits within the overall DoD Component plan" (DoD, 2006, July 7, Section 3.2.2.).[6]

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[3] "A 2008 DoD directive established nine joint capability-area portfolios, each managed by civilian and military co-leads […]. However, without […] control over resources [funding/budgets], the department is at risk […] of not knowing if its systems are being developed within available resources [funding/budgets]" (GAO, 2009, p. 11).

[4] "Typically, the last analytical section of the AoA plan deals with the planned approach for the cost-effectiveness comparisons of the study alternatives" (DoD, 2006, July 7, Section 3.3). Note that there is no mention of "affordability," but instead only an ex-post cost-effectiveness trade-off that implies a concern for affordability. Moreover, this trade-off occurs at the end of a process in which alternatives under consideration have been developed independently of any cost/budget/funding/affordability constraint. The US Marine Corps (PA&E) has a similar approach to structuring an AoA.

[5] Since this assessment requires a DoD Component corporate perspective, the affordability assessment should not be prepared by the program manager nor should it rely too heavily on the user. It requires a higher-level perspective capable of balancing budget trade-offs (affordability) across a set of users (2006, July 7, Section 3.2.2).

[6] A first step in the program's affordability assessment is to portray the projected annual modernization funding (RDT&E plus procurement, measured as TOA) in constant dollars for the six-year programming period and for twelve years beyond. Similar funding streams for other acquisition programs in the same mission area also would be included. What remains to be determined is whether this projected funding growth is realistically affordable relative to the DoD Component's most likely overall funding. The model in this study proposes structuring the Economic Evaluation of Alternatives not only for a *most likely* budget but also for an *optimistic* and *pessimistic* budget.

The Economic Evaluation of Alternatives (EEoA) essentially embeds an explicit affordability assessment into an AoA. In preparing affordability assessments, one possible source of data is the Future Years Defense Program (FYDP).[7] According to the *Defense Acquisition Guidebook*, affordability assessments should provide details as to how excess funding demands will be accommodated by reductions in other mission areas, or in other accounts.[8] This Opportunity Cost Approach is the last of six ways proposed in this study to structure an Economic Evaluation of Alternatives (EEoA).

Nesting the Requirements Generation and Defense Acquisition Systems within PPBE suggests formulating the military's acquisition problem in terms of identifying and funding specific defense investments that maximize value (performance or effectiveness) for a given budget. If AoAs were framed as a constrained optimization—i.e., maximizing performance subject to a budget constraint (or alternatively minimizing costs subject to a given level of performance)—they could be used to support resource-allocation decisions in the Programming phase of PPBE.[9] These dual constrained-optimization approaches represent the first two of six ways proposed in this study to structure an Economic Evaluation of Alternatives (EEoA).

Unfortunately, MCDM techniques typically applied to structure an AoA do not easily lend themselves to this interpretation. As a consequence, instead of being constrained by budgets, budgets are more often the output of an AoA, generating and/or supporting so-called "funding requirements." Our third approach to structuring an Economic Evaluation of Alternatives (EEoA) turns this on its head.

Instead of generating a budget through the AoA process, we propose that decision-makers or analysts forecast an *optimistic*, *pessimistic*, and *most likely* budget as part of the PPBE process, and then approach vendors to generate alternatives that fit within that budget envelope.[10] This offers an alternate approach to defense investment decisions based on explicit funding (resource/budget/affordability) scenarios. This also supports the "long-

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[7] An output of the DoD's PPBE process, the FYDP is an OSD database that contains future budget projections.

[8] Note that in the "off-year" of the biennial PPBE process, DoD Components are restricted to the second year of the biennial budget and are required to submit Program Change Proposals (PCPs) and/or Budget Change Proposals (BCPs) to account for any program-cost increases, schedule delays, etc. PCPs address issues over a multi-year period, whereas BCPs address issues focused on the upcoming budget year. Moreover, to stay within fiscal constraints, BCPs and PCPs must identify resource reductions in other programs to offset any cost growth. This is similar in spirit to the "opportunity cost" approach that we propose as one of six ways to structure an EEoA.

[9] Translating the budget implications of these decisions into the usual Congressional appropriation categories (Military Personnel, Procurement, Operations & Maintenance (O&M), Military Construction, etc.) generates the defense budget and Future Year Defense Program (FYDP).

[10] This is in the spirit of the Department of the Army's Acquisition Procedures, which explicitly state that "Cost as an Independent Variable (CAIV) applies to all defense acquisition programs [….and] treats cost as an input to, rather than an output of, the materiel requirements and acquisition processes." The Army guidance emphasizes "CAIV is focused on […] meeting operational requirements with a solution that is affordable […and that does] not exceed cost constraints [and to] establish CAIV-based cost objectives (development, procurement, and sustainment costs) early in the acquisition process." Moreover, the "RFP must […] solicit from potential suppliers an approach […] for meeting CAIV objectives" (DoA, 1999, July 15, p. 63).

standing DoD policy to seek full funding of acquisition programs, based on the most likely cost" (DoD, 2006, July 7, Chapter 3.23).

The primary goal of this study is to improve defense decisions by bringing the taxpayer up-front alongside the warfighter in the defense acquisition process. This is accomplished by explicitly introducing an affordability assessment in EEoA through *optimistic*, *pessimistic*, and *most likely* funding scenarios. Unlike traditional MCDM approaches to AoAs that focus on cost and operational effectiveness, an EEoA adds a third dimension. It makes a clear distinction between the "lifecycle cost" or "price" of an alternative, its operational effectiveness, and "funding" (budget or resources) available.

The EEoA approach responds to two fundamental challenges highlighted by the GAO that continue to face the DoD's Defense Acquisition System: "(1) [to make] better decisions about which programs should be pursued or not pursued given existing and expected funding; [and] (2) [to develop] an analytical approach to better prioritize capability needs" (GAO, 2009, March 18, Highlights).

In stressing affordability, EEoA offers an analytical approach that begins to resolve a major concern expressed by the GAO:

> DoD's processes for identifying war-fighter needs [JCIDS], allocating resources [PPBE], and developing and procuring weapon systems [DAS…] are fragmented […so that] DoD commits to more programs than resources [budgets] can support […]. DoD allows programs to begin development without a full understanding [of] the resources [budget/funding] needed.[11] (2009, March 18, Highlights)

Whereas funding decisions for major programs take place through the PPBE process, the GAO finds that:

> [T]he process does not produce an accurate picture of the department's resource needs [funding/budget requirements] for weapon system programs [...]. Ultimately, the process produces more demand for new weapon system programs than available resources can support.[12] (2009, March 18, p. 6)

The EEoA approach proposed in this study represents an important step in integrating the DoD's requirements generation and Defense Acquisition Systems with PPBE. For instance, in considering alternative budget scenarios that rely on the FYDP, it injects an explicit constrained-optimization approach into the Defense Acquisition System (DAS) that parallels the one already embedded in the PPBE process.[13]

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[11] "The lack of early systems engineering, acceptance of unreliable cost estimates based on overly optimistic assumptions, failure to commit full funding, and the addition of new requirements well into the acquisition cycle all contribute to poor outcomes" (GAO, 2009, March 18). Whereas this study focuses on funding risks, Melese, Franck, Angelis and Dillard (2007, January) introduce an economic approach called "Transaction Cost Analysis" that addresses the other GAO concerns.

[12] The cost of many programs reviewed by the GAO exceeded planned funding/budget levels (GAO, 2008, July 2).

[13] Office of Management and Budget (OMB) Circular A-11 titled Preparation and Submission of Budget Estimates is the official guidance on the preparation and submission of budget estimates to Congress. The Army's Acquisition guidance emphasizes "the requirement for presenting the full funding for an acquisition program—that is the total cost [for] a given system as reflected in the most recent FYDP […] pertains to all acquisition programs" (DoA, 1999, July 15, p. 41).

In generating alternatives under *optimistic*, *pessimistic* and *most likely* budget scenarios, the EEoA requires explicit interaction with the PPBE process. In sharp contrast with the MCDM approach that underlies most AoAs, the EEoA approaches explicitly identify and emphasize budgets, funding, and affordability. Ultimately, widespread adoption of the EEoA would contribute to the goal of:

> greater consultation between requirements, budget, and acquisition processes [that] could help improve the department's […] portfolio of weapon programs […]. This means that decision makers responsible for weapon system requirements, funding, and acquisition execution must establish an investment strategy in concert […], assuring requirements for specific weapon systems are clearly defined and achievable given available resources [funding/budgets]. (GAO, 2008, July 2, p.10, 14)

The next section offers a brief description and critical evaluation of the status quo. We review two common decision criteria used in cost-effectiveness analyses. The first is the popular "bang-for-the-buck" or Benefit/Cost ratio. The second criterion is essentially a weighted average of cost and effectiveness, a decision rule generated by the standard static, deterministic MCDM approach to cost-effectiveness analysis that underpins most contemporary AoAs.

Section 3 offers a set of alternate approaches to resolve the decision-criterion problem. Six intuitive approaches are described to structure an Economic Evaluation of Alternatives (EEoA).[14] Section 4 concludes with a Decision Map to guide analysts and decision-makers in selecting which of the six approaches is best suited for them to structure an Economic Evaluation of Alternatives (EEoA).

A Critical Evaluation of the Status Quo: Two Popular Decision Criteria

Today, most modern military investment (and disinvestment) decisions are supported by some form of cost-benefit analysis (CBA). The US Department of Defense (DoD) applies CBA to anything from milestone decisions for Major Defense Acquisition Programs (MDAPs and MAISs), to outsourcing (OMB Circular A-76; Eger & Wilsker, 2007), to public-private partnerships, to privatization, to Base Realignment and Closure (BRAC) actions (see OMB Circular A-94; FAR; DFARS; DoD 5000 series, etc.).

When benefits cannot be expressed in monetary terms, analysts develop so-called "measures of effectiveness" (MOEs), in which case CBA is generally referred to as "cost-effectiveness" analysis (OMB, 1992, October 29).[15] The most common methodology and

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[14] Appendix 3 (in the Mathematical Appendix—available upon request) reveals the static, deterministic, multi-stage, constrained-optimization, micro-economic production (procurement auction) model that underpins the central EEoA approach.

[15] Fisher (1965) argues that "numerous terms […] convey the same general meaning […] 'cost-benefit analysis,' 'cost-effectiveness analysis,' 'systems analysis,' 'operations analysis,' etc. Because of such terminological confusion, […] all of these terms are rejected and 'cost-utility analysis' is employed instead" (p. 185). Although this study uses the terms "cost-benefit" and "cost-effectiveness" interchangeably, the assumption throughout is that neither "benefits" nor "effectiveness" can be measured in monetary terms.

approach for building MOEs and structuring cost-effectiveness analyses is alternately referred to as Multiple-criteria Decision-making (MCDM), Multi-attribute Utility Theory (MAUT), or Multiple-objective Decision-making (MODM) (see French, 1986; Keeney & Raiffa, 1976; Clemen, 1996; Kirkwood, 1997; Parnell, 2006; Ramesh & Zionts, 1997; etc.).

This study describes some limitations of the current decision criteria methodology and proposes an alternate methodology derived explicitly from a constrained-optimization approach, closer in spirit to the economic origins of cost-effectiveness analysis in Gorman (1980); Hitch and McKean (1967); Michael and Becker (1973); Stigler (1945); Theil (1952); etc.—although often attributed to Lancaster (1969a; 1969b; 1971; 1979). The six approaches we offer to structure an Economic Evaluation of Alternatives (EEoA) resolves the decision-criterion problem. A key difference between the MCDM approach to an AoA and the Economic Evaluation of Alternatives (EEoA) is that instead of modeling decision alternatives from competing vendors as points in cost-effectiveness space, the EEoA models the alternatives as functions of *optimistic*, *pessimistic*, and *most likely* funding (resource/budget) scenarios.

The EEoA approach directly responds to the GAO's observation that affordability needs to be an integral part of any business case analysis of alternatives: "[o]ur work in [uncovering] best practices has found that an executable business case [requires] demonstrated evidence that […] the chosen concept can be developed and produced within existing resources [funding/budgets]" (GAO, 2008, p. 6). Benchmarking against the private sector, the GAO emphasizes that "successful commercial enterprises […] follow a disciplined integrated process during which the pros and cons of competing proposals are assessed based on strategic objectives […] and available resources [budgets/funding]" (GAO, 2009, March 18, p. 5, emphasis added).

A distinctive feature of defense investment decisions is that multiple criteria such as cost and effectiveness cannot easily be combined into a single, overall objective such as "government profitability." The problem of ranking public investments when benefits cannot be expressed in dollars has spawned an extensive literature in management science, operations research and the decision sciences.

This literature models investment alternatives as bundles of measurable characteristics (attributes or criteria). Techniques that mostly fall under the umbrella of MCDM are routinely used by analysts and decision-makers (for example, through AoAs) to guide public investment decisions. The development of "Measures of Effectiveness" (MOE's)[16] and lifecycle cost calculations are used to help rank alternatives. An ongoing concern is how to integrate costs and effectiveness in the final selection process (see Henry & Hogan, 1993; Melese & Bonsper, 1996, December; Melese, Stroup, & Lowe, 1997; etc.).

In their pioneering work applying economic analysis to defense, Hitch and McKean (1967) define a "criterion" as the "test by which we choose one alternative […] rather than

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[16] The Defense Acquisition Guidebook, Section 3.3.1: AoA Plan, states that "measures of effectiveness […] provide the details that allow the proficiency of each alternative in performing the mission tasks to be quantified […]. A measure of performance typically is a quantitative measure of a system characteristic (e.g., range, […] logistics footprint, etc.) chosen to enable calculation of one or more measures of effectiveness" (DoD, 2006, July 7).

another" (p. 160). They stress that "[t]he choice of an appropriate economic criterion is […] the central problem in designing a [cost-effectiveness] analysis" (p. 160).

The two most popular decision criteria used to integrate cost and effectiveness in AoAs are: 1) to construct Benefit/Cost (or MOE/Cost) ratios, and 2) to assign a weight on cost relative to effectiveness and construct a weighted average of cost and effectiveness (often using a linear, separable, additive "value" function). The latter decision criterion is a common prescription for AoAs that emerges from MCDM. Both approaches, however, are problematic.

We first focus on what is arguably the most commonly applied criterion—Benefit/Cost ratios. Then, we move to the most common MCDM decision criterion—to assign a relative weight to the cost (price) of alternatives in an overall value function. At first glance, the Benefit/Cost (MOE/Cost) ratio or "bang-for-the-buck" criterion is appealing. However, it turns out to be largely meaningless unless alternatives are constructed for a specific budget scenario or to achieve a specific level of effectiveness. Meanwhile, the second decision criterion can also be misleading in the absence of a specific budget scenario (and a good understanding of "opportunity costs").[17]

"Bang-for-the-Buck" (Benefit/Cost or MOE/Cost) Ratios

It is relatively well known that a Benefit/Cost ratio (or "bang-for-the-buck") decision criterion is largely meaningless unless alternatives are constructed for a specific budget scenario or to achieve a specific level of effectiveness. Yet, the next four examples illustrate that this remains a popular decision criterion, even when alternatives differ in both costs and effectiveness.

1. In a military text entitled *Executive Decision Making*, the author offers that "[w]hen we cannot fix cost or effectiveness, we might combine them to help us choose between alternatives […]. If neither can be fixed […] we can establish a cost/effectiveness ratio" (Murray, 2002, pp. 6-3, 6-10).
2. The Department of the Army's *Economic Analysis Manual*, in a section entitled *Comparing Costs and Benefits*, states: "When the results yield unequal cost and unequal benefits […] in this situation all alternatives […] may be ranked in decreasing order of their benefit/cost ratios" (DoA, 2001, February, p. 32).
3. Finally, in a recent landmark RAND study on Capabilities-based Planning, the author falls into the same trap. In a section entitled *Choosing Among Options in a Portfolio*, Paul Davis (2002) develops "A Notional Scorecard for Assessing Alternatives in a Portfolio Framework," where alternatives differ in both their costs and effectiveness. Nevertheless, the decision criterion recommended by the author to select among alternative options in "[t]he last column is the ratio of effectiveness over cost" (pp. 45-46).

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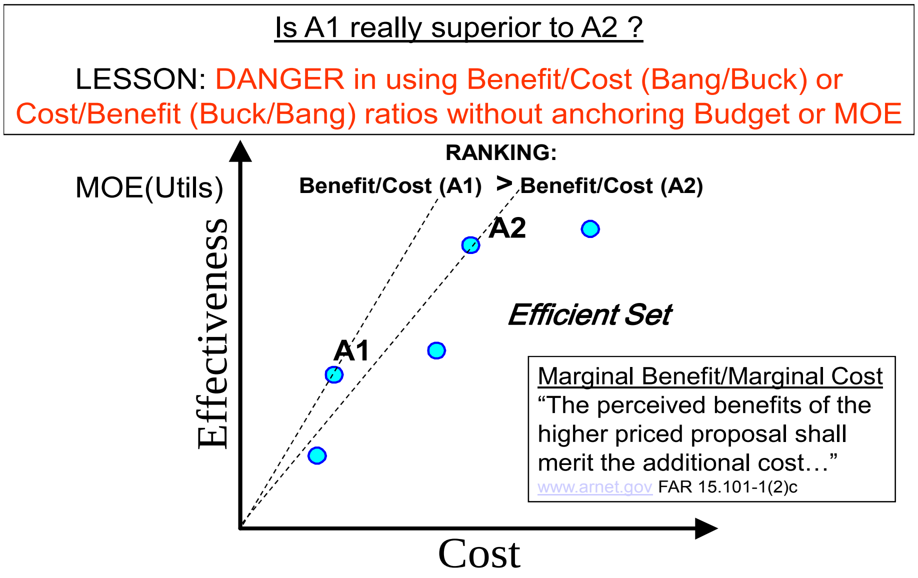
[17] Ironically, given a budget scenario, there is no need to take the MCDM approach that underpins most AoAs since it is possible to adopt the EEoA approach—which constructs alternatives to fit within a budget envelope, converting the problem into a straightforward MOE maximization.

Each of these diverse examples recommends using a Benefit/Cost ratio as the decision criterion. However, another RAND analyst, Gene Fisher (1971), clearly points out in his classic text *Cost Considerations in Systems Analysis*:

> The use of ratios usually poses no problem as long as the analysis is conducted in [a] framework […] with the level of effectiveness or cost fixed. However, it is common to encounter studies where this has not been done, with the result that the comparisons [are] essentially meaningless. (p. 11)



Is A1 really superior to A2 ?

LESSON: DANGER in using Benefit/Cost (Bang/Buck) or Cost/Benefit (Buck/Bang) ratios without anchoring Budget or MOE

Marginal Benefit/Marginal Cost
"The perceived benefits of the higher priced proposal shall merit the additional cost…"
www.arnet.gov FAR 15.101-1(2)c

Figure 1. Inappropriate Application of Benefit/Cost Ratios

A simple, extreme example helps illustrate the danger in using Benefit/Cost ratios without anchoring the Budget, or a specified Measure of Effectiveness (MOE). Suppose Alternative A1 in Figure 1 costs $10 million and yields an MOE of 10 utils, while Alternative A2 costs $1 billion and yields an MOE of 900 utils.[18] Applying the Benefit/Cost ratio criterion indicates that A1 has a bigger "bang-for-the-buck" since it returns 1 util per million dollars, while A2 only offers 0.9 utils per million dollars. Strictly using Benefit/Cost ratios to rank alternatives is dangerous in this case since it ignores the absolute magnitude of the costs involved. Suppose the situation was reversed and A2 offered a higher Benefit/Cost ratio than A1. Anyone that chooses A2 strictly on the basis of "bang-for-the-buck" would be in for an unpleasant surprise (a 1-billion vs. 10-million-dollar decision).

Since affordability and opportunity costs are always a concern in public investment decisions (especially those made through the PPBE process, requirements generation system, and Defense Acquisition System), it is imperative that analysts and decision-makers explore the budget and opportunity cost implications of going with the high-cost alternative

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[18] In Figure 1, the slope of any ray from the origin represents a constant Benefit/Cost ratio anywhere along that ray. The steeper the slope, the greater the Benefit/Cost ratio.

(for example, the extra expenditure of $990 million for an additional 890 utils of MOE) or, equivalently, of the savings in going with the low-cost alternative.

In applying economic analysis to defense, Hitch and McKean (1967) warn:

> One common “compromise criteria” is to pick that [alternative] which has the highest ratio of effectiveness to cost. [M]aximizing this ration is the [decision] criterion. [While] it may be a plausible criterion at first glance […] it allows the absolute magnitude of [effectiveness] or cost to roam at will. In fact, the only way to know what such a ratio really means is to tighten the constraint until either a single budget (or particular degree of effectiveness) is specified. And at that juncture, the ratio reduces itself to the test of maximum effectiveness for a given budget (or a specified effectiveness at minimum cost), and might better have been put that way at the outset […]. The test of maximum effectiveness for a given budget (or alternatively, minimum cost of achieving a specified level of effectiveness) […] seems much less likely to mislead the unwary.[19] (pp. 165-167)

Our Economic Evaluation of Alternatives (EEoA) approach follows this and another of Hitch and McKean’s (1967) recommendations. “As a starter […] several budget sizes can be assumed. If the same [alternative] is preferred for all […] budgets, that system is dominant […]. If the same [alternative] is not dominant the use of several […] budgets is nevertheless an essential step, because it provides vital information to the decision maker” (p. 176).

We conclude that the use of Benefit/Cost ratios as a decision criterion poses no problem as long as the analysis is structured with the level of either utility (MOE) or budget/funding fixed.[20] Since Benefit/Cost ratios are “misleading”[21] in any context in which alternatives differ in both costs (price) and benefits (MOE), decision scientists have developed another decision criterion to rank investment options in AoAs. This second popular decision criterion is examined below.

Weighted Averages of Cost and Effectiveness: Assigning a Weight to Cost

MCDM is often used as an umbrella term, and we will do so here. “In the literature the terms multi-attribute decision making (MADM), multi-criteria decision making (MCDM), and multi-objective decision making (MODM) are used almost interchangeably” (French, 1986, p. 105). In a typical MCDM evaluation, a decision-maker (DM) is asked to identify desired attributes (criteria/characteristics) of a project, program or system to fill some critical capability gap, given a specific threat scenario. Next, the DM is asked to reveal agreeable

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[19] The authors continue: “Of course, if the ratios did not alter with changes in the scale of achievement (or cost, the higher ratio would indicate the preferred system, no matter what the scale […]. But to assume that such ratios are constant is inadmissible some of the time and hazardous the rest” (Hitch & McKean, 1967, p. 167).

[20] An additional (necessary and sufficient) condition is a linear, separable, additive objective function.

[21] “Usually, ratios are regarded as potentially misleading because they mask important information” (DoD, 2006, July 7, Section 3.3.1).

trade-offs among those attributes. An exercise of this sort helps analysts uncover the DM's underlying trade-offs or "utility" function, used to generate a Measure of Effectiveness (MOE) for each alternative.[22]

In attempting to understand a DM's utility function, decision scientists beginning with Saaty (1977) bridged an important implementation gap. Objectives (analytic) hierarchy approaches were developed that help reveal underlying utility functions. For example, an objectives hierarchy can help a DM work down from a high-level objective (provide national security) to a relevant set of sub-objectives (an effective airlift capability), to specific attributes (mobility, transportability, etc.), and, finally, to measurable characteristics (mobility=speed (S), range (R); transportability=payload (P), weight (W), etc.).

The outcome in this example is a utility function for airlift capability: U=U(M(S,R); T(P,W)), where the characteristics might be measured respectively in mph, miles, cubic feet, and pounds. The standard assumption in the literature is to define a linear, separable additive utility function that generates an MOE for each alternative that is roughly analogous to a weighted average of its attributes (provided certain assumptions are satisfied such as "additive independence," etc. (see French, 1986; Keeney & Raiffa, 1976; Keeney, 1994). There is a vast literature concerned with eliciting preference weights and the normalization of characteristics data that involves several important issues discussed in the Mathematical Appendix (available upon request).

Temporarily overlooking these issues, it is interesting to note in passing that maximizing a linear multi-attribute utility function subject to a budget constraint yields a decision rule analogous to the Benefit/Cost ratio criterion discussed above. Under the assumption of a fixed budget and linear additive separable utility function, the Benefit/Cost decision rule can be used to evaluate alternatives. In this case, the winning alternative is the one that generates the highest MOE per dollar or the biggest "bang-for-the-buck." With a more general (non-linear) utility function, the equivalent optimization generates a more complex Marginal Benefit/Marginal Cost decision rule.

In reality, the MCDM techniques that underpin most AoAs often do not rely on an explicit discussion of the budget (affordability/funding/resources) to structure the decision problem. As a consequence, the problem is generally not structured as a constrained optimization, as described above.

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[22] "Measures of Effectiveness […] provide the details that allow the proficiency of each alternative in performing the mission tasks to be quantified […]. A measure of performance typically is a quantitative measure of a system characteristic (e.g., range, etc.) chosen to enable calculation of one or more measures of effectiveness […]. The cost analysis normally is performed in parallel with the operational effectiveness analysis. It is equal in importance in the overall AoA process […]. [I]ts results are later combined with the operational effectiveness analysis to portray cost-effectiveness comparisons" (DoD, 2006, July 7, Section 3.3.1).

Instead, a popular decision-analysis approach is to simply attach a weight to cost and introduce it directly into the utility function.[23] This common practice generates an overall "value" function that is essentially a weighted average of cost and effectiveness. The solution is found through an unconstrained optimization by selecting the alternative that maximizes the "overall effectiveness" or "value" function V=V(MOE; COST). "Deterministic decision analysis is concerned with finding the most preferred alternative in decision space by constructing a value function representing a decision maker's preference structure, and then using the value function to identify the most preferred solution" (Ramesh & Zionts, 1997, p. 421).

The linear, additive separable version of this value function is often used to calculate a positively weighted MOE and negatively weighted cost for each alternative. For example, see Beil & Wein (2003), Che (1993), Clemen (1996), Kirkwood (1997), French (1986), Keeney & Raiffa (1976), Keeney (1994), Hwang and Yoon (1981), Liberatore (1987), Pinker, Samuel, and Batcher (1995), Varzsonyi (1995), etc. According to the *Defense Acquisition Guidebook*: "An AoA is an analytical comparison of the operational effectiveness, suitability, and life-cycle cost of alternatives that satisfy established capability needs." (DoD, 2006, July 7, Chapter 3.3)

The typical decision sciences' approach to an AoA can be described as:

Given several Alternatives, select the preferred alternative that provides the Best Value, or Maximizes: V(MOE,COST) = w1***MOE** - w2***COST**

This requires two important modeling efforts: 1) MOE—*Building an Effectiveness model* (non-cost factors; performance=quality, schedule, etc.); and 2) COST—*Building a Cost* model (costs/prices; estimate total system lifecycle costs, total ownership costs). Once the independent modeling efforts are completed, the overwhelming challenge is to assign a relative weight to cost (w2 in the example above). A typical response in the applied literature is to ask the DM: "How important is cost relative to effectiveness?"

A key proponent of this decision methodology offers an example of administrators and regulators asking questions such as: "Which is more important, costs or pollutant concentrations?" (Keeney, 1994, p. 797). As the author is quick to point out, the problem with this approach is that without some estimate of the *total budget available* or any knowledge of *opportunity costs of funds*, one cannot expect the DM to provide a sensible answer. In fact, the author warns: "I personally do not want some administrator to give two minutes of thought to the matter and state that pollutant concentrations are three times as

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[23] "In the European Union, a legislative package intended to simplify and modernize existing public procurement laws was recently adopted. As before, the new law allows for two different award criteria: lowest cost and best economic value. The new provisions require that the procurement authority publishes ex-ante the relative weighting of each criteria used when best economic value is the basis for the award" (see European Commission, 2004a; 2004b).

important as cost"[24] (Keeney, 1994, p. 797). The *Federal Acquisition Regulations* (*FAR*) and the Office of Management and Budget (OMB) both promote similar approaches:[25]

- "The solicitation shall state whether all evaluation factors other than cost/price, when combined [i.e., MOE], are significantly more important than, approximately equal to, or significantly less important than cost/price" (General Services Administration, 2005, March, Section 15.101-1(2)).
- "The specific weight given to cost or price shall be at least equal to all other evaluation factors combined unless quantifiable performance measures can be used to assess value and can be independently evaluated" (OMB, 2003, p. B-8).

Consider an extreme case. If we suppose that affordability is not an issue, then funding is not an issue and the budget is not binding, making costs irrelevant. In this case, a zero weight should be assigned to costs and the analysis of alternatives can be made exclusively on the basis of MOEs.

Thus, any weight applied to costs must reflect an implicit concern about affordability (budgets/funding levels). Figures 2 and 3 offer an illustration. Figure 2 reflects a situation in which the decision-maker believes costs to be important enough (and thus assigns a sufficiently large relative weight, w2, to cost) that the preferred alternative is A1 (the low-cost option). The opposite case is illustrated in Figure 3.[26] How does a decision-maker (DM) decide on appropriate weights to assign to MOE and costs? A key hypothesis in the EEoA is that if a DM pays any attention to costs (i.e., places any weight on cost) it is because there is a (implicit) budget constraint or opportunity cost of funds for the program. This is directly related to our higher-level affordability discussions in Section 1 that involved requirements generation (JCIDS), the Defense Acquisition System (DAS), and PPBE.[27]

The irony, as Keeney (1994) rightly observed, is that to assign any weight to costs requires the DM to have some understanding of the budget (funding/resources) available and an appreciation of relevant opportunity costs. But if this information is known, then the DM has no reason to take the MCDM approach and assign a weight on costs since the more robust, constrained-optimization (mathematical programming) EEoA approach becomes available.

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[24] Surprisingly, the author has continued to write prolifically in this field and continued to promote this decision criterion, apparently never taking the time to reflect back on these key observations.

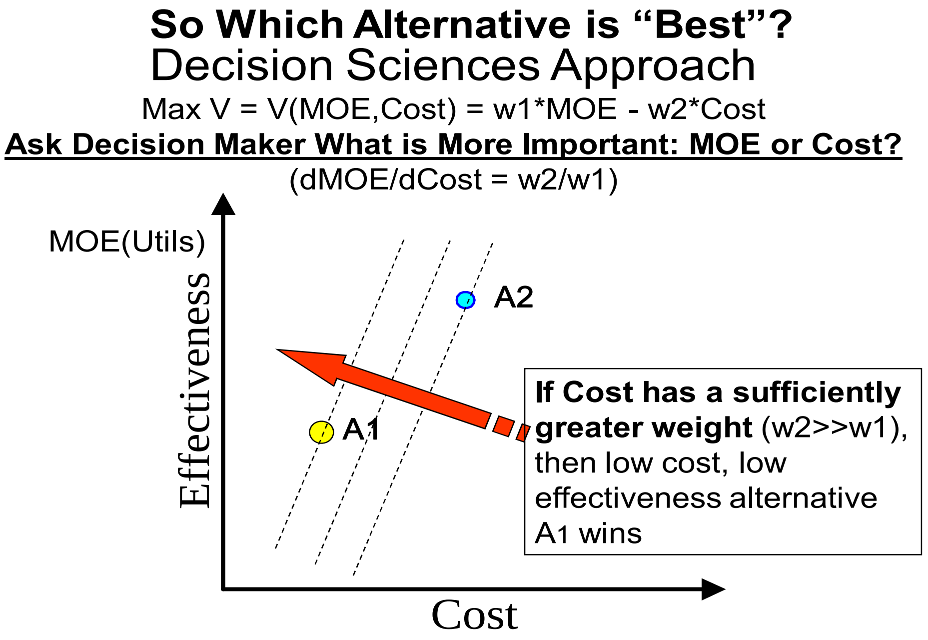
[25] According to the FAR, "source selection" is the decision process used in competitive, negotiated contracting to select the proposal that offers the "Best Value" to the government. "In different types of acquisition, the relative importance of cost or price may vary" (General Services Administration, 2005, Section 15.101). In describing some lessons learned, Gansler (2003) recommend: Use performance-based contracting; Do not list tasks [mix of inputs], instead state results sought or problems to be solved [desired attributes/characteristics of outputs/outcomes]; Choose contractors according to "Best Value"; in the source selection, trade-off performance and price instead of simply awarding to the lowest bidder (p. 15).

[26] Note that the slope of the straight-line indifference curves that reflect the DM's relative preference (or trade-offs) between MOE and Cost are given by –w2/w1.

[27] In fact, the Army's Economic Analysis (EA) Manual states that "[a] good EA should go beyond the decision-making process and become an integral part of developing requirements in the PPBE process" (DoA, 2001, February, p. 12).

In fact, it is relatively straightforward to demonstrate that even if the DM had perfect information about the budget (funding/affordability) and attempted to interpret that information through a weight assigned to the cost (price) of alternatives (as illustrated in Figures 2 and 3), the rankings that result would only coincidentally correspond to rankings obtained under the full information, constrained-optimization EEoA (in which an MOE utility function is maximized subject to the budget constraint).[28]

This is a damning result that clearly undermines the way MCDM is typically applied to support AoAs. If there is no guarantee this MCDM approach will yield consistent results under full information, then using this criterion with less than perfect information (i.e., without explicit assumptions about affordability/budgets/funding), is clearly problematic. In fact GAO emphasizes “[w]ith high levels of uncertainty […] funding needs are often understated” (GAO, 2008, September 25, p. 9).



So Which Alternative is “Best”?

Decision Sciences Approach

Max V = V(MOE,Cost) = w1*MOE - w2*Cost

Ask Decision Maker What is More Important: MOE or Cost?

(dMOE/dCost = w2/w1)

If Cost has a sufficiently greater weight (w2>>w1), then low cost, low effectiveness alternative A1 wins

Figure 2. When Cost is Relatively More Important than Effectiveness

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[28] The weight on cost in the unconstrained-optimization (MCDM) approach roughly corresponds to the Lagrangian multiplier (shadow price) of the budget constraint in the constrained-optimization (the EEoA approach).

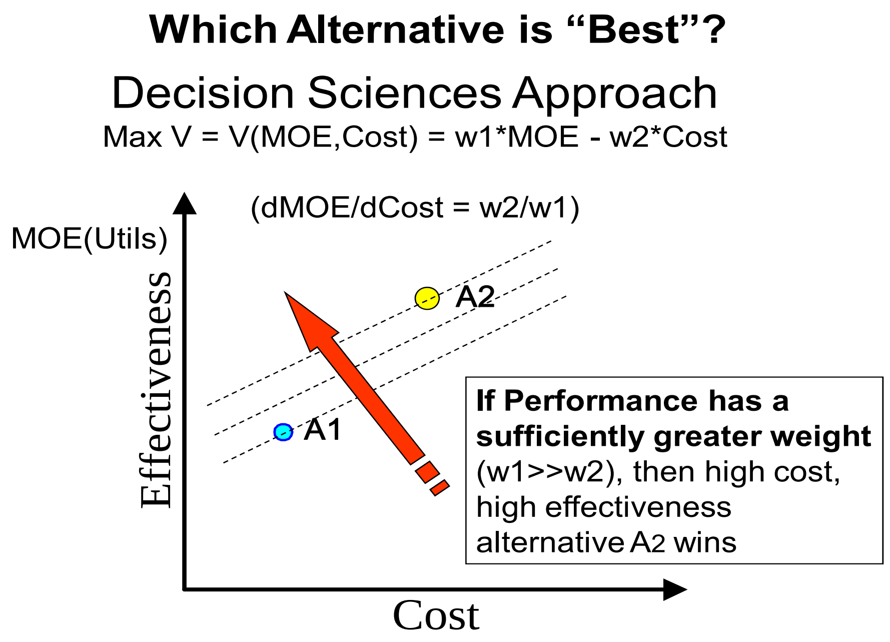

Figure 3. When Effectiveness is Relatively More Important than Cost

In conclusion, the popular MCDM, Decision Sciences approach that underpins many AoAs implicitly attempts to capture affordability through a relative weight assigned to cost in a value function such as, Maximize V = V(MOE,Cost) = w1*MOE - w2*Cost.[29] Again, to quote Hitch and McKean (1967):

> One ubiquitous source of confusion is the attempt to maximize gain [w1*MOE] while minimizing cost [w2*Cost] […] If a person approaches a problem with the intention of using such a [decision] criterion, he is confused to begin with […] [A] criterion in which the budget […] is specified has the virtue of being aboveboard. (pp.165-167)

A very real risk in this MCDM approach is that if AoAs "fail to balance needs with resources [funding/budgets], […] un-executable programs [are allowed] to move forward, [and] program managers […] are handed […] a low probability of success" (GAO, 2009, p. 10). Rather than attempt to get a DM to reveal their affordability concerns through a weight assigned to costs (or prices) of alternatives, the EEoA recommends a more transparent and accountable approach—to treat "cost as an independent variable" (CAIV).

The CAIV concept adopted here follows a definition posted on the OUSD (A&T) website in early 1999 that CAIV is the "DoD's acquisition methodology of making technical and schedule performance a function of available budgeted resources" (see Lorell & Graser,

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[29] In a section describing "Building a Model," Fisher (1965) comments: "Since by definition a model is an abstraction from reality, the model must be built on a set of assumptions. These assumptions must be made explicit. If they are not, this is to be regarded as a defect of the model design" (p. 190). It is easy to conceal the importance of affordability (budget/funding) issues in the MCDM, Decision Sciences approach that underpins many AoAs. In sharp contrast, the Economic Evaluation of Alternatives approach encourages explicit affordability (budget/funding) assumptions.

2001, p. 33). OMB Circular A-109 for Major Systems Acquisition mentions the goal of “design-to-cost”: “Under the CAIV philosophy, performance and schedule are considered dependent on the funds available for a specific program” (OMB, 1976). According to the *Defense Acquisition Guidebook*, “all participants […] are expected to recognize the reality of fiscal constraints” (DoD, 2006, July 7, Section 3.2.4).

Six Ways to Structure an “Economic Evaluation of Alternatives” (EEoA)

We have identified (what we believe are the only) six ways that analysts and decision-makers can structure a deterministic Economic Evaluation of Alternatives (EEoA) that avoid the issues (decision-criteria problems) discussed in the last section. These involve two main categories of approaches: 1) Intra-program analysis and 2) Inter-program analysis. The first, third, and fourth approaches are very much in the spirit of “cost as an independent variable” (CAIV). By recalling the earlier quote from Hitch and McKean (1967), we are reminded of the first two EEoA approaches: “[A] criterion in which the budget or level of effectiveness specified has the virtue of being aboveboard” (p. 167). The six EEoA approaches appear in Table 1.

Table 1. Six Approaches to Structure an EEoA

- I) *INTRA-PROGRAM ANALYSIS*
  - A) *Build Alternatives*
    1. Fixed Budget Approach
    2. Fixed Effectiveness Approach
    3. Expansion Path Approach (Construct alternatives as Cost-output/Effectiveness Relations or “Response Functions”: Multi-stage Micro-economic Production Model)
  - B) *Modify Existing Alternatives: “Level the Playing Field”*
    4. Modified Budget Approach: GOTO 1.
    5. Modified Effectiveness Approach: GOTO 2.
- II) *INTER-PROGRAM ANALYSIS*
    6. Opportunity Cost/Benefit Approach

In the case of Intra-program analysis, the decision-maker (DM) associated with the program is assumed to have sufficient information to be able to select an alternative without reference to competing programs. That is not the case in Inter-program analysis, which requires an explicit “opportunity cost approach.”

There are two possibilities highlighted within the Intra-program analysis approach. The first possibility is when DMs (analysts) are able to construct/define/build alternatives (“endogenous alternatives”). The second possibility is when the alternatives are already constructed/defined/built and must simply be evaluated (“exogenous alternatives”).

This section describes each of the six Economic Evaluation of Alternatives (EEoA) approaches in some detail. The Mathematical Appendix describes the static, deterministic, multi-stage, constrained-optimization, micro-economic production (procurement auction) model that underpins the third, and most general, approach to the EEoA, the Expansion Path Approach. We begin with the Fixed Budget Approach, based on the earlier quote from Hitch and McKean (1967): “The test of *maximum effectiveness for a given budget* seems much less likely to mislead the unwary” (p. 167, emphasis added).

1. Fixed Budget Approach

In his groundbreaking book *Cost Considerations in Systems Analysis*, Fisher (1971) states: “In the fixed budget case, the alternatives being considered are compared on the basis of effectiveness likely to be attainable for the specified budget level” (p. 12). In other words, Fisher also explains that, “The analysis attempts to determine that alternative (or feasible combination […]) which is likely to produce the highest effectiveness” (p. 10).

In a footnote, Fisher (1971) adds: “the fixed budget situation is somewhat analogous to the economic theory of consumer [optimization…]. For a given level of income [budget] the consumer is assumed to behave in such a way that he maximizes his utility” (p. 10). Drawing on this comparison, the Fixed Budget Approach to the EEoA leverages Lancaster’s “characteristics approach to demand theory” (Lancaster, 1969a; 1969b; 1971; 1979). Originating in the works of Gorman (1980), Stigler (1945), Theil (1952), and others (that also provided an early foundation for some of the MCDM literature), Lancaster offers economists (and defense analysts) a familiar way to analyze the consumer (or defense DM’s) choice problem (such as choosing among defense investment alternatives).

In Lancaster’s model, different vendors generate different bundles of characteristics evaluated by decision-makers (“consumers”). Lancaster’s model proposes that to choose among alternative bundles of commodities (say computers), defense decision-makers maximize their utility function, defined over a desired set of criteria, attributes, or characteristics—hence the term adopted by decision scientists, Multiple-criteria Decision-making (MCDM)—subject to a budget [funding/affordability] constraint, which is mostly not adopted by decision scientists.[30] In this approach, the cost-effective alternative is the one that, for a given budget or expenditure, generates the best mix of characteristics, evaluated using the decision-maker’s utility function.

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[30] Note that we refer to the usual deterministic “utility function” that is conventional in the economics literature. This is in contrast to the way a utility function is typically defined in the decision sciences and operations management literature as a stochastic function. The “value function” described in the latter literature is similar to our “utility function,” except that costs can enter into a value function and are excluded from our utility function since they appear as part of the budget constraint.

Cost-Effectiveness EEoA

Build Alternatives

1. Fixed Budget Approach

Maximize Effectiveness subject to Budget Constraint

(construct alternatives for given budget)

Outsourcing Opportunity:
Can we get more bang for the same bucks?

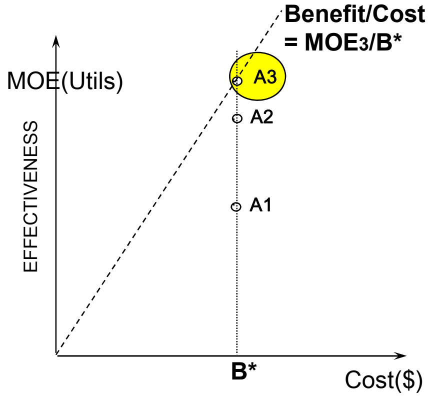

Figure 4. Fixed Budget Approach

This Fixed Budget Approach is the first of six ways proposed to structure an Economic Evaluation of Alternatives (EEoA) and is illustrated in Figure 4.[31] The Budget estimate for the program in Figure 4 is set at level B*. The three alternatives constructed given this budget are A1, A2, and A3. Given its superior performance in terms of its MOE, A3 wins the competition, which, in this case, can also be determined from its Benefit/Cost ratio.

2. Fixed Effectiveness Approach

The second way to structure an EEoA is the dual of the first: minimize the cost of achieving a given MOE. RAND Corporation's AoA for the KC-135 Recapitalization adopts this approach, stating: "in this AoA, *the most 'cost-effective' alternative* [fleet] means precisely *the alternative whose effectiveness meets the aerial refueling requirement at the lowest cost*" (Kennedy et al., 2006, p. 7, emphasis added). Figure 5 offers an illustration.

Another example is the section on cost-effectiveness analysis in *OMB Circular A-94* that states: "A program is cost-effective if, on the basis of life cycle cost analysis of competing alternatives, it is determined to have the lowest costs […] for a given amount of benefits […]. Cost-effectiveness analysis can also be used to compare programs with identical costs [budgets/funding] but differing benefits" (OMB, 1992, October 29, p. 4). The latter part of the quote refers to the first approach to structuring an EEoA, and the former refers to the second approach.

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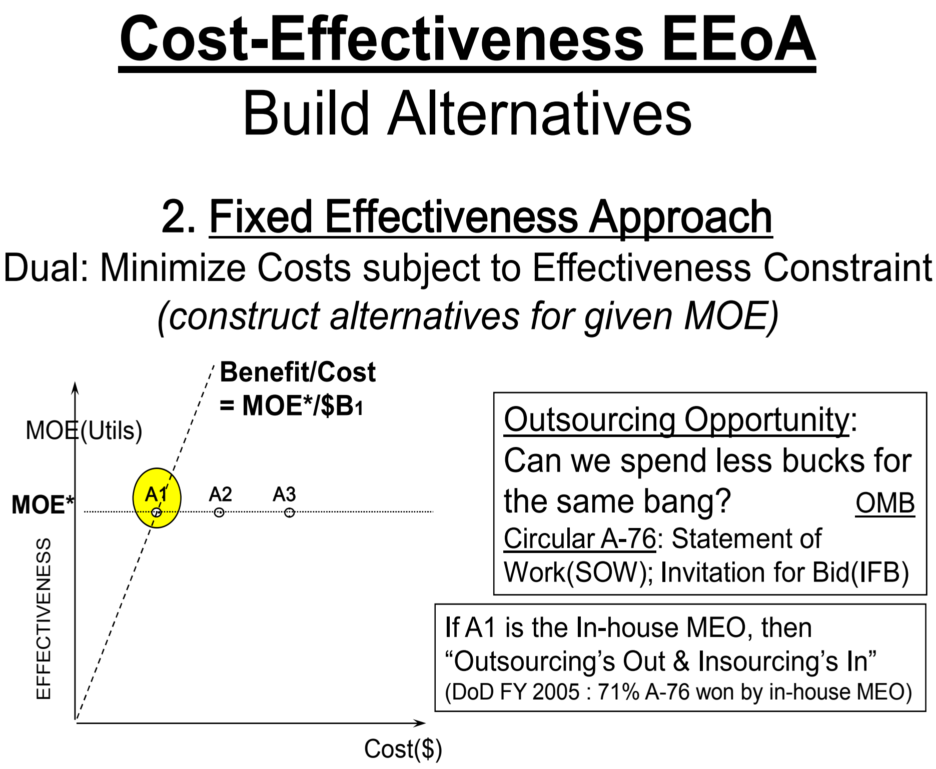
[31] Note that in the first and second EEoA approaches, since either the budget (funding level) or MOE (level of effectiveness) is anchored in the constrained optimization, the Benefit/Cost ratio decision criterion can be used as a decision rule in the selection process. The steeper the slope from the origin through an alternative (A1, A2, A3), the bigger the "bang-for-the-buck."



Cost-Effectiveness EEoA

Build Alternatives

2. Fixed Effectiveness Approach

Dual: Minimize Costs subject to Effectiveness Constraint

(construct alternatives for given MOE)

Outsourcing Opportunity: Can we spend less bucks for the same bang? OMB Circular A-76: Statement of Work(SOW); Invitation for Bid(IFB)

If A1 is the In-house MEO, then "Outsourcing's Out & Insourcing's In" (DoD FY 2005 : 71% A-76 won by in-house MEO)

Figure 5. Fixed Effectiveness Approach

Another example of the Fixed Effectiveness Approach to structuring an EEoA is given by public-private (competitive sourcing) competitions conducted under *OMB Circular A-76*, which "requires […] a structured process for [evaluating] the most efficient and cost-effective method of performance for commercial activities" (2003, May 29). This involves four steps: 1) develop a Statement of Work (SOW) or Performance Work Statement (PWS) to define desired performance/effectiveness, 2) construct the Most Efficient Organization (MEO) for the in-house competitor, 3) issue an Invitation for Bid (IFB) for well-defined, routine commercial activities (SOW or PWS), and 4) compare bids or proposals (source selection) and select the "least cost" for IFB.

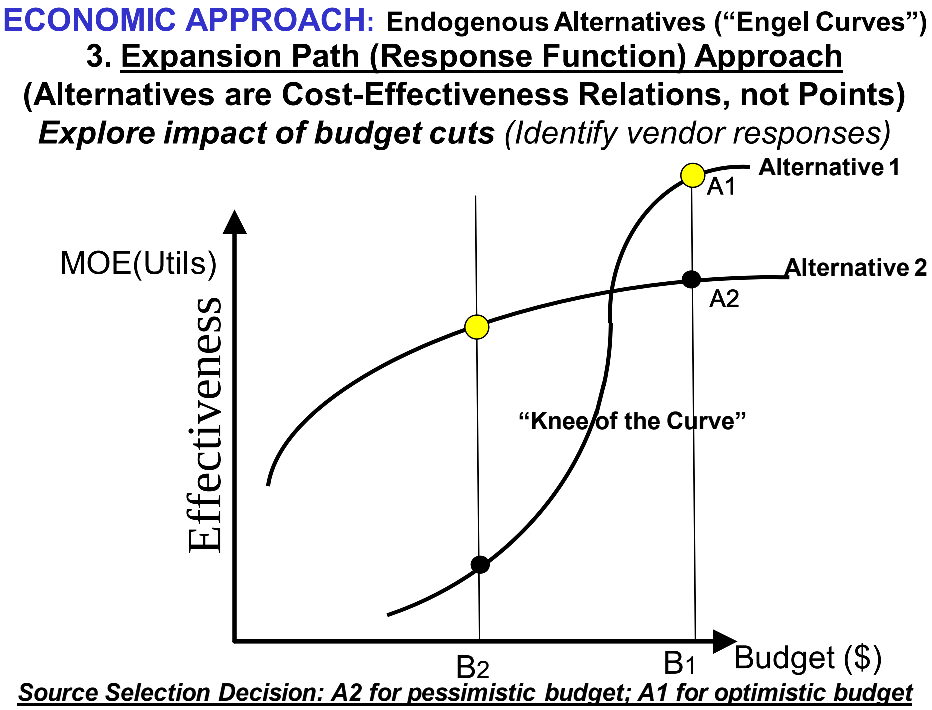
Finally, Title 10, Subtitle A, Part IV, Chapter 146, Section 2462 of the US Code reads: "A function of the Department of Defense […] may not be converted […] to performance by a contractor unless the conversion is based on the results of a public-private competition that […] examines the cost of performance of the function by Department of Defense civilian employees and the cost of performance of the function by one or more contractors to demonstrate whether converting to performance by a contractor will result in savings to the Government over the life of the contract" (2007, January 3). This offers another example of the Fixed Effectiveness Approach to structuring an EEoA.

3. Expansion Path (Response Function) Approach

Hitch and McKean (1967) strongly hint at the third way to structure an EEoA: "The test of *maximum effectiveness for a given budget* seems much less likely to mislead the unwary" (p. 167). They explain, "As a starter, […] *several budget sizes can be assumed*. If the same [alternative] is preferred for all […] budgets, that system is dominant. If the same [alternative] is not dominant, the use of several […] budgets is nevertheless an essential step, because it provides vital information to the decision maker" (p.176, emphasis added).

This third way to structure an EEoA is the foundation for all the others and is described mathematically in the Mathematical Appendix (available upon request). It is modeled as a three-step process that involves multiple players.

For ease of exposition, we assume three players: the military buyer and two private vendors. The first step is for the military buyer to publish a synopsis of the solicitation. This synopsis (solicitation) states all significant non-price factors (criteria/attributes/characteristics) that the agency expects to consider in evaluating proposals, along with *optimistic*, *pessimistic* and *most likely* estimates of the budget.



ECONOMIC APPROACH: **Endogenous Alternatives ("Engel Curves")**

3. Expansion Path (Response Function) Approach

(Alternatives are Cost-Effectiveness Relations, not Points)

Explore impact of budget cuts *(Identify vendor responses)*

Source Selection Decision: A2 for pessimistic budget; A1 for optimistic budget

Figure 6. Expansion Path Optimization Approach

Assuming the award will be made without discussions (pursuant to *FAR* 52.212-1 and 52.215-1 (General Services Administration, 2005)), the military buyer has a secret scoring rule[32] used to rank vendors that is only revealed after the award of the contract.

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[32] The buyer can request a single offer from each supplier and choose the one he prefers among the submitted offers. "We call this procedure a 'single-bid auction with secret scoring rule'" (Asker & Cantillon, 2004, p. 1).

Once a solicitation is issued in the form of an RFP or IFB, interested vendors submit their offers and the selection process begins.[33]

Each vendor is assumed to have different production and cost functions (to generate the attributes). The vendors constrained optimizations define distinct expansion paths, one for each vendor. From the Envelope Theorem, the Lagrangian multiplier in each vendor's optimization reveals the marginal product (the extra output or attribute mix possible for them to produce) from relaxing the funding constraint, i.e., using a more optimistic budget.

<u>Economic Evaluation of Alternatives Approach</u>:
<u>Military Buyer Goal</u>: Select an alternative that Maximizes
MOE = utility function = U(non-cost factors/attributes),
Subject to BUDGET constraint = TC
<u>Vendor Goal</u>: Select a mix of non-cost factors that
Maximizes Q = Production Function = Q(non-cost factors/attributes)
Subject to TC = Sum of Costs of Attributes = c1 x a1 + c2 x a2 +… <= Budget
<u>Military Buyer</u>:
(MOE) <u>build-effectiveness model</u> (non-cost factors: Performance = quality, schedule, etc.)
(COST) <u>build-cost model</u> (costs/prices: Estimate total system lifecycle costs, total ownership costs)
(BUDGET) <u>Estimate budget</u> (funding level for the program)
<u>Private Vendor</u>:
(Q) Understand Production Function Generates Attributes
(TC) Identify cost of producing each attribute
Construct Alternatives as a function of the Military Buyer's Budget constraint

This EEoA approach illustrated in Figure 6 follows Hitch and McKean's (1967) recommendations: "As a starter […] several budget sizes can be assumed. If the same [alternative] is preferred for all […] budgets, that system is dominant […]. If the same [alternative] is not dominant the use of several […] budgets is nevertheless an essential step, because it provides vital information to the decision maker" (p. 176).

The expansion path for each vendor (see Mathematical Appendix) reveals what that vendor can offer at different budget levels (e.g., *pessimistic*, *most likely* and *optimistic*). The set of each vendor's proposals under the different budget scenarios is an "alternative." When the set of expansion path proposals of each vendor are transformed (through the government's utility function) into a cost-utility or cost-effectiveness (MOE) function for that particular vendor, then, given a range of likely budgets for the program, the most effective vendor over that range of budgets can be selected (see Figure 6).

This approach explicitly addresses a key concern of the GAO that "A cost estimate is […] usually presented to decision makers as a […] point estimate that is expected to represent the most likely cost of the program but provides no information about the range of

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[33] The budget announcements are analogous to an agency exploring in order to uncover its true "reservation price" for the acquisition (given the competing demands for scarce budgets). The adoption of this approach of evaluating vendor proposals under different reservation prices could eventually lead to greater use of fixed-price contracts.

risk and uncertainty or level of confidence associated with the estimate” (GAO, 2009, p. 9). The three-stage procurement auction process is summarized in Table 2 below.

Table 2. Three Stage Multi-attribute Procurement Auction (Expansion Path Optimization Approach)

1) First Stage: (CAIV)
- **The DoD provides notional budget guidance** (B) to alternative vendors for the program. The DoD searches for the optimum product (Procurement) and/or service (R&D; O&M) package that it can obtain at that price, B. The **DoD also reveals optimistic and pessimistic budget guidance**.
- **The DoD defines the set of characteristics/attributes that it values,** and this is known to vendors. However, the DoD’s precise utility function over those characteristics is unknown to vendors (secret scoring rule).

2) Second Stage: (Target Costing)
- **Vendors have different costs and production functions** for generating products or services (defined as bundles of characteristics).
- **Each vendor maximizes its output offer** (an optimal mix of the desired characteristics) **subject to its particular budget constraint** (which includes the DoD’s budget guidance and the vendor’s individual costs to produce a unit of each characteristic).
- **This is the product and/or service package (output) a particular vendor is able to propose for each possible budget** (B), given its production function (technical production possibilities) and its costs of generating those characteristics.

3) Third Stage: (Selection)

With the latest budget forecast, the **DoD selects** among the optimized characteristic bundles proposed by each **vendor** the **bundle/alternative** (total product/service package) **that maximizes the DoD’s utility function.**

Whereas the first three ways to structure an EEoA assume that alternatives can be generated by the decision-maker, the last three assume that alternatives are exogenously determined and that the decision-maker must choose among pre-specified alternatives. The interesting cases are those in which an alternative costs more but offers greater utility, while others cost less and offer less utility.

4. Modified Budget Approach

Suppose that the overall budget or desired level of effectiveness for a program is not available and that the alternatives are derived exogenously—for example, on the basis of a manpower or squadron constraint (e.g., one computer per person or a certain number of aircraft per squadron). Then, it is likely that the pre-specified alternatives solicited from different vendors have different costs and yield different measures of effectiveness (MOE). The first step might be to create a scatter plot of effectiveness versus cost (see Figure 7). In the absence of any other information, the highest cost alternative a DM is willing to consider can be used as a notional budget estimate for the program.

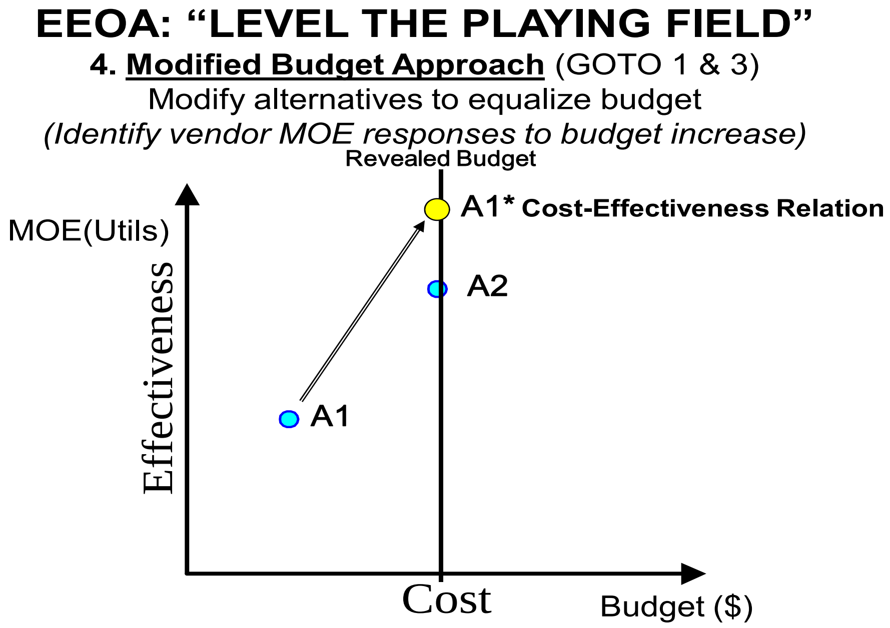

Figure 7. Modified Budget Approach

The fourth way to structure an EEoA recognizes that the highest-cost (highest-utility) alternative under consideration (for example, A2 in Figure 7) reveals a possible budget constraint. By "leveling the playing field," the decision-maker asks how the extra money might be used by the lower-cost (lower-utility) vendor (A1) to increase the utility of that alternative (from A1 to A1*).[34] Note that this effectively returns the problem to the first (and third) way of structuring an EEoA.

5. Modified Effectiveness Approach

Similarly, the fifth way to structure an EEoA levels the playing field for a threshold choice of utility (or effectiveness), returning the problem to the second (and third) way of structuring an EEoA. For example, in Figure 8, anchoring the desired MOE at a target level such as that offered by vendor 2, the government would return to vendor 1 and ask, how much would it cost to achieve the same target level of MOE? In Figure 8, vendor 1 is preferred since the response (A1=>A1*) minimizes the budget required.

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[34] Alternatively, different valuable uses for the money saved by choosing the lower-cost alternative could be brought into the effectiveness calculation. Some will recognize this search for the "next best alternative use of funds" as the standard economic definition of opportunity costs. This sets the stage for the sixth way to structure an EEoA.

EOA: “LEVEL THE PLAYING FIELD”

5. Modified Effectiveness Approach (GOTO 2 & 3)
Modify alternatives to equalize MOE
(Identify vendor COST responses to higher MOE requirement)

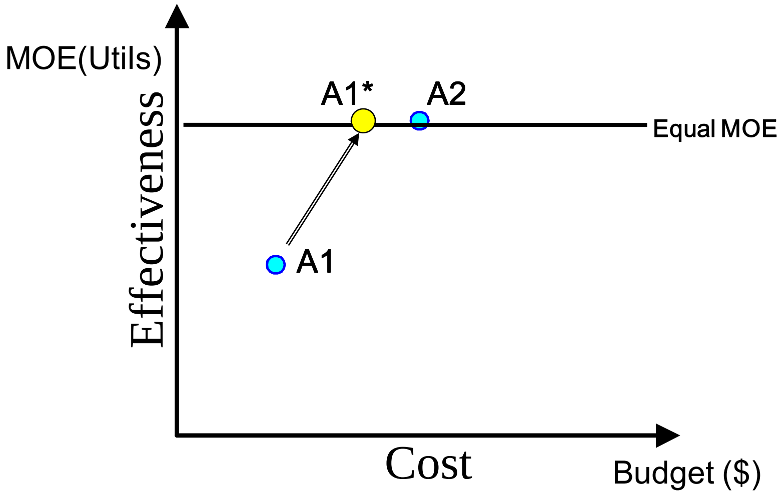

Figure 8. Modified Effectiveness Approach

6. Opportunity Cost (or Effectiveness) Approach

Finally, what if 1) we cannot modify alternatives to obtain response functions, and 2) we don’t know, or cannot assume, a given budget or desired level of MOE? In this case, some alternatives (bundles) cost more but offer more effectiveness, while others cost less and offer less effectiveness (“efficient set”). The sixth and final way to structure an EEoA involves an inter-program comparison we call the Opportunity Cost Approach.

Rather than modify the alternatives to level the playing field, the Opportunity Cost Approach accepts both lower-cost, lower-effectiveness alternatives (A1 in Figure 9) and higher-cost, higher-effectiveness alternatives (A2) but requires a more challenging inter-program analysis.

The main challenge in selecting an alternative in this context is that the DM must reach beyond the immediate program, A, into higher-level inter-program considerations (perhaps entering the requirements generation system or the PPBE process).

If the alternatives are exogenously determined, and it is not possible to level the playing field, then to find the most cost-effective solution requires information about other competing programs (e.g., program B in Figure 9). “[T]he assessment should provide details as to how excess funding […] demands will be accommodated by reductions in other mission areas, or in other […] accounts” (DoD, 2006, July 7, Section 3.2.2).

This involves an inter-program analysis similar to that illustrated in Figure 9. What is the loss in utility in other programs that might be sacrificed (B2=>B1) for the funds to be made available to purchase greater utility in the program under review (A1=>A2)? Alternatively, how much more utility might the extra money generate somewhere else if we went with the low-cost alternative (A1)? These are tough but useful questions that break through the sub-optimization of most traditional AoAs. In this way, the EEoA approach encourages critical communication to take place between different layers of the organization.[35]

6. Opportunity Cost Approach
(INTER-PROGRAM Marginal Analysis)

A) Question: Where is the extra money coming from if I buy the high cost alternative?
B) Question: Where is the extra money going if I buy the low cost alternative?

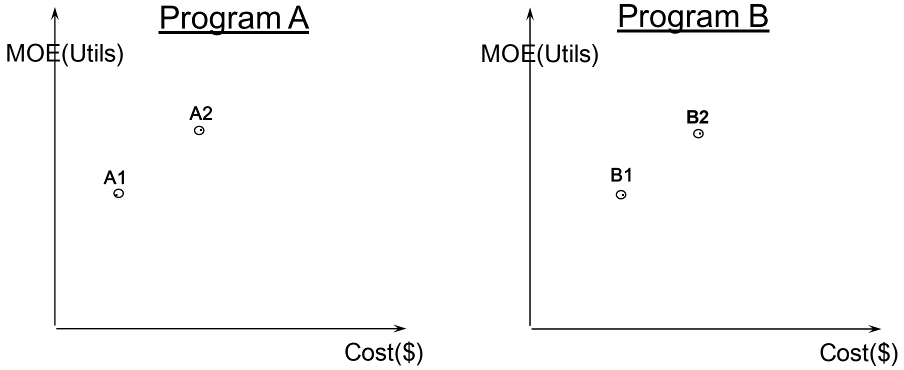

Figure 9. Opportunity Cost Approach

The bottom line is that it is often more transparent, efficient, and effective to develop MOEs that are independent of costs and to treat costs as an independent variable (CAIV). Equally important are the roles of budget (funding) forecasts and opportunity costs in helping structure defense investment decisions. Structuring an Economic Evaluation of Alternatives (EEoA) using one of the six approaches summarized in Table 1 could help achieve the primary goal of defense acquisition reform—to help coordinate the requirements generation system (JCIDS), Defense Acquisition System (DAS), and PPBE to lower the costs of defense investments and improve performance and schedules.

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[35] Fisher (1965) quotes Secretary of Defense Robert McNamara: “Suppose we have two tactical aircraft which are identical in every important measure of performance [MOE] except one—aircraft A can fly ten miles per hour faster than Aircraft B. Thus, if we need about 1,000 aircraft, the total additional cost would be $10million. If we approach this problem from the viewpoint of a given amount of resources, the additional combat effectiveness […] of Aircraft A would have to be weighed against the additional combat effectiveness which the same $10million could produce if applied to other defense purposes—more Aircraft B, more or better aircraft munitions, or more ships, or even more military family housing […] This kind of determination is the heart of the planning-programming-budgeting […] problem with the Defense Department.” (p.182)

Conclusion: A Decision Map for Decision-makers

This study identified several major challenges that face current military cost-effectiveness analyses. It also critically examined key assumptions of the decision sciences' literature, which are frequently used by the military to structure acquisition decisions. An alternative micro-economic set of approaches to structure acquisition decisions was proposed, called the Economic Evaluation of Alternatives (EEoA).

This study points to a significant weakness in the multiple-criteria, decision-making (MCDM) approach that underpins many contemporary AoAs. The weakness is that while MCDM techniques, and therefore most AoAs, correctly focus on lifecycle costs and the operational effectiveness of individual alternatives, affordability is often only implicitly addressed through a weight assigned to costs.

In contrast, the EEoA approach recommended in this study encourages analysts and decision-makers to include affordability explicitly in the AoA. This requires working with vendors to build alternatives based on different funding (budget/affordability) scenarios. Supported by a static, deterministic, multi-stage, constrained-optimization, micro-economic production (procurement auction) model described in Section 3, this EEoA approach explicitly addresses affordability up-front. The key difference between the MCDM approach to AoA, and the EEoA approach, is that instead of modeling decision alternatives from competing vendors as points in cost-effectiveness space, the EEoA models alternatives as functions of *optimistic*, *pessimistic* and *most likely* funding (resource/budget) scenarios.

The primary goal of this study was to help improve public investment decisions by providing a set of six approaches practitioners (acquisition officials and others) can employ to structure an Economic Evaluation of Alternatives (EEoA). An important secondary goal of the study was to develop a Decision Map to guide practitioners and acquisition officials in structuring cost-effectiveness analyses to improve defense acquisition outcomes. The Decision Map to structure an EEoA appears below.

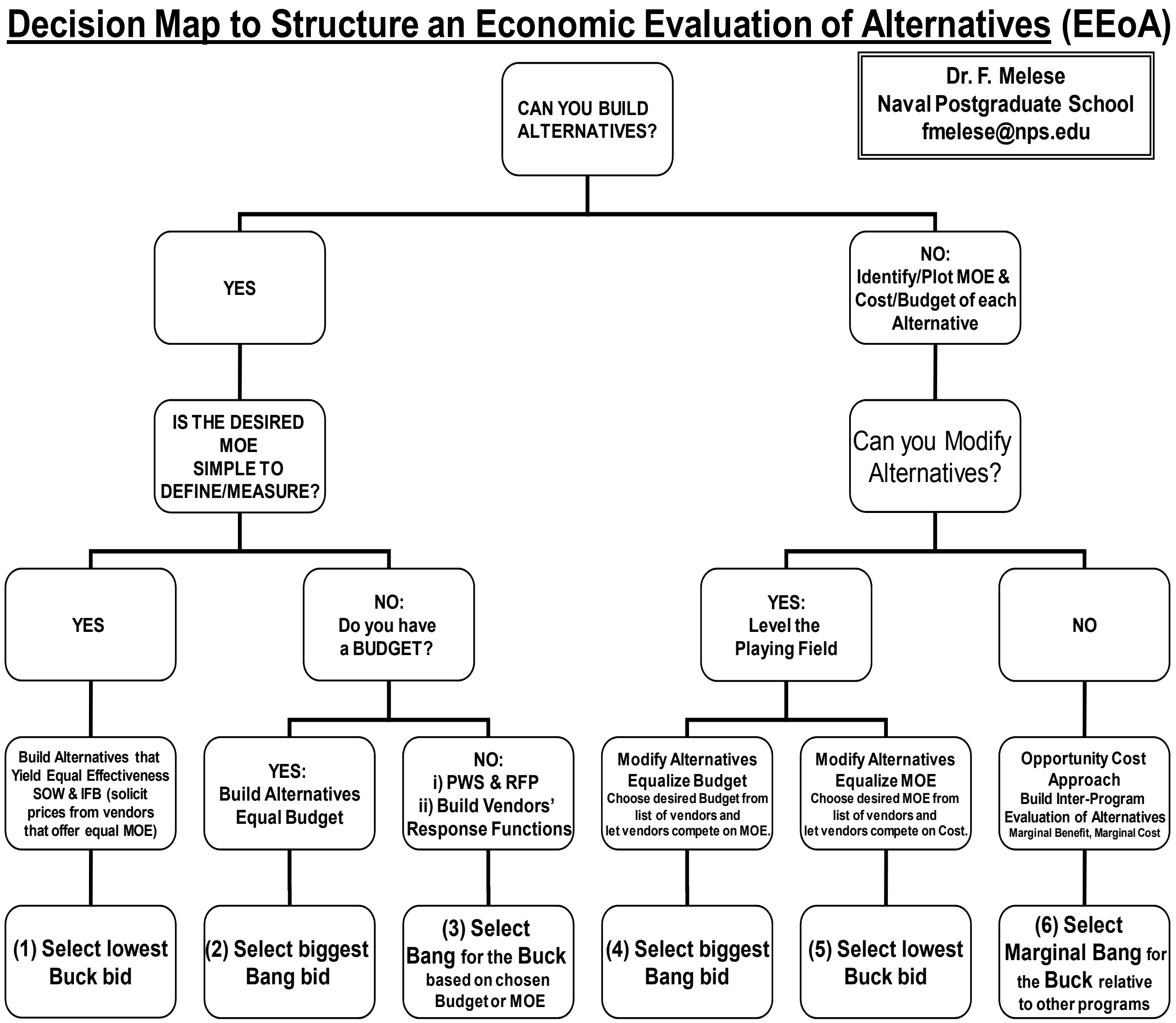

Figure 10. Decision Map to Structure EEoAs

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Panel 3 - Acquisition Management of Systems-of-systems

Wednesday, May 13, 2009 11:15 a.m. – 12:45 p.m.	Panel 3 - Acquisition Management of Systems-of-systems
	Chair: Reuben Pitts, III, President, Lyceum Consulting, LLC **Discussant: Colonel Raymond D. Jones, US Army**, Program Manager, Airborne, Maritime and Fixed Station, Joint Tactical Radio System ***Acquisition Management for Systems-of-systems: Exploratory Model Development and Experimentation*** **Daniel DeLaurentis** and **Muharrem Mane**, Purdue University ***Acquisition of Capabilities through Systems-of-systems: Case Studies and Lessons from Naval Aviation*** **Michael Pryce**, Manchester Business School

Chair: Reuben S. Pitts, III, has a BS in Mechanical Engineering from Mississippi State University and has completed graduate studies in Engineering Mechanics from VPI&SU and the University of Oklahoma. He has also completed graduate studies in Public Administration from the University of Northern Colorado and has attended the Federal Executive Institute.

Early successes in ordnance test and design at NSWCDD earned Pitts a promotion as the Navy's Gun Ammunition Design Agent Principal Engineer for gun ammunition design. Then, as Design Manager for the 8-inch Guided Projectile project team, he achieved the first successful firing of guided munitions from shipboard guns. As Head, Intelligence Systems Processing Branch, he directed the development of the first mobile, field-deployable, computer-based Intelligence Analysis Center (IAC) for the Marine Corps. He subsequently served on the planning team to reintroduce the Navy to Wallops Island, VA, currently a multiple ship combat, over-the-water weapons testing lab for Surface Ship Combat Systems, Fighter Aircraft and live missile firings. His outstanding service as the deployed Science Advisor to Commander, US Sixth Fleet was recognized with the Navy's Superior Civilian Service (NSCS) Award and the Navy Science Assistance Program Science Advisor of the Year Award.

Pitts was selected to lead the technical analysis team in support of the formal JAG investigation of the downing of Iran Air Flight 655 by USS Vincennes, and participated in subsequent briefings to CENTCOM, the Chairman of the Joint Chiefs, and the Secretary of Defense. As Head, Surface Ship Program Office and Aegis Program Manager, Pitts was awarded a second NSCS, the James Colvard Award, and the John Adolphus Dahlgren Award (Dahlgren's highest honor) for his achievements in the fields of science, engineering, and management. Anticipating the future course of combatant surface ships, Pitts co-founded the NSWCDD Advanced Computing Technology effort, which eventually became the Aegis/DARPA-sponsored High Performance Distributed Computing Program: the world's most advanced distributed real-time computing technology effort. That effort was the foundation for the Navy's current Open Architecture Initiative. Pitts led the applications of total ship system engineering to surface ship combat system developments at the platform level, integrating combat systems and Hull, Mechanical & Electrical functions and achieving commonality of technologies, equipment, and computer programs across ship classes. While in this position, he was promoted to the rank of Senior Science and Technology Manager (SSTM). In 2003, Pitts accepted responsibility as Technical Director for PEO Integrated Warfare Systems (IWS), the overall technical authority for the PEO. In September of that year, he was reassigned as the Major Program Manager for Integrated Combat Systems in the PEO. In this position, he was the Program Manager for the Combat Systems and Training Systems for all US Navy Surface Combatants—including Aircraft Carriers, Cruisers, Destroyers, Frigates, Amphibious Ships, and auxiliaries—with total obligation authority that approached $6 billion. In this position, he began the Navy's Warfare System Way Ahead effort that formed the Navy's basis for future budget strategies; he began the Enterprise Test and Evaluation effort which demonstrated savings of hundreds of millions of dollars, and he established the Navy strategy for acquisition of Warfare Systems based on Open Architecture principles. For this work, he was awarded a Navy Meritorious Civilian Service Award.

In July, 2006, Mr. Pitts returned to NSWCDD to form and head the Warfare Systems Department, a hands-on research and development organization with 700 employees and an active budget of over $400 million. Under his leadership, the department became the leading Navy field activity voice for the future of Navy Surface Warfare Systems and Warfare System architectures and technologies. While in this position, he maintained his personal technical involvement as the certification official for Surface Navy Combat Systems. He also served as Chair of the Combat System Configuration Control Board and Chair of the Mission Readiness Panel for Operation Burnt Frost, the killing of inoperative satellite USA 193. Pitts has been a guest speaker/lecturer and symposium panelist at a many NAVSEA-level and DoD symposiums, conferences and at the Naval Postgraduate School, the Defense Systems Management College, the Applied Physics Lab of the Johns Hopkins University, and the National Defense University. For 19 years, Pitts was the sole certification authority of all Aegis Combat System computer programs for fleet use. He retired from the US Civil Service in September 2008, with over 40 years of service to the Navy, and now heads his own consulting company, Lyceum Consulting, LLC.

Discussant: Colonel Raymond D. Jones, US Army, recently assumed the responsibilities as the Program Manager for the Airborne, Maritime, and Fixed Domain, Joint Tactical Radio System (PM AMF JTRS) in San Diego, CA. This is a Joint Service Acquisition Defense Category I D (ACAT ID) program reporting to the Joint Program Executive Officer JTRS and the Under Secretary of Defense, Acquisition Technology and Logistics.

He is a 1983 graduate of the United States Military Academy, with a Bachelor of Science Degree in Aerospace Engineering. He also earned a Master of Science Degree in Aeronautical Engineering from the Naval Postgraduate School in Monterey, CA, holds a Master of Business Administration from Regis University in Denver, CO, and attended the Industrial College of the Armed Forces, where he graduated as a distinguished Academic Honor Graduate with a Master's in National Resource Strategy.

Jones is a graduate of the US Naval Test Pilot School with over ten years and 3000 hours of flight test experience in 43 different types of aircraft, including both fixed and rotary wing. Some of his other military education includes: the Infantry Officers Basic Course, the Army Command and General Staff College, and the Advanced and Executive Program Manager's Courses at the Defense Systems Management College.

His previous military assignments include Project Manager for Modular Brigade Enhancements (MBE), an ACATI D program, reporting to the Program Executive Officer for Ground Combat Systems. Prior to serving as PM MBE, he served as the Military Deputy to the Director for Acquisition Resources and Analysis in the Office of the Under Secretary of Defense for

Acquisition Technology and Logistics. Jones also served as the Commander for the Kwajalein Missile Range in the Republic of the Marshall Islands, had multiple experimental and developmental flight test tours at Fort Monmouth, NJ, and Fort Rucker, AL, and served multiple operational tours—including three and a half years with the First Cavalry Division at Fort Hood, TX, and over two years in the Republic of Korea with the 17th Aviation Brigade.

His military decorations include the Defense Superior Service Medal, Legion of Merit, Meritorious Service Medal with four oak leaf clusters, Army Commendation Medal with one oak leaf cluster, the Master Aviator's Badge, Office of the Secretary of Defense Service badge, Army Staff badge, and the Airborne and Air Assault Badges.

Jones is married to Nancy E. Huth-Jones and has two children, Sam and Nona.

Acquisition Management for Systems-of-systems: Exploratory Model Development and Experimentation

Presenter: Daniel DeLaurentis is an Assistant Professor in the School of Aeronautics and Astronautics Engineering, Purdue University. He received his PhD from Georgia Institute of Technology in Aerospace Engineering in 1998. His current research interests are in Mathematical modeling and object-oriented frameworks for the design of system-of systems (especially those for which air vehicles are a main element), and approaches for robust design—including robust control analogies and uncertainty modeling/management in multidisciplinary design.

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Abstract

In recent years, the Department of Defense (DoD) has placed a growing emphasis on the pursuit of agile capabilities via net-enabled operations. In this setting, systems are increasingly required to interoperate along several dimensions. Yet, the manner in which components of these “system-of-systems” (SoS) are acquired (designed, developed, tested and fielded) has not kept pace with the shifts in operational doctrine. Acquisition programs have struggled with complexities in both program management and engineering design. We have developed a conceptual model for pre-acquisition and acquisition strategy in an SoS environment and have implemented it in an exploratory, dynamic model. The model allows acquisition professionals to develop intuition for procuring and deploying system-of-systems by providing a venue for experimentation through which they can develop insights that will underpin successful acquisition of SoS-oriented defense capabilities. This paper presents example studies that demonstrate the capabilities of the dynamic model and highlight the importance of project characteristics. Specifically, we investigate the impact of SoS attributes—requirement interdependency, project risk, and span-of-control of SoS managers and engineers—on the completion time of SoS projects.

Introduction

A system-of-systems (SoS) consists of multiple, heterogeneous, distributed systems that can (and do) operate independently but can also assemble in networks and collaborate to achieve a goal. According to Maier (1998), the SoS typically demonstrate traits of operational and managerial independence, emergent behavior, evolutionary development and geographic distribution. Networks of component systems often form among a hierarchy of levels and evolve over time as systems are added to or removed from the SoS. However, these component systems are often developed outside of the context of their interactions with the future SoS. As a result, the systems may be unable to fully interact with the future SoS, adapt to any emergent behavior, or be robust in the face of external disturbances.

The Future Combat System (FCS) program exemplifies a Department of Defense (DoD) acquisition process for an SoS. FCS seeks to modernize the US Army and provide soldiers with leading-edge technologies and capabilities—allowing them to dominate in asymmetric ground warfare and to sustain themselves in remote places (US Army, 2009). The FCS has faced technical and management challenges that have come to typify acquisitions in SoS environments.

In 2003, the FCS program was comprised of an information network and 18 primary systems (categorized as manned ground systems, unmanned ground systems, and unmanned air vehicles). The Army's initial schedule allotted a 56-month system development and demonstration (SDD) phase (2003-2008), with the goal of achieving full operational capability by 2013. The Army's initial cost estimate was $108 billion (GAO, 2003). Over the past four years, the FCS has been restructured twice in an effort to reduce the high risk attributed to both the presence of immature technologies in critical paths as well as the challenges of concurrently developing these technologies with product development. The Government Accountability Office (GAO) criticized the Army's acquisition strategy and concluded that the total cost for the FCS program had increased by 76% ($160.7 billion) from the Army's first estimate of $108 billion. However, independent estimates predicted an increase to $234 billion (116%).

In addition to the technical challenges, the FCS program also faced managerial challenges stemming from the Army's partnership with an industry Lead System Integrator (LSI). The role of the LSI is to reach across Army organizations to manage development of the SoS (GAO, 2007, June). Given the high risk involved in implementing a complex SoS, the GAO specifically underlined the importance of oversight challenges faced by the LSI in this area (GAO, 2007, March). The challenges of the FCS Program have pushed the Army to decrease the scope of the program to 14 systems and to extend the time estimate for achieving full capability to 2030 instead of 2013.

Other non-DoD organizations are also struggling with systems integration of a collection of complex systems. The US Coast Guard's (USCG) Integrated Deepwater System (IDS) is an example of a Department of Homeland Security (DHS) acquisition process for an SoS that has also faced challenges. These challenges have stemmed from the lack of collaboration between contractors and the marginal influence wielded by system integrators to compel decisions between them (GAO, 2006). The NextGen Air Transportation System and the NASA Constellation program are also facing similar challenges as they attempt to apply generic system engineering processes for acquisition in an SoS environment. Integration challenges faced by the Constellation Program are documented in a recent NRC report (Committee on System Integration for Project Constellation, 2004). These examples possess the key drivers motivating the research described in this paper.

The overarching goal of our research is to understand the types of complexities present in acquisition management for SoS, and then to develop approaches that can increase the success of an acquisition process in the SoS setting. The three research questions derived from this goal are:

1. Is there a taxonomy by which one can *detect* classes of complexities in particular SoS applications?
2. What are the underlying systems engineering (SE) and program management functions that are affected?
3. How can exploratory modeling generate SE and acquisition management modifications to improve the probability of success?

In order to answer some of the questions posed, we aim to:

1. Identify the complexities in the acquisition of SoS based on historical trends of “failures,” especially in the context of the DoD
2. Develop a conceptual model of a generic acquisition process that is customizable to different SoS applications.
3. Develop a computational model based on the conceptual model and, through simulation, provide insight on and answer questions about process modifications.

Complexities

Simon (1996) and Bar-Yam (2003) define complexity as the amount of information necessary to describe a system effectively. In the context of a system-of-systems, the necessary information encompasses both the systems that comprise the SoS and their time-varying interactions with each other and the “externalities.” Rouse (2007) summarized that the complexity of a system (or model of a system) is related to: the intentions with which one addresses the systems, the characteristics of the representation that appropriately accounts for the system’s boundaries, architecture, interconnections and information flows, and the multiple representations of a system—all of which are simplifications. Hence, complexity is inevitably underestimated and context-dependent. Polzer, DeLaurentis, and Fry (2007) explored the issue of multiplicity of perspectives, in which perspective is a system’s version of operational context.

Historical data from previous unsuccessful defense acquisition programs show a distinct correlation with the causes for complexity identified by Fowler (1994). Such data suggest some of the causes for the failure of the Defense Acquisition Process to be “over specification and an overly rigid approach on development,” unreasonably detailed cost estimates of development and production, impractical schedules, and extremely large bureaucratic overhead. Dr. Pedro Rustan, Director of Advanced Systems and Technology at the National Reconnaissance Office, identified four specific shortcomings in the acquisition process for defense space systems: initial weapons performance requirements that are too detailed and lacking flexibility, insufficient flexibility in the budget process, a propensity to increase performance requirements in the middle of the acquisition cycle, and demands to field entirely new spacecraft to meet new requirement (Spring, 2005).

Using the above examples, we summarize the common causes of failure (Rouse, 2007) within SoS acquisition processes as: a) *misalignment* of objectives among the systems, b) limited *span-of-control* of the SoS engineer on the component systems of the SoS, c) *evolution* of the SoS, d) *inflexibility* of the component system designs, e) *emergent behavior* revealing hidden dependencies within systems, f) *perceived complexity* of systems and g) the challenges in *system representation*.

To provide context, in Ghose and DeLaurentis (2008), we mapped these complexities to a System-of-systems Engineering (SoSE) Process Model designed specifically for SoS applications by Sage and Biemer (2007). This mapping represents points at which complexities might arise and how they may affect the acquisition process.

Development of a Conceptual Model

Pre-acquisition Model

We developed a pre-acquisition model to understand the impact of external stakeholders on the acquisition process. The model is based loosely on the Sage and Biemer (2007) SoSE Process Model and categorizes the external inputs to the SoS acquisition strategy model into “Capabilities & Possibilities” (CAP), “Technology Assessment, Development, Investment and Affordability Plan” (ADIA) and the funding received (Ghose & DeLaurentis, 2008). The CAP and the Technology ADIA Plan translate into technical requirements for the SoS. Provision of a computational model of the pre-acquisition activities is outside the scope of this paper. Instead, we focus on realizing a model for the acquisition strategy, described next.

Acquisition Strategy Model

Development of a “brand new” SoS has been and will remain a rare occurrence. In their 2005 study on SoS, the United States Air Force (USAF) Scientific Advisory Board (Saunders et al., 2005) stated that one of the challenges in building an SoS is accounting for contributions and constraints of legacy systems. These legacy systems may be used “as-is” or may need re-engineering to fulfill the needs of the new SoS. New systems are also incorporated to develop the capabilities of the SoS. Again, the new systems may range from off-the-shelf, plug-and-play products to custom-built systems dependent of the working of a legacy system. Sub-categories arise when the two or more categories overlap (Figure 2).

The conceptual model for acquisition strategy proposed in this section is based on the 16 basic technical management and technical system-engineering processes outlined in the *Defense Acquisition Guidebook* (DoD, 2003), often referred to as the 5000-series guide. However, an SoS environment changes the way these processes are applied. The *Systems Engineering Guide for System-of-Systems* (*SoS-SE*) (DoD, 2008) addresses these considerations by modifying (in some cases revamping) some of the 16 processes in accord with an SoS environment. These new processes and their functions are described in Table 1. Our conceptual model for acquisition in an SoS environment (illustrated in Figure 3) is centered on these revised processes, depicted in a hierarchy to show the flow of control between the processes throughout the acquisition lifecycle.

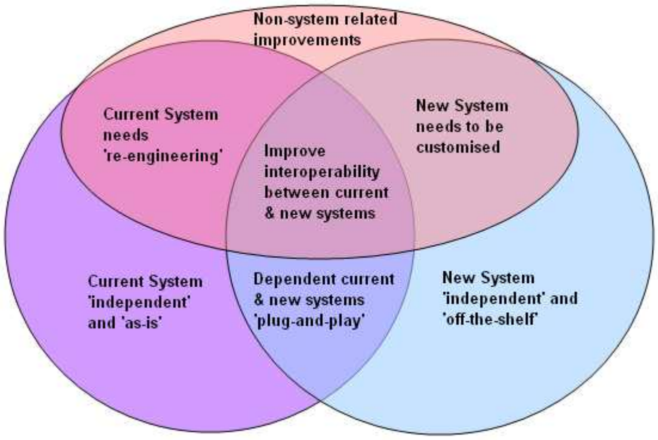


Figure 1. Heterogeneity of Component Systems in an SoS

Table 1. Modified Technical Management and Technical Processes as Described in the *SoS-SE Guide*
(DoD, 2003)

Requirements Development	Takes all inputs from relevant stakeholders and translates the inputs into technical requirements.
Logical Analysis	Obtains sets of logical solutions to improve the understanding of the defined requirements and the relationships among the requirements (e.g., functional, behavioral, temporal).
Design Solution	Translates the outputs of the Requirements Development and Logical Analysis processes into alternative design solutions and selects a final design solution.
Decision Analysis	Provides the basis for evaluating and selecting alternatives when decisions need to be made.
Implementation	Yields the lowest-level system elements in the system hierarchy. The system element is made, bought or reused.
Integration	Incorporates the lower-level system elements into a high-level system element in the physical architecture.
Verification	Confirms that the system element meets the design-to or build-to specifications. It answers the question “Did you build it right?”
Validation	Answers the question of “Did you build the right thing?”
Transition	Applies the process required to move the end-item system to the user.
Technical Planning	Ensures that the systems engineering processes are applied properly throughout a system’s lifecycle.
Technical Assessment	Measures technical progress and the effectiveness of plans and requirements.
Requirements Management	Provides traceability back to user-defined capabilities
Risk Management	Helps ensure program cost, schedule and performance objectives are achieved at every stage in the lifecycle and communicates to all stakeholders the process for uncovering, determining the scope of, and managing program uncertainties.
Configuration Management	Ensures the application of sound business practices to establish and maintain consistency of a product’s attributes with its requirements and product configuration information.
Data Management	Addresses the handling of information necessary for or associated with product development and sustainment.
Interface Management	Ensures interface definition and compliance among the elements that compose the system, as well as with other systems with which the system or systems elements must interoperate.

A detailed description of the conceptual model and the acquisition stages it models (Figure 2) is presented in Ghose and DeLaurentis (2008).

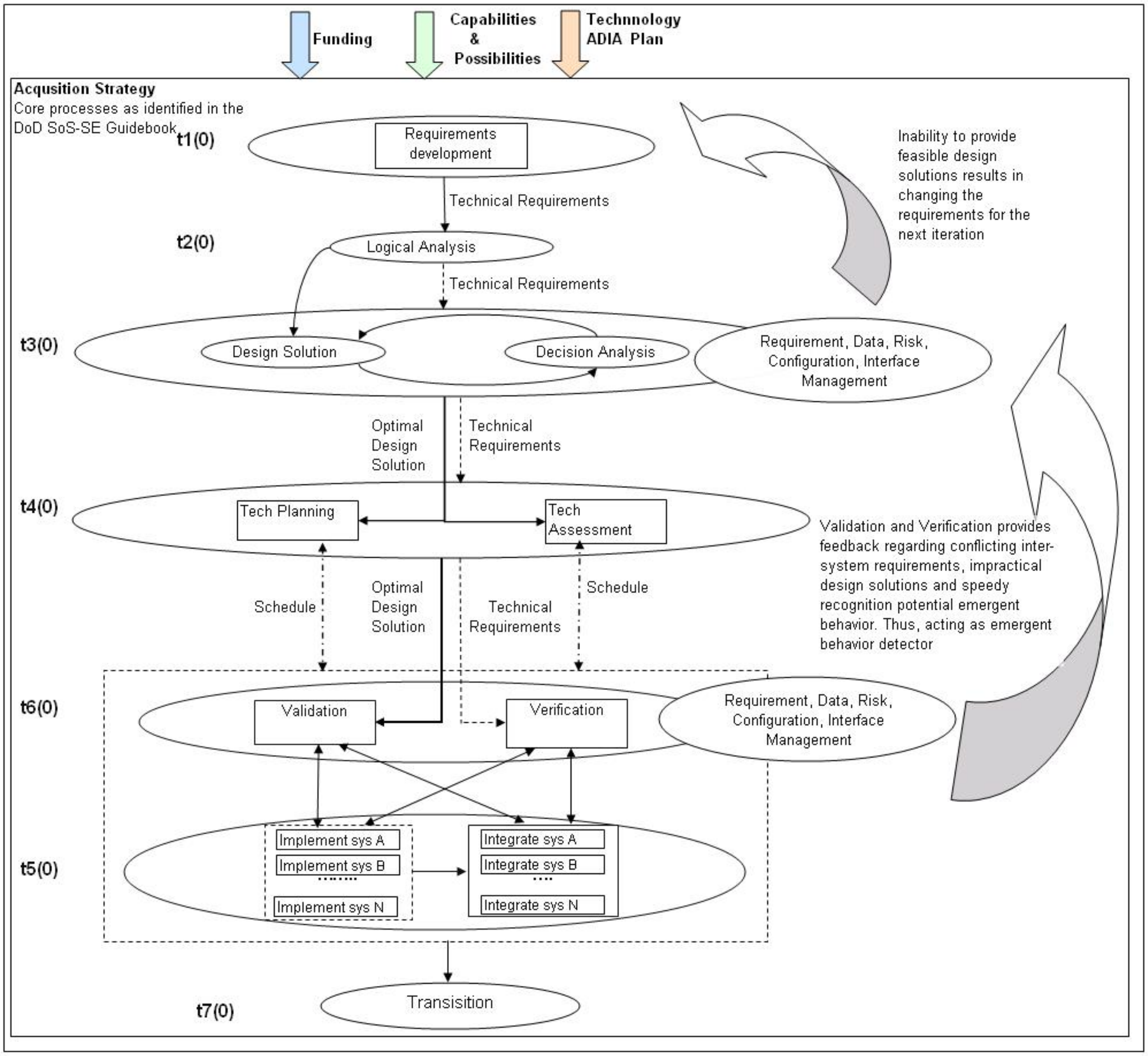


Figure 2. Conceptual Model of Acquisition Strategy Based on SoSE Process Described in Table 1

The purpose of the exploratory computational model is to help acquisition professionals develop intuition for procuring and deploying systems in a system-of-systems context, not to provide a tool validated for use in managing real acquisition programs. A model that captures all the complexity of the acquisition process for SoS in a modest span of time and effort is impossible. The exercise of the model described in this paper specifically targets complexities stemming from the interdependencies among systems, the evolutionary development of the SoS and the span-of-control of the SoS managers and engineers. An abstraction of the model is presented in Figure 3.

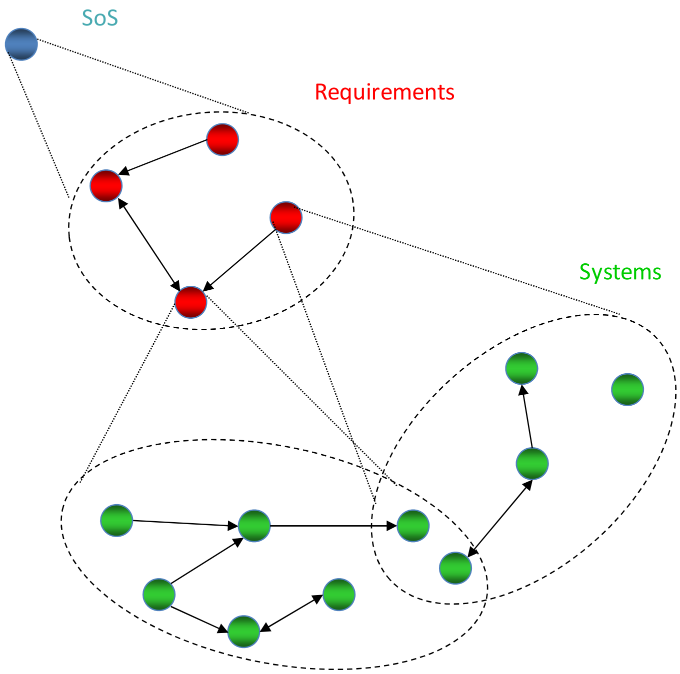


Figure 3. Node/link Picture of Acquisition Model

At the requirement level, each node represents a requirement, while each link represents the interdependency between requirements. Similarly, at the system level, each node represents a system and each link the interdependency between systems. Groupings of interdependent systems are needed to fulfill a requirement. In our computational model, the user can specify the number of requirements and their interdependencies as well as the number of systems and their interdependencies for each requirement, or the user can randomly generate the requirement and system interdependencies. It is with this layered network concept/representation that the computational model progresses through the acquisition stages described in Figure 2.

Developing the Exploratory Computational Model

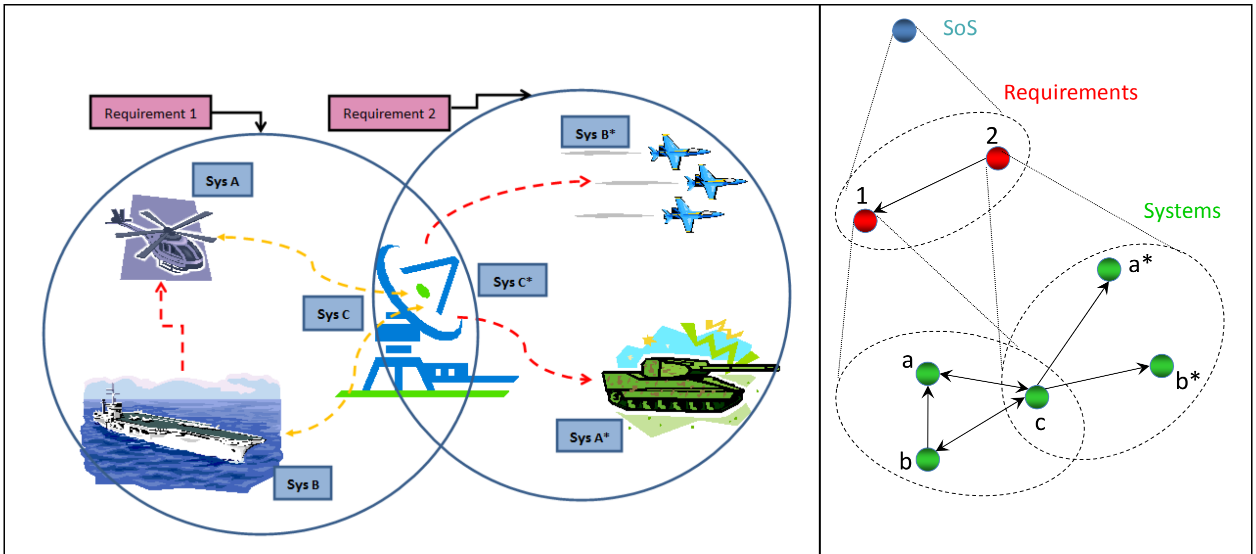
Overview

Several challenges arise in transforming the acquisition model to a computational one for the purposes of simulation and learning. One challenge lies in converting all the qualitative concepts into quantitative measures to support the computational model for SoS acquisition. Disruptions occur at various stages in the model and are governed by the risk associated with the project. A high-risk project, for example, will be more vulnerable to disruptions than a low-risk project. A second challenge is building a model that can accommodate the dynamic addition and removal of components in the SoS. In addition, these component systems need to reflect the heterogeneity of the systems in a real acquisition process. We included parameters such as *level of completeness* to demonstrate the difference between legacy systems, new systems and partially implemented/integrated systems. A third challenge arises from the numerous methodologies that can be applied to reflect the integration and implementation processes. In a simplified model, it is much easier to begin integration once all the systems have been implemented. However, this method is neither cost- nor time-efficient, especially in multi-year projects involving numerous systems. On the other hand, dynamically implementing and integrating systems is time-efficient but often not possible when dependent systems are outside the span-of-control of the systems' engineers.

As stated previously, a model that captures all the complexity of the acquisition process for SoS in a modest span of time is impossible. Therefore, our coarse-scale engineering model will specifically target challenges related to the evolution of the SoS and the span-of-control of the SoS engineer(s).

Simple SoS Example

A simple SoS acquisition strategy with two requirements and five component systems (Figure 4) is first presented to illustrate the model workings. Figure 4(a) shows the physical composition of the SoS, while Figure 4(b) presents the layered network of this simple SoS.



a) Example of SoS

b) Model Structure for Example SoS

Figure 4. Simple Example of SoS

Requirement 1 is to improve rescue operations performed by a certain fleet, while Requirement 2 is to improve communication and coordination between air and ground units. The three types of component systems fulfilling Requirement 1 are helicopter (A), ship (B) and communication system (C). Similarly, the three component systems fulfilling Requirement 2 are ground units (A*), airborne units (B*) and a communication system (C*).

Since Requirement 2 needs to use the communication system (C) built by Requirement 1, Requirement 2 is dependent on Requirement 1. The directional dependencies within the component systems fulfilling each requirement are shown in Figure 4(a) using dashed yellow (bidirectional) and red (unidirectional) lines. The requirement level dependency matrix and the system-level dependency matrices for each requirement are shown in Table 2.

Table 2. Dependency Matrices

Requirement Dependency Matrix	$\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$

Requirement	System Dependenc y Matrix
1	$\begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$
2	$\begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$

Model Inputs

Three levels of inputs are used in the model: project-level, requirement-level and system-level. The three user-defined project-level inputs are project-risk, span-of-control of SoS managers and engineers, and estimated amount of time needed to complete the project. A project can have low, medium or high project-risk profile. This profile determines: a) the probability of the project being affected by disruptions at *Design Solution* (Level t3(0), Figure 2) and *Implementation & Integration* (Level t5(0), Figure 2) stage, and b) the probability of a new requirement being added during the project lifecycle. The span-of-control of an SoS engineer or manager indicates whether component systems are directly or indirectly accountable to the SoS manager or engineer. A project's span-of-control is either "0" or "1," where "0" represents low span-of-control. A project with low span-of-control implements dependent systems sequentially instead of in parallel. The requirement-level inputs to the exploratory computational model are initial number of requirements, dependencies between requirements, component systems fulfilling each requirement, and the dependencies between the component systems.

The dependencies between the requirements determine the schedule by which the requirements will be implemented. For the simple example problem, as shown in Table 2, there are two requirements (1, 2), and each has a dependency vector associated with it. The vectors are concatenated to form the dependency matrix for requirements ("0" is placed for all diagonal elements since a requirement cannot be dependent on itself). The vector for Requirement 1 ([0 1]) shows that Requirement "1" is dependent on Requirement "2," and "1" cannot be realized until "2" is implemented. In real-world applications, communication upgrade to the North-Atlantic fleet may be independent of the weaponry upgrade for the same group of systems. In such a case, both the requirements on the same group of systems may be implemented simultaneously. Each requirement affects a subset of the systems present in the SoS, and the systems in each subset share a unique dependency matrix with other systems in that subset.

All component systems of the SoS have user-defined and calculated system-level parameters that expose their heterogeneity and help track their progress through the acquisition process. Some of the parameters used to describe each system in the SoS are described in Table 3.

Table 3. System-level Parameters Used to Describe Component System of the SoS

Parameter	Description
ID	Unique ID assigned to the system
Imp.completeness[]	An array that tracks the progress of the system in the implementation phase
Imp.dependencies[]	Dependency vector that shows if system implementation is dependent on information from any other system
Imp.time	Maximum time needed to complete implementation
Int.completeness[]	An array that tracks the progress of the system in the integration phase
Int.dependencies[]	Dependency vector that shows if system integration is dependent on information from any other system
Int.time	Maximum time needed to complete integration

While most of the parameters are user-defined, Imp.completeness and Int.completeness are only initialized by the user, and ID is assigned by the model. Implementation or Integration of a system[A] is either dependent on information from other systems satisfying the requirement or independent of any such information. Thus, all the tasks necessary to successfully implement or integrate system[A] can be divided into smaller subsets depending upon which systems they need information from. At a given time-step, the *level of completeness* of system[A] with regard to system[X] is defined as the percent of tasks needed to successfully implement/integrate system[A] that are dependent on information from system[X] and have been completed. *Level of completeness* for both integration and implementation processes can vary between 0 and 100%. The *level of completeness* of system[A] with regard to *N* individual systems is summed to calculate the total *level of completeness* of system[A]. Note that although the tasks are dependent on information from system[A], the *level of completeness* says nothing about the status of system[A]. Note also that the model works in discrete time.

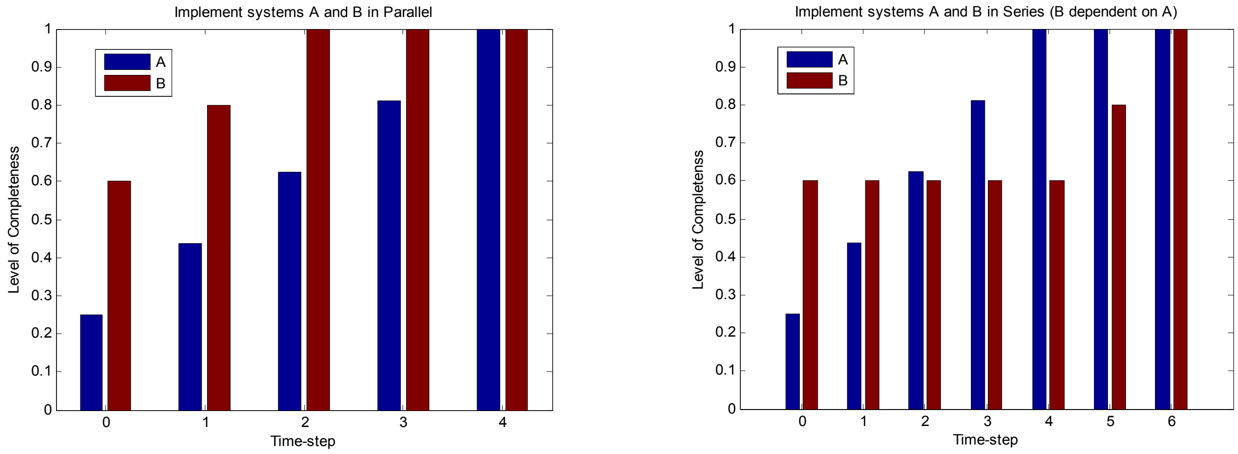
Similar to requirements, each system has a pre-defined dependency vector for implementation and integration processes. These vectors are concatenated to form a dependency matrix for the systems fulfilling each requirement.

Model Dynamics

The model begins at the *Requirement Development* (Level t0(0), Figure 3) stage, which initializes requirements to be implemented, project span-of-control and project risk. Disruptors at the requirement level can take the form of change in existing requirements or addition of new requirements. The user-defined inputs from *Requirement Development* are passed to *Logical Analysis* (Level t2(0), Figure 2), which generates a schedule to realize the given requirements either in series or in parallel (per the dependencies). Each requirement then enters its own *Design Solution* and *Decision Analysis* (Level t3(0), Figure 2) process. The *Design Solution* and *Decision Analysis* processes feed into each other, and any disruptions at this stage imply that the design solution provided is not feasible. If the solution fails in multiple consecutive time-steps, then the requirement is sent back to the *Requirement Development* stage; otherwise, the set of component systems and their user-defined parameters are sent to the *Technology Planning* and *Technology Assessment* (Level t4(0), Figure 2) processes.

Implementation (Level t5(0), Figure 2) of systems occur in series or parallel, depending on the system dependencies and the span-of-control of the project. The *level of completeness* for implementation increases by the iteration rate at every time-step until it reaches a completeness value of 1. The incremental increase in the level of completeness of two dependent systems in a project with high span-of-control (“1”) occurs simultaneously, as shown in Figure 5(a). In a case of low span-of-control (“0”), dependent systems are implemented sequentially, as shown in Figure 5(b).

When a system achieves the implementation completeness = 1, it enters the *Integration* stage.



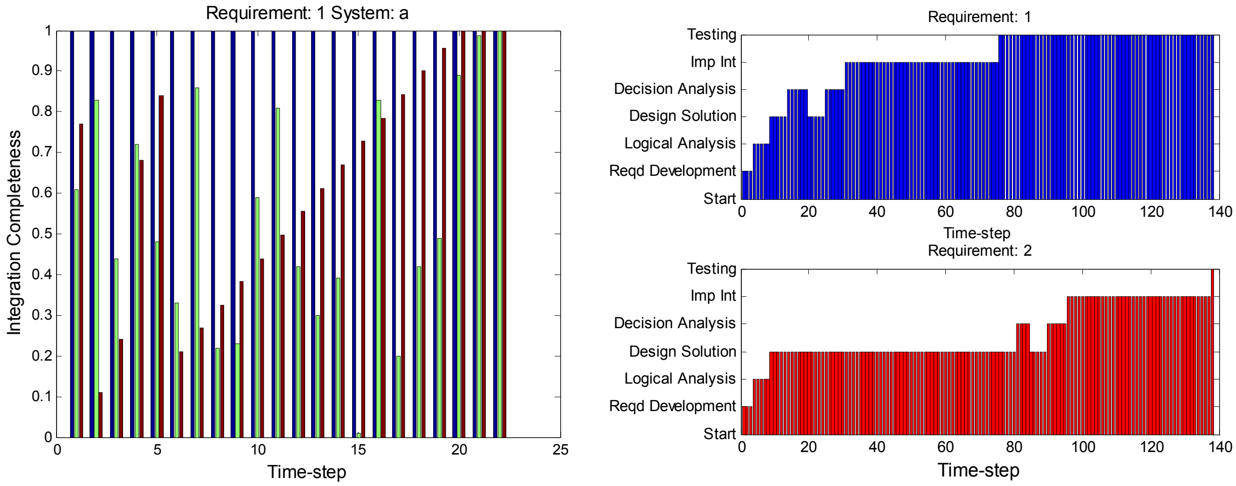
a) Independent

b) Dependent Systems

Figure 5. Incremental Increase in Implementation Completeness

Similar to *Implementation*, systems can be integrated in series or in parallel depending on the span-of-control. When both the *Implementation* and *Integration* processes for the given requirement are complete, the *Validation* and *Verification* phase (Level t6(0), Figure 2) checks for a completeness level of “1” for all component systems. If the requirement successfully passes *Validation* and *Verification*, it is said to be ready for *Testing*. A more detailed description of these stages is presented by Ghose and DeLaurentis (2008).

To present an example of output generated by the computational model, we simulate the acquisition process of the simple SoS presented in Figure 4. We assume that this project has a high span-of-control and a low risk level. All systems have random initial completeness levels as well as implementation and integration times. Results for this simple example from the computational model are presented in Figure 6. Results similar to the ones presented on the left plot are available for all systems that comprise the acquisition project in this example.



a) Integration completeness of system "a"

b) Completeness history of entire project

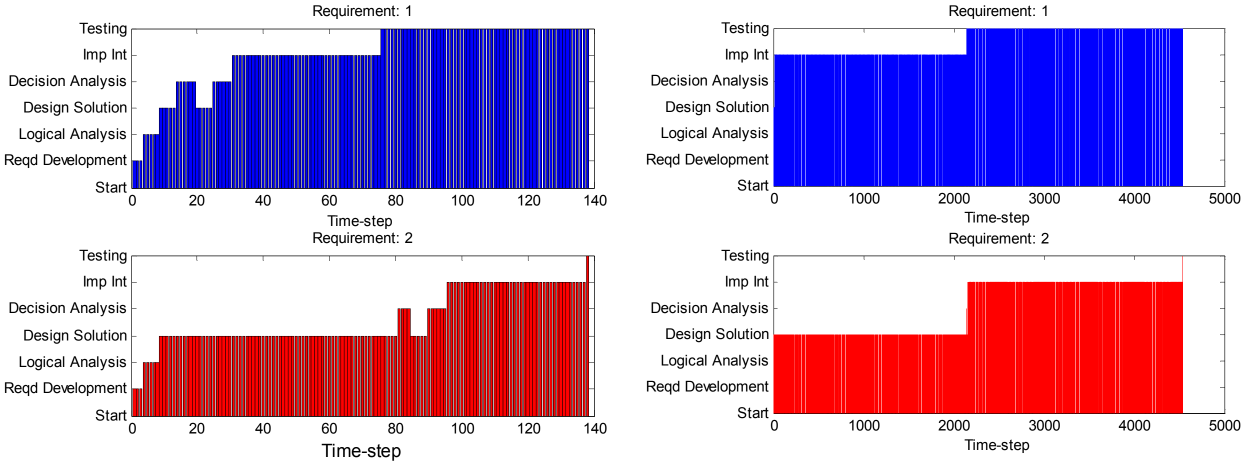
Figure 6. Sample Results of Computational Model for Example Problem

In Figure 6(a), each bar represents a system that is part of requirement 1. Because we are observing system "a," its integration with itself has a value of "1." The integration completeness of system "a" with systems "b" and "c" fluctuates (due to disruptions—occurring here with a uniformly random probability) until after 22 time-steps, at which point integration is complete. The numerous set-backs in integrating systems "b" and "c" indicate key dynamic features of this model. Though modeled as uniformly random here, we envision more meaningful probability functions for the occurrence of disruptions that relate to physical or actual observed patterns. When the system histories are compiled, the result is the acquisition process history shown in Figure 6(b). Evidence of the impact of disruptions on completeness is noticeable. The completion time of this acquisition project is 138 time units. Note, however, that requirement 2 shows no activity after the *Design Solutions* phase from 10 to 81 time units; requirement 2 is dependent on requirement 1, which is completed after 81 time units.

Case Studies

Management organization and the complexity of requirements vary from SoS project to project. Further, component systems that comprise the SoS have different risk levels that add to the complexity and uncertainty of a given SoS. In these case studies, we utilize the exploratory model to test the dynamics underlining the acquisition management in an SoS environment. We explore the impact of span-of-control, requirement dependency, and system risk on the completion-time of an SoS. First, we study the impact of span-of-control by simulating the acquisition process for low and high span-of-control. Then, we simulate twelve scenarios—which result from the combination of low and high span-of-control, dependent and independent requirements, and low, medium, and high risk profile—and study the impact of these project and system characteristics on the project's completion time.

The effect of span-of-control is studied by simulating the acquisition process of the example problem described in Figure 4 for low and high span-of-control. All the values of the input parameters are the same (same probability of occurrence of disruptions and low risk level) for each scenario, while the span-of-control is varied from low to high. Figure 7 present the results for these two scenarios.



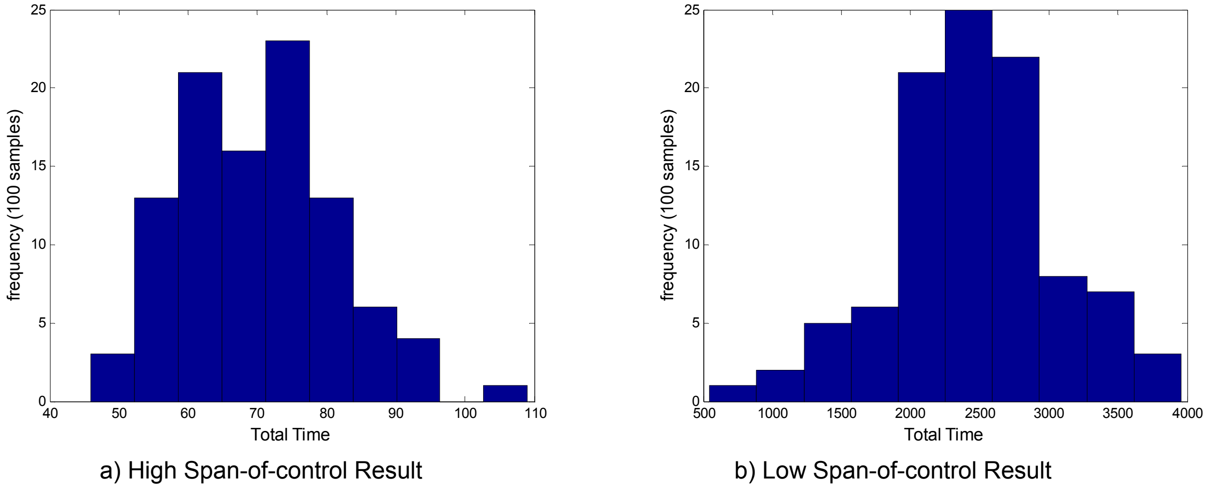
a) High Span-of-control Result b) Low Span-of-control Result

Figure 7. Impact of Span-of-control

Because the example presented in Figure 6 already considered the high span-of-control scenario, the same result is presented here in Figure 7(a). Figure 7(b), on the other hand, presents the results of the scenario when the SoS has low span-of-control. The comparison of these two scenarios makes obvious the impact of the span-of-control parameter. For low span-of-control, the project completion time is about 4500 time units, while high span-of-control permits the completion of the same project in 138 time units.

Since the probability of disruptions is never zero, disruptions inevitably occur that impact the system completeness level and, ultimately, the project completion time. Because the model is probabilistic in nature, 100 different runs are performed for each scenario, and the mean completion time is recorded. To isolate the effect of the random disruptions, we enforce all systems to have the same initial completeness level for all 100 runs; furthermore, we assume that when a disruption occurs, it will not reduce the completeness level below the initial value.

Figure 8 presents a distribution of the completion time for each of these scenarios. As expected, the mean completion time when span-of-control is high (70 time units) is lower than when span-of-control is low (2,474 time units, a 35-fold increase).



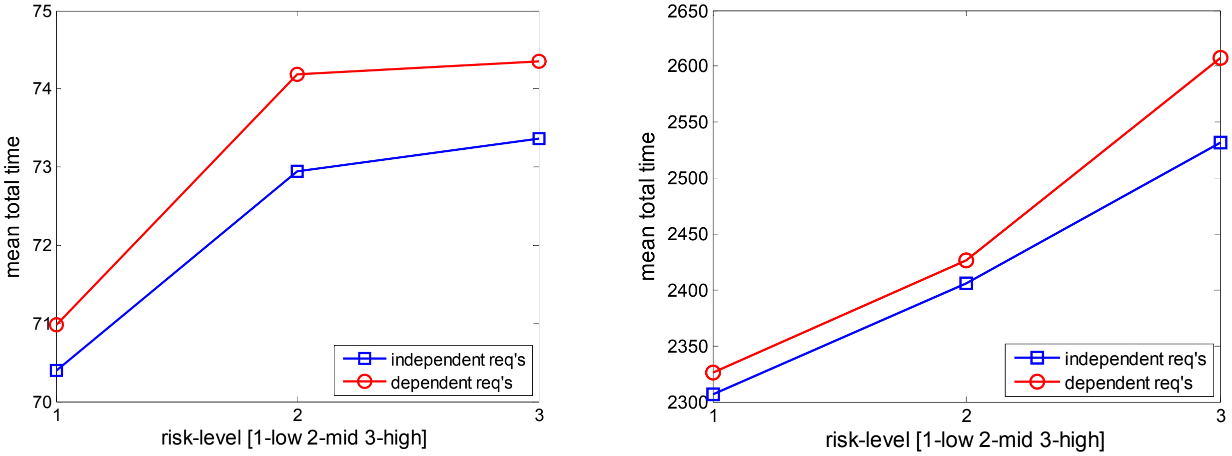
a) High Span-of-control Result

b) Low Span-of-control Result

Figure 8. Distribution for Completion Time for Low and High Span-of-control

This behavior seems reasonable when we consider that when the span-of-control is low, systems are integrated and implemented sequentially, which increases the probability of disruptions. The variance is also lower in the high span-of-control case.

As previously mentioned, the acquisition model also uses risk level to describe the probability of disruptions during the design of component systems. Its impact on the completion time when coupled with span-of-control and requirement interdependency is, thus, also investigated. Figure 9 displays the results for combinations of low and high span-of-control with low, medium, and high risk levels—all for cases of both dependent and independent requirements.



a) High Span-of-control Results

b) Low Span-of-control Results

Figure 9. Comparison of Project and System Characteristics

Each data point in Figure 9 represents the mean completion time after 100 runs. As expected, these mean total time results show that span-of-control has the largest impact on completion time. Additionally, the impact of dependent requirements is much greater in the low span-of-control case. A dependent requirement must wait for the completion of the requirement on which it depends, and when both requirements must sequentially implement and integrate component systems (low span-of-control), the result is a substantial increase in completion time.

The results from these twelve test cases are used next in a sensitivity analysis to quantify the relative importance of each of the three parameters on the total time needed to complete the project.

Sensitivity Analysis

Sensitivity analysis further investigates the impact of the three parameters (requirement dependency, span-of-control, and risk profile) studied in the twelve test cases.

Requirement Dependency: Compare completion time in cases of dependent versus independent requirements while keeping span-of-control and risk profile constant. Table 5 presents the ratio of the mean completion time of the scenarios with dependent requirements to the mean completion time of the scenarios with independent requirements. Risk profiles are labeled “1” for Low, “2” for Medium and “3” for High. These results show that scenarios with dependent requirements take marginally longer when compared to projects with independent requirements. Note, however, that as Figure 9 showed, for low span-of-control, the absolute increase in the mean completion time is still relatively large.

Table 5. Effect of Requirement Dependency

Span-of-control	Risk	Ratio	Span-of-control	Risk	Ratio
1	1	1.008	0	1	1.008
1	2	1.017	0	2	1.008
1	3	1.013	0	3	1.030

Span-of-Control: Compared cases of low versus high span-of-control while keeping requirement-dependency and risk profile constant. Table 6 presents the ratio of the mean completion time of the scenarios with low span-of-control to the mean completion time of the scenarios with high span-of-control. The six results indicate the level of risk of each scenario (labeled “1” for Low, “2” for Medium and “3” for High) and whether requirements are dependent or independent (labeled “I” for independent and “D” for dependent). These results show that low span-of-control increases the mean completion time by a factor of 32.70 to 35.08. Also of note is that the largest increases in completion time occur when requirements are dependent. This is an expected result because dependent requirements are completed sequentially instead of in parallel.

Table 6. Effect of Span-of-control

I/D	Risk	Ratio	I/D	Risk	Ratio
I	1	32.77	D	1	32.77
I	2	32.98	D	2	32.70
I	3	34.51	D	3	35.08

Risk Profile: Compared cases of three risk profiles, while keeping requirement dependency and span-of-control constant. Table 7 presents the ratio in mean completion time between scenarios with risk "2" and "3" and risk "1." These ratios indicate that as risk increases, so does the mean completion time. As expected, the highest increase is observed for high risk levels (risk with value "3") for both low and high span-of-control scenarios. For example: for a project with independent requirements and high span-of-control, the ratio of the mean completion time for a high risk ("3") profile versus a low risk ("1") profile is 1.042.

Table 7. Effect of Increasing Project Risk

I/D	Span-of-control	Risk	Ratio	I/D	Span-of-control	Risk	Ratio
I	1	1	-	I	0	1	-
I	1	2	1.036	I	0	2	1.043
I	1	3	1.042	I	0	3	1.098
D	1	1	-	D	0	1	-
D	1	2	1.045	D	0	2	1.043
D	1	3	1.047	D	0	3	1.121

Results

Some insights gained from testing the exploratory model via the sensitivity analysis are:

1. As expected, time to implement dependent requirements is always greater than the independent case; completion time strongly depends on the span-of-control of the SoS managers and engineers, as well as on the project risk.
2. Time needed to implement projects with higher risk profiles is always greater than the time needed to implement the project with lower risk profiles.
3. The sensitivity analysis shows that the time needed to complete a project is much more sensitive to the span-of-control of the SoS engineers and managers than to the project risk or the dependencies between the requirements.
4. A project with high span-of-control is better equipped to recover from the debilitating disruptions associated with a high risk, thus making the acquisition process more resilient.

Conclusions

We have developed a conceptual model for pre-acquisition and acquisition strategy activities by mapping the sources of complexity to a section of the SoSE Process Model by Sage and Biemer (2007) in conjunction with the 16 technical and technical-management SE processes identified by the *SoS-SE Guide* (DoD, 2008). This mapping and conceptual model provide a basis for a computational exploratory model for acquisition strategy in an SoS environment. The purpose of the model is to explore the complexities that arise in SoS acquisition programs due to evolutionary development of the SoS, heterogeneity of the component systems, as well as the effect of management parameters on the acquisition programs. Based on user-defined inputs for the requirements and their interdependencies, the model uses series and parallel processing to implement and integrate the component systems that comprise the SoS while allowing the impact of disruptors to propagate through the various processes in the acquisition hierarchy.

In this study, we use the dynamic exploratory model to investigate the impact of requirement interdependency, project risk, and span-of-control on the completion time of SoS projects. Results from test scenarios and sensitivity analysis underline the importance of span-of-control of SoS managers and engineers on the timely completion of projects. Projects with a low span-of-control always require more time to complete than projects with high span-of-control. Furthermore, the effects of requirement interdependency and project risk are always overshadowed by the impact of span-of-control. A high span-of-control positively affects completion time by making the acquisition process more resilient and agile in the face of disruptions. While some of these observations confirm intuition, the computational model provides a means to test acquisition and/or management strategies and explore new approaches for the SoS acquisition process.

The uniqueness of the models (both conceptual and computational) lies in their ability to provide decision-makers with a better understanding of the acquisition process in an SoS environment. The models also offer computational tools to aid decision-making for the higher levels of SoS management. We hope that the insights gained from this research will improve the probability of success of future acquisition programs of complex SoS.

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Acquisition of Capabilities through Systems-of-systems: Case Studies and Lessons from Naval Aviation

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Abstract

The acquisition community in many nations faces novel challenges with the transition to systems-of-systems, capabilities-based solutions to meet military requirements. Much of the "tribal knowledge" and experience of those in acquisition, both in industry and government, has stemmed from platform-centred development strategies. It is questionable to what extent lessons from these can be applied to systems-of-systems acquisition. How does the acquisition expert trade off platform capabilities against the capabilities of a network of systems that might be composed of new and existing platforms used in new or old ways?

This paper presents case studies from past and present, illustrating such issues, and seeks to draw out lessons from experience that may be useful. It draws on many years of empirical research, undertaken with those involved in addressing such issues in the acquisition community.

Introduction

Much work in the acquisition community, in many nations, has been undertaken in recent years toward achieving enhanced military capabilities through the use of systems-of-systems, network-centric or -enabled capabilities and through life management of these. This work has been motivated by many different factors—evolving threats and military doctrines, changes in technology, force re-structuring, etc. Central to these efforts has been a desire to achieve interoperability of forces, allowing the deployment of capabilities that, hopefully, are more than the sum of their parts.

While much of this work has rightly focussed on the opportunities offered by new, notably digital, technologies, more prosaic (perhaps what could be seen as "old-fashioned") issues also have a significant impact. Capability depends on the interaction of all system components and their differing characteristics. In this paper, the effects of capabilities of such prosaic issues will be explored, with the focus on one of the oldest "systems-of-systems," the aircraft carrier and its aircraft. In a near century of evolution, the aircraft carrier and military aircraft have evolved both independently and together in the face of, and in response to, changing military needs. The success of their evolutionary ability means that they are still seen as providing important capabilities for the long term.

Aircraft and aircraft carriers form symbiotic system for the delivery of capability. A view of aircraft carriers as mere infrastructure, a floating runway and hangar for the aircraft it carries, misses much of its importance. In order to understand how to acquire such capabilities, we need to understand the interactions between the aircraft carrier and its aircraft. In this paper, the prosaic issues that matter in operating aircraft from ships will be illustrated. This is not to diminish the modern need for digital interoperability, etc., but rather to illustrate how matters such as simply being able to move aircraft around the deck and hangar of a ship in an effective manner can have significant effects on capability.

This paper examines the issue from the perspective of the United Kingdom's Royal Navy and its experiences of deploying Short Take Off and Vertical Landing (STOVL) aircraft onboard its carrier fleet over several decades. Current acquisition policy in the UK is concerned with delivering capability using Through Life Capability Management (TLCM). This is defined as, "translating the requirements of Defence policy into an approved programme that delivers the required capabilities, through-life, across all Defence Lines of Development" (MoD, 2009).

The Defence Lines of Development (DLODs) allow for the co-ordination of the development of the different aspects of capability that are needed to create a real military capability. These aspects are:

- Training
- Equipment
- Personnel
- Information
- Concepts & Doctrine
- Organisation
- Infrastructure
- Logistics

It is only by addressing all the lines of development that the acquisition (and sustainment) community can effectively deliver capability to the UK armed forces, through the various force elements (ships, aircraft, army units, etc.), which are then used to create Joint Capability Packages. These are tailored by a force commander to undertake particular missions or tasks, taking into account coalition forces, threats and the overall operating environment. This is shown in Figure 1.

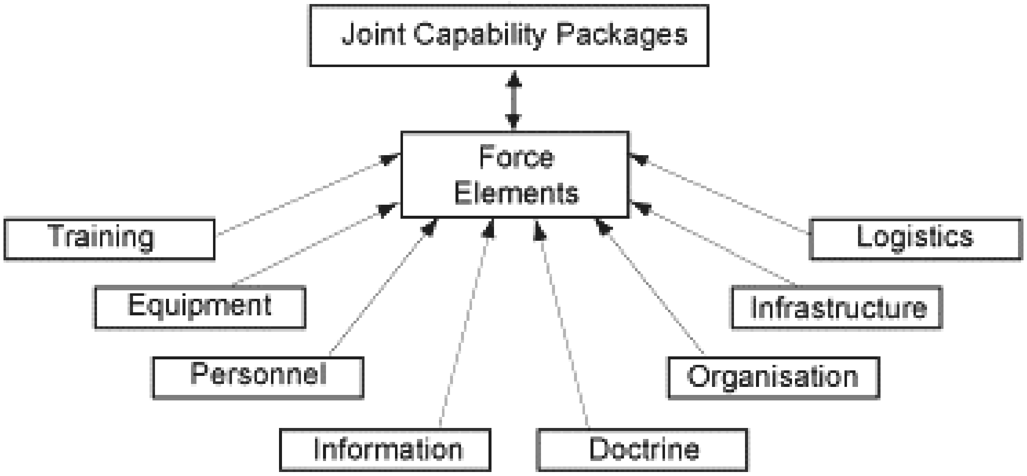

Figure 1. The Role of the UK Defence Lines of Development in the Creation of Capability

The DLODS can therefore be seen as being the primary constituents of capability and forms a useful analytical tool to understand the impact of differing ways of delivering capability. In this paper, we are concerned with the UK Royal Navy's use of STOVL aircraft from its carriers. An illustration of how the choice of STOVL aircraft can impact on the DLODs is shown in Figure 2.

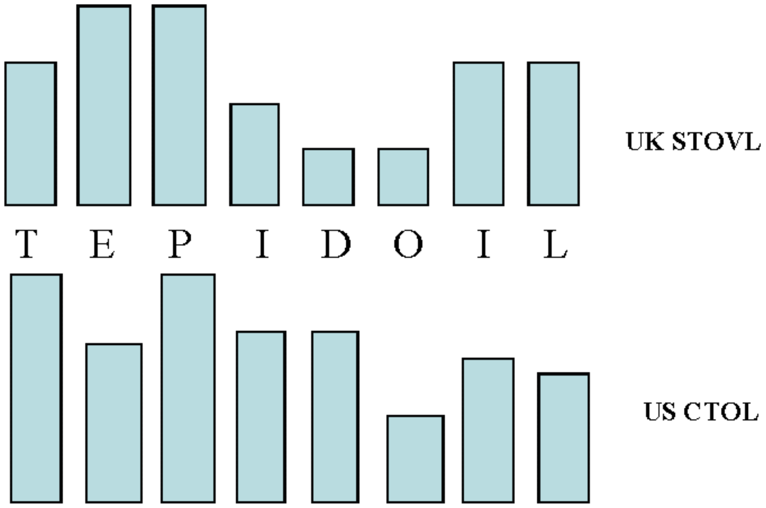

Figure 2. Comparison of UK and US Naval Strike Fighter Costs across the UK Defence Lines of Development
(Stanford, 2008)

This figure illustrates how, for the achievement of a given capability, the costs are allocated for the two examples across the DLODs, due both to the innate differences between two different types of aircraft and also to the differing operational employment of STOVL and CTOL aircraft. The UK STOVL aircraft training costs are lower than for the US aircraft, attributable to the needs of "cat and trap" landings at 140 knots on the US Navy supercarrier. However, the lower warload of the UK STOVL aircraft may account for the higher overall equipment costs while the difference in costs attributable to doctrine is perhaps the most marked, reflecting the greater flexibility of the STOVL aircraft carrier and its aircraft.

While STOVL aircraft may be "easier" to integrate at one level with a ship (with no catapult or arrestor wires and the ability for STOVL aircraft to operate from smaller ships), what this example really illustrates is that the costs are distributed differently for a given capability depending on the nature of the systems used to deliver it. In the case of aircraft carriers and their aircraft, it is important to note that both are complex systems in their own right, with differing design, testing, manufacturing and support approaches. As Andrews (2003) has rightly pointed out, a ship does not have a prototype, unlike aircraft, and therefore, there is a need for the designer to ensure that it is "right first time." However, in the case of an aircraft carrier, it is only once it is operating aircraft, or when a new generation of aircraft are introduced, that it can be determined if the design was indeed right—and that while it may be right first time, it may not be right second time, with new aircraft onboard.

For the acquisition community, the issues attendant on developing and sustaining capability using ships and aircraft in combination present formidable challenges. While traditional approaches to designing them separately may be seen as less than ideal, the rest of this paper will explore how the acquisition process of the past has managed to achieve a large measure of success in doing this, despite being focussed largely around projects rather than overall capability.

Harrier and Invincible Class Experience and Design

One of the main "transformational" military technologies of the twentieth century was the development of aircraft to provide a new dimension to warfare. The impact of aircraft on naval warfare became apparent during World War II, notably in the great battles of the Pacific War, with Japan and the United States relying on aircraft and aircraft carriers as the centrepiece of their fleets. Post-1945, the aircraft carrier continued in this central role in major navies, and helicopters allowed the provision of air power to be extended to smaller vessels and lesser navies.

In the United Kingdom, attempts to sustain a viable force of major aircraft carriers foundered due to budgetary restrictions. Nevertheless, in order to retain a viable naval force, it was recognised (despite considerable inter-service debate) that some form of organic air power was still required to deliver the Royal Navy's key NATO role of anti-submarine warfare in the Eastern Atlantic. This was a highly complex environment with threats from Soviet submarines, surface combatants and aircraft (both land- and ship-based) requiring a mix of capabilities to be able to respond to them.

In order to meet these threats, the Royal Navy was largely forced to adapt the land-based Harrier STOVL strike aircraft to meet their needs. The ability of the Harrier to land on many types of ship had been demonstrated since 1963, from full-size aircraft carriers to the helicopter decks of cruisers. The adoption of the Harrier by the US Marine Corps during the 1970s had led to the regular use of the aircraft from the assault ships of the US Navy, although only those (LPH and LPD) with full flight decks and hangars had Harriers based on them.

The Royal Navy was already planning a fore of anti-submarine warfare (ASW) cruisers during the early 1970s, to operate helicopters only. However, the need for the ships to carry more than six helicopters to meet the submarine threat from the Soviet Union led to the adoption of a “through deck” layout for the ships, essentially a miniature aircraft carrier, and in many ways the same basic layout as the US Navy’s assault ships from which the Harrier was already operating. The recognition of the inability of surface-to-air missiles to fully meet the threat of “shadowing” reconnaissance aircraft of the Soviet Navy (providing targeting data for submarine launched anti-ship missiles) led the Royal Navy to push for the adoption of the Harrier to operate from the new class of ASW cruisers, with a small number of the aircraft operating alongside the helicopters. This led to the development of the British Aerospace (BAe) Sea Harrier, which first flew in 1978 (Brown & Moore, 2003).

However, the design of the ships, which became known as the Invincible class, was largely fixed before the decision to develop the Sea Harrier—HMS Invincible was laid down in 1973, while the Sea Harrier was not funded for development until 1978. This meant that, with the Sea Harrier being an adaptation of the land-based Harrier, neither the ship nor the aircraft was designed specifically for the other. For the ship, the hangar, flight deck, maintenance and stores (fuel, weapons, spares) facilities were all designed around the Sea King ASW helicopter. They were also designed “to have the ability to take future VSTOL” (i.e., STOVL) aircraft, with provision made for STOVL aircraft (in terms of some additional space being allocated and with the aircraft lifts) sized for STOVL aircraft. This latter assumed a generation of aircraft in advance of the Harrier, although it led to the assumption that such an aircraft would have similar dimensions to an earlier STOVL project, which had been cancelled while still under development in 1965: the Hawker Siddeley P.1154. The latter had been essentially a larger, faster, more powerful version of the Harrier concept (Andrews, 2009, February 12).

Adapting the Harrier for use in a maritime environment proved relatively straightforward, with new avionics and minor systems improvements in addition to a more noticeable new front fuselage. As the aircraft was relatively small, major modifications such as wing folding were not required, although the radome folded for maintenance access and to reduce the spotting factor. Tie-down lugs were added to the aircraft’s undercarriage to secure it to the deck, but, all told, “navalisation” added only an extra 100 pounds of weight. This low figure was largely attributable to the ability of the Sea Harrier to land vertically, so eliminating the need for strengthening to cope with arrested landings, as well as the aircraft’s ability to take-off without the need for catapulting, with similar structural “beefing up” obviated (Fozard, 1978).

In place of the catapult, one innovation allowed the Sea Harrier to operate at higher weights from aircraft carriers. This was the “ski jump” ramp, an upwardly curved addition to the end of the flight deck runway that enabled the Sea Harrier to take-off at either lower airspeeds or at higher weights for a given deck run than a “flat deck” take-off. The ramp also offered safety benefits, as it meant that the Sea Harrier should almost always be launched on an upwards trajectory even if the bows of the ship were pointing down, as often happened in heavy seas. Trials on land during the latter half of the 1970s proved the concept of the ramp, and showed that only relatively trivial modifications to the Sea Harrier’s undercarriage were required to allow it to use the new “ski jump” technique (Fozard, 1978; Davies & Thornborough, 1996).

The first installation of the “ski jump” on a ship was on the old light fleet carrier HMS Hermes, which was given a 12-degree ramp during a refit and took Sea Harriers onboard for trials in 1979. These trials showed that the concept would work at sea, although it had already been decided to add ramps to the Invincible class during build—although on the first two ships of the class, the ramp was at the lower angle of 7 degrees. This was due to the ships being fitted with a substantial anti-aircraft missile launcher in the bows, the firing arc of which required the lower-angle ramp. This reduced the benefits of the ramp, but still allowed a useful addition in payload or reduction in take-off run for the Sea Harrier (Brown & Moore, 2003).

Once HMS Invincible had been commissioned and began operating Sea Harriers, it became clear that the two systems had not been designed for each other. The dimensions of the ships’ hangar had been defined by two main constraints—the need to change the rotor head of the Sea King helicopter and by the need for the ship’s own gas turbine propulsion system uptakes to pass next to the hangar. This produced a “dumbbell” shaped hangar that was wider at its ends than in the middle section. While this was adequate for the Sea King, the absence of wing folding on the Sea Harrier did mean that they were already approaching the limits of the hangar width in this area. Even greater strains were caused by the Sea Harrier’s support onboard the ship, with perhaps three times as much fuel, spares, etc., required for each Sea Harrier than for each Sea King helicopter. In addition, the need to remove the wing of the Sea Harrier in order to change its engine meant that a specialised hoist was installed in the hangar, with an engine change requiring the aircraft to be trestled and secured to the hangar floor. The entire engine change evolution could take several days, monopolising a major part of the hangar and reducing the scope for aircraft movements in the hangar (Andrews, 2009, February 12; Davies & Thornborough, 1996).

While these limitations were coming to light, there were benefits to using the Sea Harrier onboard the Invincible class. It quickly became apparent that the vectored thrust engine of the Sea Harrier allowed it to “back taxi” under its own power, reducing the requirement for tractors and towing gear and considerably speeding up the process of moving aircraft to and from parking areas on deck. This meant that landing and take-off cycles could be increased, adding to the other benefits of operating STOVL aircraft such as the ability to dispense with “go around” fuel margins, reduced weather minima and high sortie generation rates.

All these aspects were proven of value during the Falklands conflict in 1982, in which the Sea Harrier and Invincible class both proved their worth in a real conflict (Davies & Thornborough, 1996). Subsequently, both were updated, with the Sea Harrier receiving a new weapons system, and the Invincible class adapted with additional weapons and the ablity to operate a larger number of Sea Harriers (and later land-based Harriers). The anti-aircraft missile system was removed from the ships, allowing an increase in deck area and larger weapons magazines for the aircraft, and further operational experience has proven that these adaptations have been valuable.

Figure 3. Royal Navy Sea Harriers Operating from an Aircraft Carrier during the Falklands War
*Note the proximity of the deck crews, a problem in later studies for a Sea Harrier successor.
(Harrier.org.uk, 2009)

However, it can be seen from this brief and incomplete history that designing the ships and the aircraft as separate projects—only loosely associated during development—came at a considerable price in terms of reduced efficiency and difficulties in operation. These were offset by the personnel of the Royal Navy and Fleet Air Arm who proved adept at coping with these difficulties. However, the costs of the equipment line of development were considerable, and adding costs in terms of personnel, training and additions to the equipment to overcome deficiencies identified during use was undesirable, as was the in-built high logistics cost of the difficult nature of some Sea Harrier maintenance operations and the confined spaces of the Invincible class hangar.

Sea Harrier Replacement Design and Invincible Class

With the experience of the Falklands War and the emergence of new threats for the Soviet Union (notably the deployment of Soviet aircraft carriers, fighters and long-range maritime strike aircraft), meant that by the early 1980s, the Royal Navy was actively pursuing a Sea Harrier replacement programme, in addition to updating the earlier aircraft. One basic assumption was that such an aircraft would be in service during the lifetime of the Invincible class, so it had to be compatible with those ships. This allowed the opportunity to design new aircraft with the issues of operating from the Invincible class in mind, rather than evolving the aircraft design separately from the ship.

As part of the threat analysis and operational research into how to meet such a threat, work in the UK Ministry of Defence (MoD) into the characteristics of a Sea Harrier replacement showed that supersonic speed would be a valuable asset. In meeting a notional attack from Soviet forces, it was seen that a smaller number of supersonic aircraft could cover the threat than was the case with subsonic aircraft using similar sensors and weapons. For some threats, only supersonic speed in the aircraft could provide an adequate response. This issue of aircraft numbers was important as the relatively small size of the Invincible class (plus the ships' need to also accommodate anti-submarine helicopters) meant that the total number of aircraft carried was unlikely to exceed the number of Sea Harriers the ships could accommodate, about 8 STOVL aircraft (Pryce, 2008).

In industrial studies to develop a Sea Harrier successor aircraft (involving British Aerospace and Rolls Royce), the need to provide supersonic speed led to a number of design issues becoming the focus of much work. The most significant of these was that a much more powerful and energetic engine would be needed than that used in the Sea Harrier. This provided a number of environmental difficulties when operating aircraft onboard ships—as the noise, jet temperatures and velocities could adversely impact the deck environment of the ship as well as the aircraft itself to a significant extent (Pryce, 2008). One result of the work was that it was seen that it may be possible that when supersonic STOVL aircraft were hovering in advance of landing, the deck crew might need to use some form of refuge or shelter as the noise level could induce nausea and possible unconsciousness, and the high velocity jets of the aircraft could readily blow crew members overboard (Brooklands Museum Archive File HSA/SHR/047). Clearly, this would be unacceptable, as the role of the deck crew was to enable aircraft operations (see Figure 3).

The effort to obviate such potential risks in the design stage led to a number of propulsion systems and operating techniques that sought to reduce such adverse effects (Pryce, 2008). However, these brought with them a range of operational drawbacks as well—such as the loss of the ability to "back taxi" and the introduction of engines that were too large for the engine maintenance and storage spaces of the Invincible class. A visit by the aircraft design team from BAe to an Invincible class ship revealed further complications that had not been assumed in their design studies, such as ruts in the hangar deck that could mean that if the nose undercarriage of some designs went into such a rut, the tail of the aircraft could "scrape" the hangar roof—despite the ruts only being an inch or so deep. In addition, it was realised that the highly integrated avionics proposed for some of the new aircraft would require a complete re-arrangement of both the maintenance spaces of the ship and the trade structure of the maintenance personnel (Brooklands Museum Archive File HSA/SHR/047).

While these issues were not faced by all the new aircraft designs proposed (and many of them managed to successfully address the existing problems with the Sea Harrier, such as the difficult engine change evolution), it was apparent that the need for supersonic speed and the innate limitations of the Invincible class would cause problems. In the aircraft design studies, it was to be assumed that the ships were not to be modified with special devices such as deck blast deflectors to accommodate the new aircraft. It was discovered that a key limitation was the strength of the ski jump ramp of the ships, as the new aircraft were much heavier, and that strength limitations of the ramp, as well as in the undercarriage of the aircraft, meant that in some cases the aircraft could not take-off with a full load of fuel or weapons (National Archive File AVIA 6/25876).

While the aircraft designers were wrestling with these difficulties, additional analytical studies in the MoD and in BAe showed that further ship/aircraft interaction-dependent characteristics also provided limitations. With only a relatively small number of aircraft carried by the Invincible class, high levels of availability were essential to meet the threats assumed. While the aircraft could possibly be more reliable than the Sea Harrier, it became clear from assessment work of the deck and hangar movements of the aircraft onboard the ship that critical limitations on availability were imposed on all aircraft designs, with reductions in the number of aircraft actually available for operations disproportionately affected by these limitations (Pryce, 2008; Brooklands Museum Archive File HSA/SHR/047).

For example, the ability of the Sea Harrier to "back taxi" under its own power meant that it was able to move quickly into deck parking spaces. However, the configuration of the propulsion systems of the some of the proposed successor aircraft meant that this was not possible, so they would need to be towed around on deck. While a slower process in itself, the realisation that the turning circle of an aircraft plus tow bar and tractor may be much larger than a Sea Harrier meant that not only were manoeuvres slower, but also required greater free deck area to be carried out. Such free area may not be available as the deck was already congested—with many areas used for more than one purpose (see Figure 4), and a "traffic jam" situation would result. Similar problems arose when the size of the aircraft designs reached a point at which the size limits of the lifts or hangar were approached—narrow margins meant much more careful positioning was required, which the crew were likely to have to do much more slowly. It was realised that while crew training and possibly increase personnel numbers may make it possible ways to ameliorate such matters, it was difficult to accommodate additional crew onboard the ship and impossible to show the extent of training required to ensure high levels of availability (Pryce, 2008; Brooklands Museum Archive File HSA/SHR/047).

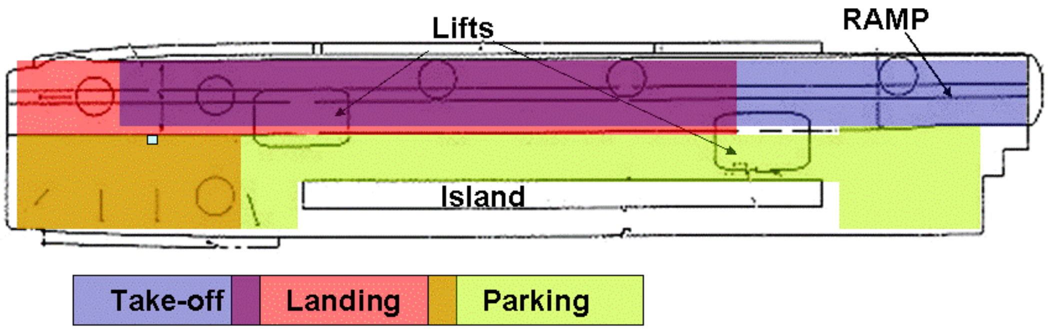

Figure 4. Invincible Class Deck Layout and Uses

(The colours show the different uses of the deck, and how these uses could overlap. An aircraft landing on the deck could slow down take-off operations if it was unable to clear the landing area or to park quickly (Brooklands Museum Archive File HSA/SHR/047).)

Once these ship-dependent aspects of replacing the Sea Harrier were looked into, it became clear that being able to design a new aircraft "around" the Invincible class as it already existed was extremely difficult—as the change in the threat that the new aircraft were intended to meet meant that the aircraft had features that the Invincible class found difficult to accommodate. Attempting to trade-off aircraft performance levels against the deck environment and "traffic" issues on deck also proved extremely difficult, and once wider issues such as the higher fuel/weapon loads of the new aircraft (leading to more frequent replenishment operations) were considered, the work led to the somewhat startling realisation that a new, "better" aircraft could lead to a reduction in capability compared to the Sea Harrier if it had to operate from an Invincible class ship (Brooklands Museum Archive File BAe/PRJ/065—NST.6464).

Harrier/Invincible Experience and CVF/JSF

Although the attempts at developing a replacement for the Sea Harrier foundered during the 1980s, the Royal Navy eventually transitioned to a force of Harrier aircraft operated in conjunction with the Royal Air Force in what is known as Joint Force Harrier. With heavy commitments to operations in Afghanistan, there has been only limited opportunity in recent years to deploy these aircraft aboard the two Invincible class ships still in service, but it is the intention of the Royal Navy to replace these vessels in the next decade with two much larger ships, under the CVF programme.

These vessels are intended to employ the Joint Strike Fighter (JSF), in particular the STOVL F-35B Lightning II version of the JSF. They will, therefore, be able to build upon the experience of STOVL operations at sea built up over many years by the Royal Navy, while at the same time benefitting from being able to design both systems in parallel in order to maximise the capabilities they can provide.

One clear lesson that has been adopted on the CVF programme is that a large ship is helpful in operating even STOVL aircraft, as it gives much more space for moving aircraft around, which has been a problem in past operations and studies. Based on the idea that "air is free and steel is cheap," this appears to be a welcome move, albeit one that may seem to reduce the need for using STOVL aircraft at all. Indeed, the CVF design has been developed so that it can be adapted for the later adoption of CTOL aircraft, including the CTOL version of the JSF. However, this would require not only a significant shift in UK procurement policy but also a re-assessment of all the lines of development for the CVF and JSF. As Figure 2 showed, the costs are distributed differently for the different types of aircraft, although basing them on versions of the JSF should reduce such differences.

Nevertheless, the current plan to deploy STOVL aircraft on the CVF means that the experience built up on the Harrier will be of use. This does not just depend on the service use of the Harrier, but also on research programmes that have used the aircraft. Most notable among these is the VAAC Harrier programme, which has been used to develop the flight control aspects of the STOVL JSF. In the Harrier family, the control of the aircraft was difficult because the pilot had a high work load when hovering the aircraft. For the JSF, the intention is that this can be reduced significantly, requiring much less training and greater flight safety, at the cost of a more complex flight control system.

Tests with the VAAC Harrier have revealed that the control system that came to be preferred from land-based trials needed some modifications when applied at sea (Denham, Krumenacker, D'Mello & Lewis, 2002). In addition, the VAAC Harrier has been used to develop the proposed Shipboard Rolling Vertical Landing (SRVL) technique that will allow the JSF to land at low speeds on the CVF, significantly increasing the "bring back" payload while reducing engine "wear and tear" (Rosa, 2008). While this should allow savings in terms of reduced maintenance as well as operations of the aircraft at higher weights and the deliverance of greater capability, there may be issues to address that may offset these savings in other lines of development, such as training for pilots and deck crew, and the development of additional deck lighting patterns and deck parking arrangements (Hodge & Wilson, 2008).

Further benefits from previous experience with the Harrier, and studies into replacing it, are shown by the adoption of a "ski jump" ramp for take-off. Despite the fact that the CVF is much larger than the Invincible class and that the JSF has a completely different propulsion system, the ramp still gives the same benefits as it did on earlier ships: boosting capability by increasing payloads and enhancing safety, as well as freeing up more deck area for aircraft parking and recovery (Fry, 2008; Rolfe, 2008). This is also assisted by the use of a jet blast deflector, the value of which was first indicated in the Sea Harrier replacement studies. Again, despite the larger size of CVF, the area of deck that it frees up for other uses is of great value, as is the enhancement of the safety of deck crew by reducing the chances of them being blown overboard (Morrison, Dockton & Underhill, 2008).

It is possible that the first aircraft to operate from the CVF will be those of Joint Force Harrier, as the ships may undertake trials (or be in operation) before the UK's JSF fleet is ready to come aboard. If so, the experience of decades of Harrier operation will be able to be directly applied to the new ships, while new lessons about the greater capability of the larger ship could be directly related to the experience of using the Harrier onboard the Invincible class. In addition, such an opportunity could allow validation of some of the Harrier-based research work that has helped to underpin the JSF development. Although the equipment line of development subsumes many aspects of such research and technology programmes, there is little doubt that this work has provided a significant contribution to reducing costs across the lines of development.

Overview, Conclusions and Further Work

This paper has provided a limited view of the vast subject of operating STOVL aircraft from ships. Its aim has been to illustrate how the experiences of the "prosaic" issues covered matter in delivering capability, and how this capability is a product of the effect of these issues across the Defence Lines of Development.

In summary, it is hoped that this paper has shown that aircraft and aircraft carriers may benefit from being designed with each other in mind, but that they need to adapt to changing operational, technical and other circumstances (budgetary!). The timescale for designing, building and operating aircraft and ships extends over many decades, so it is simply not possible to design to a single "point." Flexibility is an important attribute of both STOVL aircraft and aircraft carriers, with both able to contribute to capabilities independently of each other, but the flexibility of the combined system-of-systems that they deliver when brought together depends on an understanding of how the system functions over time. A key aspect of this is that it is extremely difficult, and probably undesirable, to tailor aircraft and ship designs to each other. This is because the lifecycles of each differ, and it may mean that they are then unable to contribute effectively to capability delivery when operated apart.

It is this difficult issue of optimising platforms as part of a flexible system that confronts acquisition managers. While it may be possible to use standards and protocols to ensure interoperability of digital systems or of weapon pylon attachments and other “lesser” mechanically based systems, at the level of complex, independent systems such as STOVL aircraft and aircraft carriers, it becomes a matter of having (at some point) to abandon the quest for an analytical “optimum” solution and instead to use judgement to decide on the best mix of platform characteristics and interactions to deliver capability. It is then up to the skills and bravery of service personnel to adapt the platforms, and to adapt to using them, in order to deliver a truly flexible range of capabilities using the systems they are given.

In order to support those involved in acquisition that need to use such judgement, as well to reduce the burden on service personnel later on, we will end with an outline suggestion for further research that may prove fruitful. Based on the researcher’s own past efforts, and on discussions with practitioners in the field of aircraft and ship design, the researcher would suggest that attempts at understanding the real processes of designing ships and aircraft, understanding how design is done and not just assuming that it is done “by the book,” offers a route to providing a basis for sound judgement. Design is a multi-faceted activity: but from an acquisition perspective, it would appear that understanding the early conceptual, or project design, stage matters most. This is because many of the irrevocable decisions about a platform or system are made at this stage, while trade-offs can be made against other platforms and systems—in an attempt to achieve desired capabilities—relatively cheaply in terms of actual expenditures.

However, doing this in isolation would miss important lessons, and it would appear that learning how to link current use of existing systems to the design of future ones would be useful too. If we can see how the assumptions and decisions of yesterday’s acquisition experts have come to be used by today’s service personnel, perhaps we can learn how to anticipate a little better the needs of the future. Hopefully this paper has made some small contribution to just such an endeavour.

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Panel 4 - Search and Storage Techniques for Enabling Software Reuse

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Wednesday, May 13, 2009

11:15 a.m. – 12:45 p.m.

Panel 4 - Search and Storage Techniques for Enabling Software Reuse

Chair: Carl R. Siel, Jr., Chief Engineer of the Navy; Office of the Assistant Secretary of the Navy (Research, Development & Acquisition)

Discussant: Nickolas Guertin, Director, Open Architecture, PEO Integrated Warfare Systems

Ontology-based Solutions for Software Reuse

Jean Johnson and **Curtis Blais**, Naval Postgraduate School

ReSEARCH: A Requirements Search Engine: Progress Report 2

Craig Martell, Paige Adams, Grant Gehrke, Ralucca Gera, Marco Draeger, and **Kevin Squire**, Naval Postgraduate School and **Pranav Anand**, University of California, Santa Cruz

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Chair: Mr. Carl R. Siel, Jr., currently serves as the Chief Engineer for the Assistant Secretary of the Navy for Research, Development and Acquisition. He provides senior leadership for the integration and interoperability of combat, weapon, and command, control, communications and computers and intelligence systems across Navy and Marine Corps programs, and supports the Assistant Secretary in his responsibility for establishing policy and procedures to manage these activities consistent with Department of Defense directives. Siel was appointed to the Senior Executive Service in May 2004.

Upon receiving his undergraduate degree in Civil Engineering from the University of Dayton, Siel began his civil service career in 1980 as a structural project engineer employed with the David Taylor Naval Research Center in Rockville, MD. In 1985, Siel transferred to the SEAWOLF Class Submarine Program Management Office, Naval Sea Systems Command in Arlington, VA. Under this program, he worked in engineering and acquisition management positions and became responsible for the systems engineering, integration and evaluation of the SEAWOLF Hull, Mechanical, and Electrical Systems. After nearly nine years with the SEAWOLF acquisition program, he was selected as the Director of Advanced Submarine Concepts in 1994 and spent several years developing plans and leading research initiatives to advance the mission capabilities of existing and future submarine classes.

In 1997, Siel joined the Space and Naval Warfare Systems Command in San Diego, CA, where he spent over six years in a variety of engineering and acquisition management positions. In 1998, he was selected as the Deputy Program Manager for the Submarine Communications Program Office and led a multi-faceted communications program focused on enabling the submarine force to fully participate in network-centric warfare operations. He was selected as the Program Manager for Navy Information Security Systems in 2000, where he directed the development, evaluation and fielding of information security systems across Navy ships and shore command sites worldwide. Post September 11, 2001, he was appointed by Commander, Space and Naval Warfare Systems

Command to serve as the Command's Homeland Security Director and was given an Emergency Limited appointment to the Senior Executive Service. In this capacity, he engaged in extensive assessments, evaluations and forums aimed at identifying opportunities to effectively deploy SPAWAR products and capabilities that addressed Homeland Security defense requirements for the Navy, as well as Federal, State and Local law enforcement, emergency service and intelligence agencies.

Siel is a graduate of the DoD Senior Executive Service APEX Orientation Program, Advanced Program Manager's Course, Defense Systems Management College, and a member of the Department of Defense Acquisition Professional Community. He has earned certifications in Program Management and in Systems Planning, Research and Development and Engineering. Siel is also a recipient of the Department of the Navy Meritorious Civilian Service Medal.

Discussant: Mr. Nickolas Guertin's duties as the Deputy Director for OA center on enabling the Navy to buy and build systems as a coordinated enterprise effort. Over the past year, the Naval Open Architecture (NOA) initiative has garnered the attention of both the Chief of Naval Operations (CNO) as well as members of Congress.

Guertin's past duties included Chief Engineer for submarine combat control, which incorporated the business and technical processes of the use of commercial-off-the-shelf (COTS) equipment in the Acoustic Rapid COTS Insertion (ARCI) program. He also served as a systems engineer for submarine sonar—including Acoustic Rapid COTS Insertion sonar system, as a heavyweight torpedo depot engineer, and as a naval shipyard nuclear test engineer. He is also a retired Naval Reserve officer with submarine service and various engineering-duty ship repair and construction assignments, leading up to command of a ship repair team.

Guertin has also sat down with CHIPS to discuss the NOA initiative, its past accomplishments and significant next steps for this effort, which is considered critical to the future of the Navy enterprise.

Ontology-based Solutions for Software Reuse

Presenter: Ms. Jean M. Johnson is a Lecturer in the Systems Engineering Department at the Naval Postgraduate School, Monterey, California. After serving on active duty in the US Navy, she supported the NAVSEA Warfare Systems Engineering Directorate (NAVSEA06) before coming to Naval Postgraduate School. Her current research focus areas are software repositories to enable reuse and the use of modeling and simulation in DoD acquisition. She holds an ME in Operations Research and Systems Analysis and a BS in Applied Mathematics from Old Dominion University and is currently a PhD candidate in Software Engineering.

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Author: Curtis Blais is a Research Associate Professor with the Naval Postgraduate School Modeling, Virtual Environments, and Simulation (MOVES) Institute. His primary areas of research and development include application of semantic web technologies to improve interoperability and for identifying and delivering valued information in network-centric environments such as the Global Information Grid. Blais earned Bachelor of Science and Master of Science degrees in Mathematics from the University of Notre Dame.

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Abstract

The commonly recognized benefits of software reuse are increased productivity, higher quality, shorter time-to-market, and reduced development and maintenance costs. Software reuse is a key thrust of DoD acquisition improvement initiatives including the Naval Open Architecture program. Successful reuse depends on many aspects of a reuse program, ranging from organizational climate to technical solutions. As technical solutions, current software repositories do not provide robust search and discovery capabilities due to limitations of current information organization practices.

This research explores potential solutions that are enabled when ontologies are used as the framework for information contained in the software repository. In this paper, we will briefly summarize previous work on an ontology-based repository framework. We will then present current efforts to specify a software repository tool that exploits the framework to enable more sophisticated search and discovery.

The suggested tool will emphasize human interaction and allow users to bring their context to the search process. New navigation techniques will be employed that guide human users, offering suggestions based on projected needs. The improved search capability will encourage developers to consider reuse and aid in its success.

Introduction

In August 2006, Program Executive Officer of Integrated Warfare Systems (PEO-IWS) established the Software Hardware Asset Reuse Enterprise (SHARE) repository to enable the reuse of combat system software and related assets. In July 2007, the Naval Postgraduate School (NPS) was tasked to develop a component specification and ontology for the SHARE repository.

A description of SHARE and the requirements for a component specification and ontology supporting this repository are available in Johnson (2008). A vision of the component specification and ontology for the repository framework, a brief survey of initiatives and technologies relevant to desired repository capabilities, a development approach, and initial design are described in Johnson and Blais (2008, March). In Johnson and Blais (2008, September) we provided the initial component specification and ontology for the repository framework, as well as initial information models supporting future implementation of stronger semantic representations of assets and artifacts in the repository.

This paper and presentation summarize the previous work and discuss the current research being conducted, which will result in a requirements specification for improved software repository tools.

Repository Framework

In Johnson and Blais (2008, March), we proposed a repository framework for SHARE, consisting of two major aspects: a component specification and ontology. The component specification is a description or model of the items in the repository and consists of two parts: metadata and software behavior representation. The ontology describes concepts and relationships to create various perspectives or contexts for examining the contents of the repository. These aspects of the framework are discussed below.

1. Component Specification: Metadata

The metadata for each artifact should incorporate all necessary data for discovery and implementation. The metadata will aid repository users in determining if the item is suited for their use and will provide information about how to use the asset when it is retrieved. We refer to this as “standard” or “typical” metadata since there are many existing examples of metadata we can use to develop the metadata for SHARE.

We developed a metadata schema for the SHARE repository and presented its details in Johnson and Blais (2008, September). An initial list of required asset information developed by the SHARE Program Office at Naval Surface Warfare Center, Dahlgren, VA, was used as a starting point. We began by creating an Extensible Markup Language (XML) Schema for this metadata set and then enhanced the schema based on a more current “wizard” that leads a user through the SHARE asset information entry process.

After careful analysis of this initial schema, as well as known metadata examples found in existing software repositories, we began to modify the schema by reorganizing the data and complementing the fields with information that should be included. We also incorporated the necessary information to place each artifact in the appropriate context based on the ontology development. Finally, we evaluated the schema against the minimum requirements of the DoD Discovery Metadata Specification (Deputy Assistant Secretary of Defense, 2007) to promote future exposure of SHARE contents across the DoD Enterprise.

The most significant recommended change to the current SHARE approach to handling metadata is the level of application. It is our assertion that to enable the satisfaction of repository user needs, metadata must be applied at the artifact level rather than at the asset level, which is the current methodology for SHARE.

To be clear, we must provide our definition of these two concepts. The Navy Open Architecture (OA) program has adopted similar definitions for asset and artifact as those used in the Object Management Group (OMG) Reusable Asset Specification (RAS). In the RAS, artifacts are defined as “any work products from the software development lifecycle,” and assets are a grouping of artifacts that “provide a solution to a problem for a given context” (Object Management Group, 2005, p. 7). Accordingly, the RAS describes an approach for packaging artifacts into an asset.

This is consistent with the current SHARE approach and remains consistent in the proposed metadata schema. However, the current SHARE approach is to package artifacts into assets at the convenience of the submitter and to enable the current retrieval process. We believe it is more useful to enable packaging of artifacts into assets based on users’ needs. This means that the grouping of artifacts into an asset should have the capability of being user-defined. In order to enable this approach, the users must be able to discover the artifacts of potential value to their particular context in order to solve a particular problem and then package those artifacts into an asset for retrieval.

Therefore, the proposed metadata schema includes separate definitions of structures for artifacts and assets. This does not preclude the pre-packaging of artifacts into assets for submission to the repository or for extraction to solve common problems. We envision the capability for users to discover a problem solution by either locating a prepackaged (reusable) asset or by building an asset from artifacts they believe will help solve their particular problem.

Splitting the metadata into two schemas, one for assets and another for artifacts, also enables a clearer distinction about the data that needs to be collected for each. For example, the current SHARE metadata collects data on the type of artifacts included in the asset, such as whether they are documents or code. Then, it separately asks for thousands of lines of code (KSLOC) for the asset. This would more likely be tied to particular artifacts that are of the type “code” in the asset. By separating the asset and artifact schemas, we can better distinguish the necessary data for an asset from the necessary data for an artifact, and we will be able to manipulate the data more appropriately with tools that implement the search.

Collecting metadata information for each artifact may seem like a daunting task when compared to the current method. However, it is highly likely that a good portion of the metadata that applies to one artifact also applies to the remaining artifacts in a group of submitted artifacts. The submission tool can be constructed to minimize duplicative entries of data by prompting users to verify that the information being entered applies to all the artifacts in a group. This construction would minimize the individual entries required in the submission and metadata collection process. It is also possible to create tools that automate much of the metadata collection from the artifacts themselves. Other organizations are conducting research and development to auto-generate metadata from the source products.

This is a critical capability in making legacy content available for search and discovery. Adoption of structured metadata makes autogeneration feasible, although certainly nontrivial. This is a recommended area for future research and development in the SHARE program.

Artifact Schema

The artifacts schema is designed to be flexible in its implementation. All the elements, types and attributes in the schema are defined globally so they can be reused in other schemas that developers may create for working with artifact information. The root element, *Artifacts*, is simply a container for any number of artifacts contained in a single instance of the schema, as shown in Figure 1. Repository managers and tool designers can decide if they wish to keep a separate XML file describing each artifact or if they prefer to group multiple artifact descriptions into a single XML file.

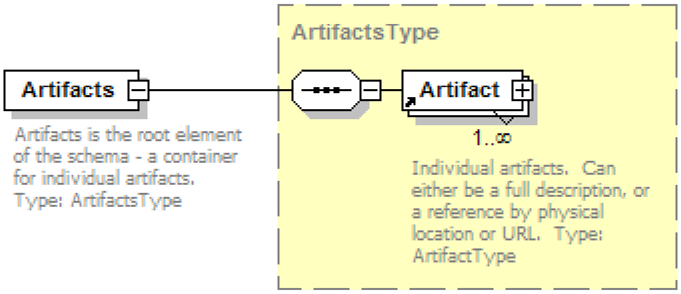


Figure 1. Artifacts Element

The individual descriptions of each artifact are also designed to be flexible. A specific artifact can be incorporated into the file in one of three ways. The first is by providing the full artifact description. This full description represents the heart of the metadata development effort and should be considered the preferred method for representing an artifact. However, if the full description is not available, or if the information required is provided in some other location, the schema allows the inclusion of the artifact representation by reference—either to a physical location or by URL. This is shown in Figure 2.

The full description of each artifact, contained in the element *ArtifactFullDescription*, is composed of eight sub-elements as depicted in Figure 3. Each sub-element is discussed in detail in Johnson and Blais (2008, September).

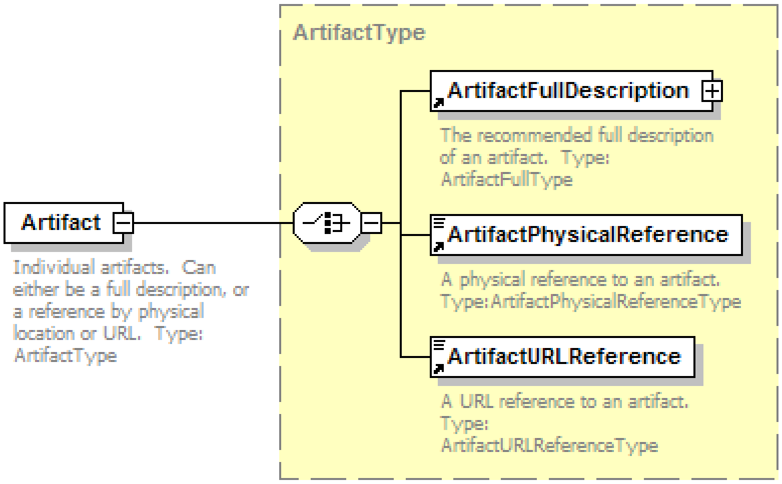


Figure 2. Artifact Element

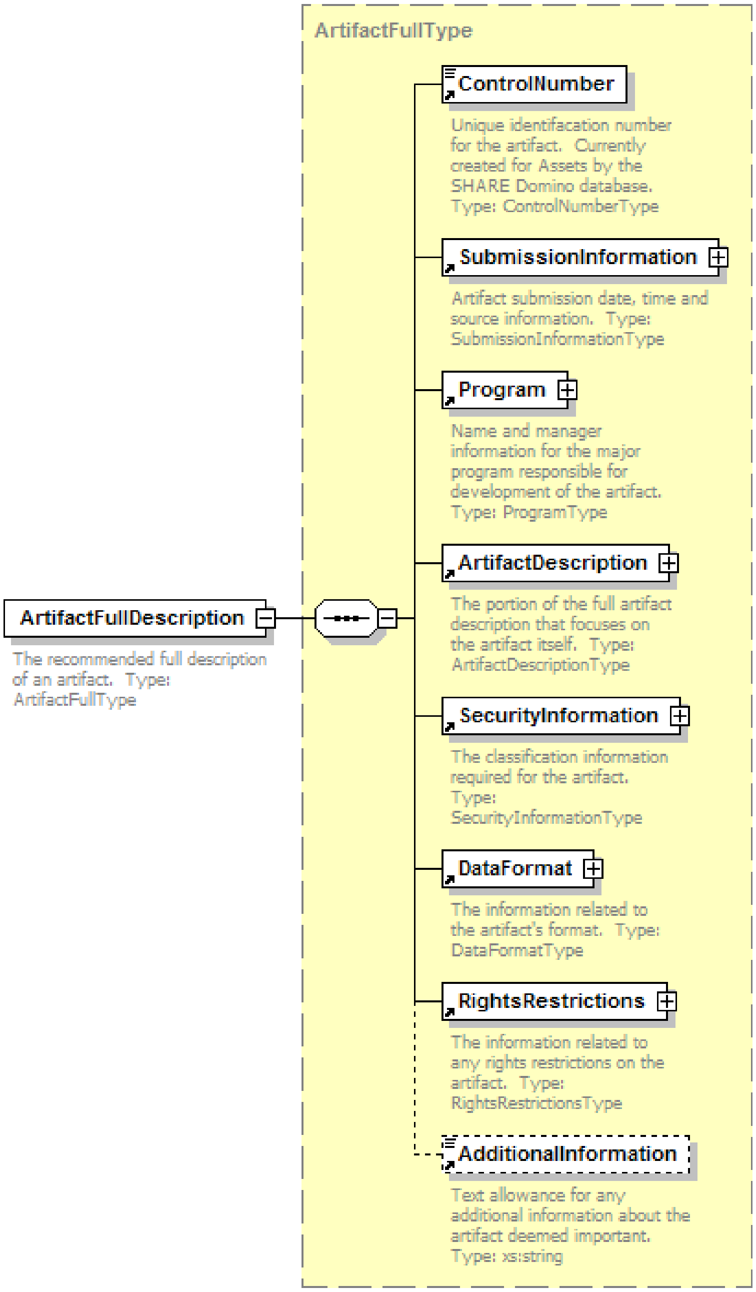
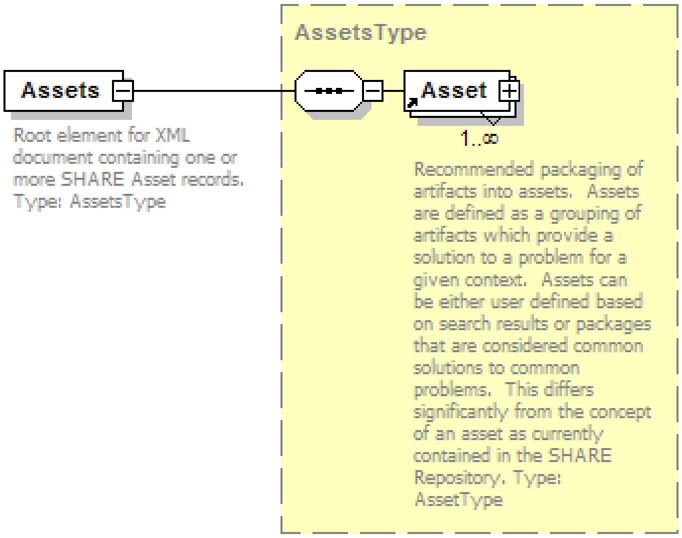


Figure 3. Artifact Full Description Element

Asset Schema

In the preceding description of artifacts, we see that much of the detail about a submission has been moved to the artifact level. The information needed to describe an asset is thus simplified to be primarily an identification of the artifacts contained in the asset. The root element of the assets XML structure is a container for one or more asset records, as shown in Figure 4. The proposed top-level XML structure for an asset is shown in Figure 5.



Root element for XML document containing one or more SHARE Asset records. Type: AssetsType

Recommended packaging of artifacts into assets. Assets are defined as a grouping of artifacts which provide a solution to a problem for a given context. Assets can be either user defined based on search results or packages that are considered common solutions to common problems. This differs significantly from the concept of an asset as currently contained in the SHARE Repository. Type: AssetType

Figure 4. Assets Root Element

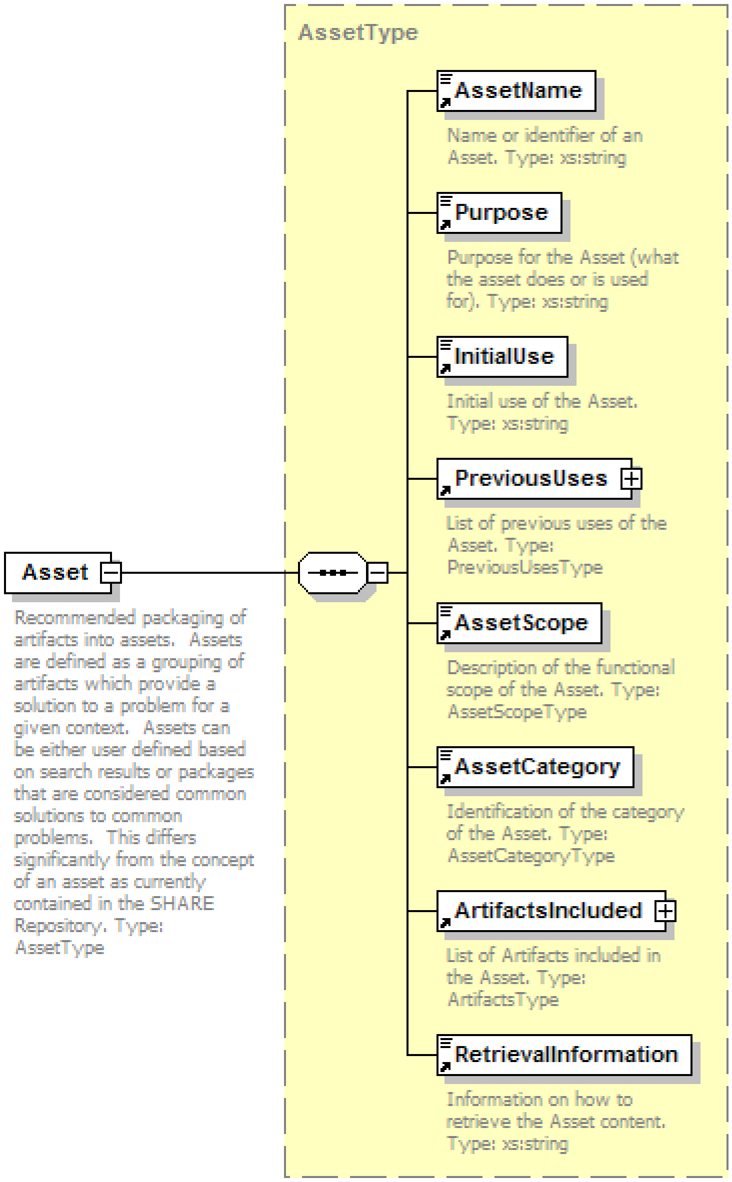


Figure 5. Asset Element

The remaining sub-elements of the asset schema are described in Johnson and Blais (2008, September).

2. Component Specification: Software Behavior

The metadata for many current repositories fail to capture a searchable representation of the behavior of the items outside general categories of functionality (e.g., Archiving Compression Conversion, Control Flow Utilities, Graphics, and Security) and text-based search of code descriptions. Unlike current practice, the SHARE component specification will consist of both typical metadata and a behavioral model of the component. Since this piece of the component specification is not commonly incorporated into repositories in a standardized manner, we feel it is a specific focus area to identify the appropriate representation mechanisms for software behavior in the repository context.

One of the loftier goals of a software repository is to support automatic composition of systems from reusable components. This is a difficult problem, which many have tried to solve.[1] It is especially difficult if the components were not originally designed for reuse. As a necessary first step towards more sophisticated uses of a repository, behavioral descriptions must be machine-readable in order to support automated search and discovery. Furthermore, the behavior descriptions must be formalized and consistently applied to each item in the repository if the intent is to automatically compose them into a larger functioning system.

In our efforts towards standardized specification of software behavior for the SHARE repository, we have sought a balance between method robustness and ease of implementation. Each type of presented representation offers advantages for certain purposes. However, it is recognized that the array of contributors to SHARE requires caution in dictating standards that will impact the development processes of the asset developers.

We explored characterization of software interfaces based on current and emerging Web Services (e.g., WSDL) and Semantic Web Services (e.g., WS-BPEL, OWL-S) approaches. However, the work is preliminary, since the current approach to describing code artifacts making up an asset is extremely limited. It will be necessary to adopt a more precise description of code artifacts to introduce these techniques. As a start, we included the option of inserting a WSDL description of software services in the *SoftwareBehaviorDescription* element.

We also proposed a near-term solution that uses domain information to standardize descriptions of software functionality; namely, the well-established Common System Function List (CSFL).[2] We developed a taxonomy based on the CSFL and incorporated fields into the metadata (XML schema) that will assign functions to repository items. If we require asset submitters to state the functionality of the components in these terms, we can then build the tools to guide users in selecting desired behavior in the same terms.

The CSFL was captured in an OWL structure to use as an initial characterization of software behavior. The process by which the taxonomy was generated is a good example of methods for creating a practical set of structured data from initial raw formats. The taxonomy was constructed from a Microsoft Excel spreadsheet (CSFL version 3.0). The spreadsheet provided definitions of the domains and functions, identified what the domain or function is derived from and identified sources of the definitions. Microsoft Excel provides the capability to export the content of the spreadsheet to XML format. A simple Extensible Stylesheet Language for Transformations (XSLT) was written to transform the source XML format (spreadsheet data) to a target XML format (OWL). The transformation created a simple class/subclass hierarchy expressed in OWL. A portion of the resulting OWL structure is shown in the Protégé ontology editing tool in Figure 6.

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[1] The proceedings from the International Symposium on Software Composition, an annual event, provide examples of research into the breadth of research topics currently being pursued in the area of software composition. The website for the 2008 conference is located at http://www.2008.software-composition.org/

[2] DoD Warfighter Service Components in the DoD Enterprise Architecture Service Component Reference Model are derived from the DoN CSFL.

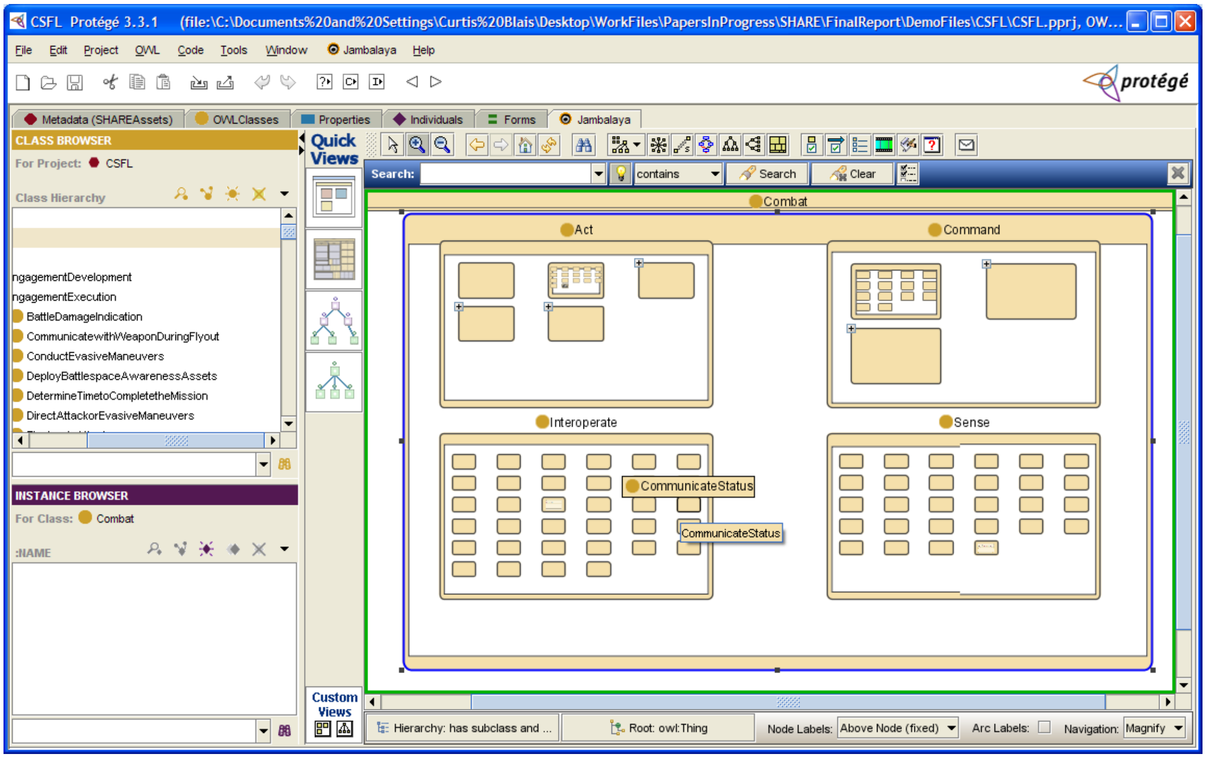

Figure 6. Portion of the CSFL Taxonomy Displayed in Protégé under the Jambalaya Graphics Tab

Other similar lists have been developed for operational activities (i.e., the Common Operational Activities List (COAL)) and for information elements (Common Information Element List (CIEL)). It may be valuable to also capture these in OWL classes and then create interrelationships across the classes (e.g., what information elements are generally employed in performing certain system functions and what information elements are generally produced by performing certain system functions, etc.). Further exploration with subject-matter experts is needed to determine potential benefit from such approaches.

Although we cannot solve the software composition problem in the near-term, initial descriptions of software behavior through identification of functionality and specification of interfaces are necessary steps toward that capability. These intermediate steps toward formalized behavior descriptions will prove useful in the near-term and helpful in advancing long-term goals.

3. Ontology of Framework Relationships

The framework ontology includes descriptions of the component relationships to form a contextual model of the repository items.[3] These relationships may include the component's use/role in existing systems, its mapping to reference or domain architectures, and its utility in various software development lifecycle phases. Contextual information about

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[3] Throughout the document, *ontology* is used as a general term for describing concepts and relationships among concepts, with *taxonomy* as a special case in which the classes in the ontology are related by a single property, such as "is-a" or "has-a."

the artifact can be exploited to enable sophisticated search and discovery methods that more closely match recommended retrieval items to a user's problem context.

Assets and artifacts in the SHARE repository can be examined from a number of perspectives, reflecting a variety of associations. We chose to create initial classification schemes that can provide benefit in the near-term. The resulting taxonomies and ontologies are meant to be illustrative, not exhaustive. The taxonomies/ontologies we developed for SHARE are based on several types of relationships between the items in the repository, as well as with relevant domain architectural descriptions and other information. They capture an artifact's place in the software engineering lifecycle (see Figure 7), its architectural fit in its original system (see Figure 8), its architectural fit in any system in which it was subsequently used, identification of the component's fit in the Surface Navy Objective Architecture (see Figure 9), and the semantic relationships of various documents in the repository. Each of these ontologies is discussed in detail in Johnson and Blais (2008, September).

This enriched semantic specification of the assets in the SHARE repository will enable users to more readily find resources that meet their needs in their context. Extensive work in the Web community is providing tools and techniques that can be applied to the framework when it is based on these ontologies. We have created an initial semantic foundation on which enhanced capabilities can be implemented.

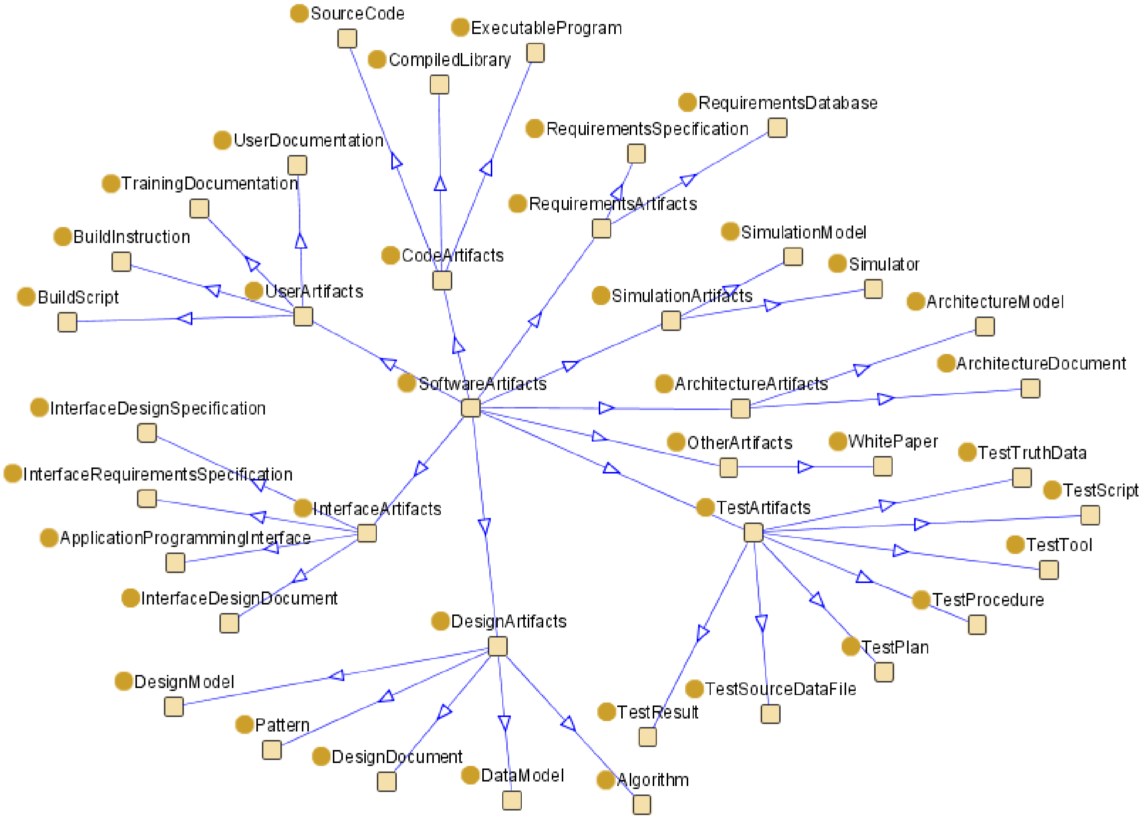

Figure 7. Software Artifact Taxonomy

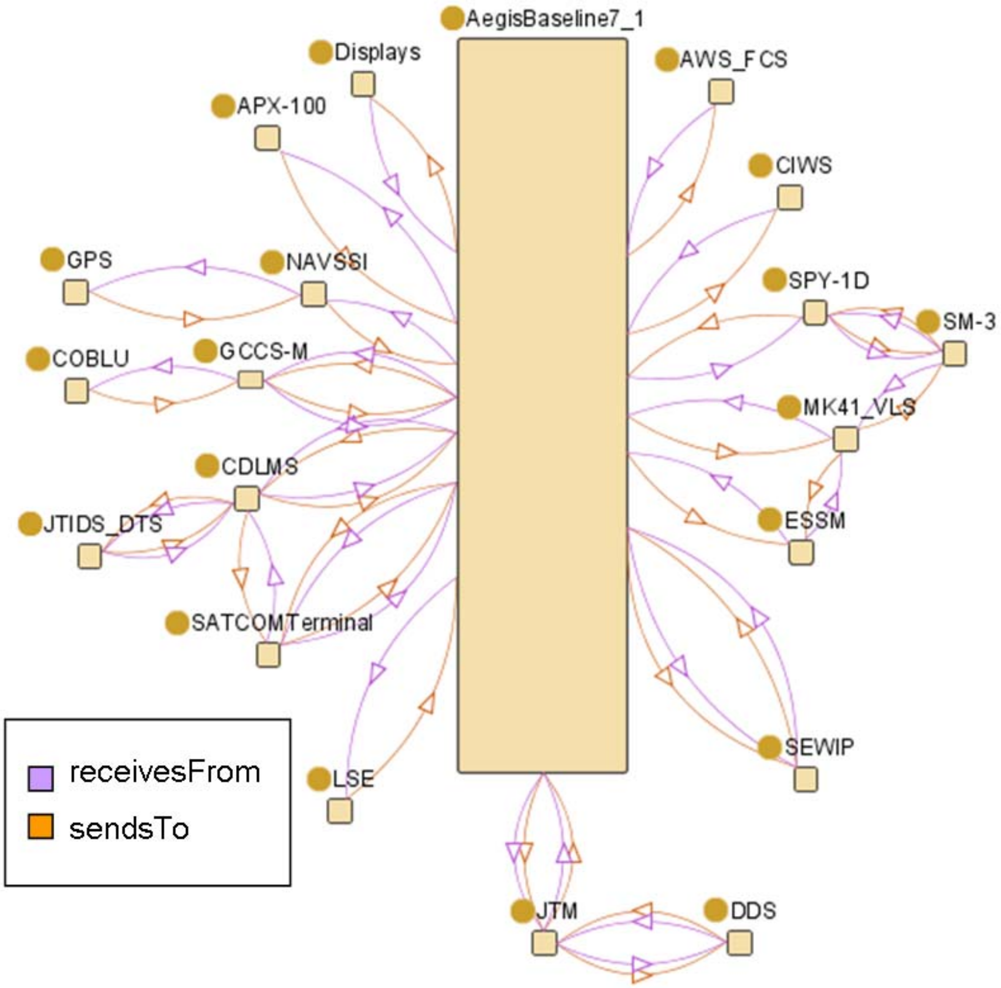

Figure 8. System Ontology Example (AEGIS)

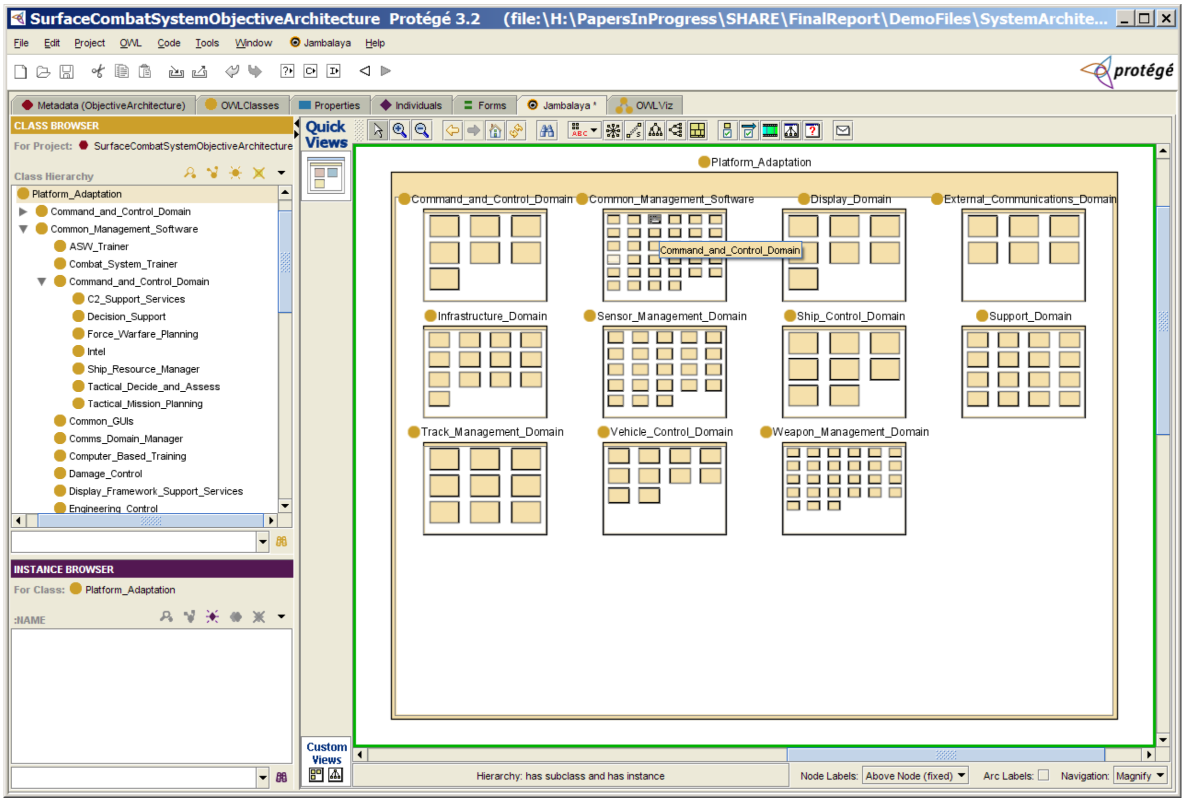

Figure 9. Surface Combat System Top-level Objective Architecture Described as a Taxonomy in OWL (Jambalaya Graphic Tab in Protégé)

Current Research

Current research efforts focus on designing repository tools that allow for guided navigation of artifacts in software repositories. These tools will take advantage of the improved repository framework developed during the previous effort. The value of the repository tools will be demonstrated through use case demonstrations, sponsor evaluations, and a focus group study.

The results will be detailed requirements specifications for user tools associated with the new repository framework, including specifications for both the repository user interface tool as well as the asset-submission tool. The repository user interface tool will enable multiple views of repository contents for improved search efficiency. The tool will be open-ended to allow extension based on the domain knowledge of the repository manager and users. The asset-submission tool will aid software developers in properly describing and characterizing items as they are submitted into a repository. When implemented as a repository system, these products will enable sophisticated search and discovery of reusable artifacts and maintenance of the repository, which will improve the current state-of-the-art.

Summary

Each piece of the repository framework enhances the search capabilities in different ways. The basic metadata in the XML schemas provides search criteria for finding components of interest in the repository as well as specific information about the artifacts in order to determine if they are appropriate for retrieval. OWL taxonomies and ontologies enable identification of functionality and associated resources that may be beneficial to users. In short:

- The metadata is evaluated to enable retrieval decisions.
- The software behavior representations enable searches based on functionality.
- The ontologies point users to helpful artifacts they may not have initially considered.

The current efforts will result in designs for repository tools that will take full advantage of the repository framework to enable guided search and discover as well as asset submission.

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ReSEARCH: A Requirements Search Engine: Progress Report 2

Presenter: Craig Martell

Authors: Paige Adams, Pranav Anand, Grant Gehrke, Ralucca Gera, Marco Draeger and **Kevin Squire**

Abstract

This research addresses three closely related problems: (1) Most current search technology is based on a popularity metric (e.g., PageRank or ExpertRand) but not on the semantic content of the document. (2) When building components in a service-oriented architecture (SOA), developers must investigate whether components that meet certain requirements already exist. (3) There is no easy way for writers of requirements documents to formally specify the meaning and domain of their requirements. Our goal in the research presented here is to address these concerns by designing a search engine that searches over the “meanings” of requirements documents. In this paper, we present the current state of the ReSEARCH project.

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Panel 5 - Assessing System Maturity

Wednesday, May 13, 2009 **1:45 p.m. – 3:15 p.m.**	Panel 5 - Assessing System Maturity
	Chair: Rear Admiral William E. Landay, III, US Navy, Program Executive Officer SHIPS
	Using a System Maturity Index to Monitor and Evaluate the Development of Systems
	Brian Sauser, Romulo Magnaye and **Jose Ramirez-Marquez**, Stevens Institute of Technology
	Dynamic Multipoint Optimization Application to Corporate Portfolio Management
	Robert Cuellar, DoD, and **Brian Sauser**, Stevens Institute of Technology
	Implementation of a Methodology Supporting a Comprehensive System-of-systems Maturity Analysis for Use by the Littoral Combat Ship Mission Module Program
	Eric Forbes, Richard Volkert, Peter Gentile and **Ken Michaud**, Northrop Grumman Corporation

Chair: Rear Admiral William E. "Bill" Landay, III, graduated from the United States Naval Academy in 1978 and was commissioned as a Surface Warfare Officer. His first assignment was as gunnery assistant and combat information center officer aboard USS *Hepburn* (FF 1055). Subsequent sea tours included Ship Control Officer aboard USS *Nicholas* (FFG 47), Commanding Officer of USS *Aquila* (PHM 4), and commanding officer of USS *Paul Hamilton* (DDG 60). During Landay's tour, Paul Hamilton was awarded the Battle Efficiency "E" for operational performance, two Silver Anchor awards for retention excellence and the Spokane Trophy for outstanding Combat Systems Readiness.

Ashore, he has served as a team training instructor and Harpoon course director at Fleet Combat Training Center, Pacific; C4I Program Officer and Executive Assistant to the Director of Command, Control, Communications and Computer Systems at the United States Transportation Command. Acquisition tours included assignment as Surface, Strike and Underwater Warfare Manager and Fleet Support Officer in the AEGIS Program Office; Executive Assistant to the Commander, Naval Sea Systems Command; Deputy for Fleet and Lifetime Support in the Program Executive Office, Theater Surface Combatants; and Executive Assistant and Naval Aide to the Assistant Secretary of the Navy (Research, Development and Acquisition). As a flag officer, he served as the Program Executive Officer for littoral and mine warfare from 2004 through 2005, as Chief of Naval Research, Deputy commandant of the Marine Corps for Science and Technology and director, Test and Evaluation and Technology Requirements from 2006 to 2008.

In August 2008, Landay became Program Executive Officer for Ships.

He holds a Bachelor of Science in Systems Engineering from the Naval Academy, a Master of Science in Systems Technology (C4I) from the Naval Postgraduate School and is a graduate of the Program for Management Development at the Harvard Business School. He was the 1998-99 Navy Fellow in the Defense Systems Management College, Military Research Fellowship Program. He is a level-3 certified acquisition professional and a proven subspecialist in C4I Systems.

Landay's personal awards include the Distinguished Service Medal, Legion of Merit (3 awards), Defense Meritorious Service Medal, Meritorious Service Medal (2 awards), as well as various unit awards.

Using a System Maturity Scale to Monitor and Evaluate the Development of Systems

Presenter: Romulo B. Magnaye received his BS in Mining Engineering and MBA from the University of the Philippines and a postgraduate research Diploma in Mineral Technology from Camborne School of Mines in England. He is currently a Robert Crooks Stanley fellow pursuing his PhD in Engineering Management at Stevens Institute of Technology in the School of Systems and Enterprises.

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Abstract

The readiness of a system under development cannot be adequately measured by using traditional project management tools that focus predominantly on cost and schedule.

An alternative principally utilized by NASA, the DoD and the DoE to address this has been the prescriptive metric known as Technology Readiness Level (TRL). However, TRL is only meant to measure the readiness of technology elements and does not address their integration or some other challenges of systems development.

To address integration, the Systems Development & Maturity Laboratory (SD&ML) at Stevens Institute of Technology introduced another prescriptive metric called Integration Readiness Level (IRL). Combining TRL and IRL scales, SD&ML has formulated a System Readiness Level (SRL). SRL is an aggregate measure that characterizes the progress that has been accomplished by a system under development based on the observable readiness characteristics of the technology and integration elements, not the cost and schedule values.

This paper describes the application of SRL to a constrained resource optimization model to determine an optimal development plan that identifies which technologies and integration elements should be matured to which levels such that a specific level of system readiness is achieved by a certain time. This optimal plan can be used to monitor and evaluate the actual progress of the system—it can be the basis of a systems lifecycle maturity management approach called System Earned Readiness Management (SERM). A simple example is used to illustrate SERM.

1. Introduction

“How much progress have I accomplished against my original plan?” Program managers ask this is the fundamental question in order to keep track of the development of their systems. To answer this, they have relied on assessment and evaluation tools. Abba (1997) describes the evolution of these techniques from the “Spend Plan” approach to Program Evaluation and Review Technique (PERT), which was then modified by the Navy into PERT COST in an attempt to improve cost management in 1960. Combining its own experiences with those of the Navy’s, the Air Force in 1963 formulated the earliest version of an Earned Value Management (EVM) approach by developing Cost/Schedule Planning and Specification (C/SPEC) to manage the Minuteman program. This initiative evolved into the 1967 Department of Defense (DoD) Instruction called Cost/Schedule Control Systems Criteria or C/SCSC (DoD, 1967). Initially developed by financial managers, C/SCSC was primarily concerned with cost and was generally ignored by project managers who were more concerned with technical and performance considerations (Abba, 1997). In 1989, the organization within the DoD tasked with C/SCSC was transferred from the Controller’s office to Acquisition. By 1995, EVM was designated as the preferred tool for managing risky, cost-based contracts (Kaminski, 1995). Along with these developments, the DoD also developed the pioneering EVM software *Performance Analyzer.* The DoD encouraged the private sector to enhance and eventually replace this software with tools that are commercially available today.

EVM as a primary tool has been credited with reducing total cost overrun on the largest, most risky DoD contracts to 5.5% by 1999, (Abba 2001). Currently, however, there is growing concern that EVM, which evaluates cost and schedule performances, does not adequately report the proper maturation of complex systems under development. In particular, while EVM is quite effective in capturing and representing the accomplishment of work packages, it is unable to state whether these completions are actually leading to the maturity of the system’s critical components. Thus, it is unable to estimate the maturity or readiness of the entire system at a given time during its development. This is especially true when there is a high degree of uncertainty due to the novelty and high technological content of the system. Such systems require numerous iterations before requirements and design can be frozen. Once they are, then EVM becomes a most effective tool. However, until that point in a system's development is reached, a different kind of assessment method is needed.

This new assessment method will require the following elements: metrics that can measure maturity of technologies—their integration links and the system itself; the identification of optimal development plans (based on these metrics) that can meet the development strategy of the system; and a mechanism for reporting the periodic status of the system against the optimal development plan so variances can be measured, explained and corrective measures may be formulated.

To begin to address these elements of an alternative or modified EVM approach, we will describe the application of a system maturity metric (i.e., System Readiness Level) and its application to a constrained resource optimization model to determine an optimal development plan that identifies which technologies and integration elements should be matured to which levels, such that a specific level of readiness is achieved by a certain time. We will then use the optimal plan to demonstrate how this technology can be used to monitor and evaluate the actual progress of a system. Thus, it can become the basis of a system's lifecycle maturity management approach, which we have defined as System Earned Readiness Management (SERM). We conclude with a simple example to illustrate SERM.

2. System Readiness Metrics

In order to measure the maturity of a complex system, Sauser, Verma, Ramirez-Marquez, and Gove (2006) proposed the System Readiness Level scale or SRL. This was eventually refined into its latest form, which was presented to this Symposium last year (Sauser, Magnaye, Ramirez-Marquez & Tan, 2008b) and later published in length in the *International Journal of Defense Acquisition Management* (Sauser, Magnaye, Ramirez-Marquez & Tan, 2008a). It combines the widely accepted Technology Readiness Level (TRL) scale (Mankins, 1995; 2002; DoD, 2005), which is used to evaluate critical technology elements and an Integration Readiness Level (IRL) scale developed by Sauser et al. (2006) and refined by Gove (2007). TRL is presented in Table 1 while IRL is shown in Table 2 below.

Table 1. Technology Readiness Levels

TRL	Definition	Description (DoD, 2005)
	Actual System Proven Through Successful Mission Operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.
8	Actual System Completed and Qualified Through Test and Demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
7	System Prototype Demonstration in Operational Environment	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft
6	System/Subsystem Model or Prototype Demonstration in Relevant Environment	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
5	Component and/or Breadboard Validation in Relevant Environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include “high fidelity” laboratory integration of components.
4	Component and/or Breadboard Validation in Laboratory Environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of “ad hoc” hardware in a laboratory.
3	Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
2	Technology Concept and/or Application Formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
1	Basic Principles Observed and Reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.

Table 2. Integration Readiness Levels

(Gove, 2007)

IRL	Definition	Description
9	Integration is **Mission Proven** through successful mission operations.	IRL 9 represents the integrated technologies being used in the system environment successfully. In order for a technology to move to TRL 9 it must first be integrated into the system and then proven in the relevant environment, so attempting to move to IRL 9 also implies maturing the component technology to TRL 9.
8	Actual integration completed and **Mission Qualified** through test and demonstration, in the system environment.	IRL 8 represents not only the integration meeting requirements, but also a system-level demonstration in the relevant environment. This will reveal any unknown bugs/defects that could not be discovered until the interaction of the two integrating technologies was observed in the system environment.
7	The integration of technologies has been **Verified and Validated** with sufficient detail to be actionable.	IRL 7 represents a significant step beyond IRL 6; the integration has to work from a technical perspective, but also from a requirements perspective. IRL 7 represents the integration meeting requirements such as performance, throughput, and reliability.
6	The integrating technologies can **Accept, Translate, and Structure Information** for its intended application.	IRL 6 is the highest technical level to be achieved, it includes the ability to not only control integration, but to specify what information to exchange, unit labels to specify what the information is, and the ability to translate from a foreign data structure to a local one.
5	There is sufficient **Control** between technologies necessary to establish, manage, and terminate the integration.	IRL 5 simply denotes the ability of one or more of the integrating technologies to control the integration itself; this includes establishing, maintaining, and terminating.
4	There is sufficient detail in the **Quality and Assurance** of the integration between technologies.	Many technology integration failures never progress past IRL 3, due to the assumption that if two technologies can exchange information successfully, then they are fully integrated. IRL 4 goes beyond simple data exchange and requires that the data sent is the data received and there exists a mechanism for checking it.
3	There is **Compatibility** (i.e., common language) between technologies to orderly and efficiently integrate and interact.	IRL 3 represents the minimum required level to provide successful integration. This means that the two technologies are able to not only influence each other, but also communicate interpretable data. IRL 3 represents the first tangible step in the maturity process.
2	There is some level of specificity to characterize the I**nteraction** (i.e., ability to influence) between technologies through their interface.	Once a medium has been defined, a “signaling” method must be selected such that two integrating technologies are able to influence each other over that medium. Since IRL 2 represents the ability of two technologies to influence each other over a given medium, this represents integration proof-of-concept.
1	An **Interface** between technologies has been identified with sufficient detail to allow characterization of the relationship.	This is the lowest level of integration readiness and describes the selection of a medium for integration.

The SRL scale is calculated by using a normalized matrix of pair-wise comparisons of TRLs and IRLs that reflects the actual architecture of the system. Briefly stated, the IRL matrix is obtained as a symmetric square matrix (of size *n*×*n*) of all possible integrations between any two technologies in the system. For technology integration to itself, perfect integration is assumed (IRL= 9) while an IRL of zero is used when there is no integration between two technologies. Likewise, the vector TRL defines the readiness level of each of the technologies in the system. In its current form, the SRL is calculated as

$$[SRL] = \begin{bmatrix} SRL_1 \\ SRL_2 \\ \ldots \\ SRL_n \end{bmatrix} = \begin{bmatrix} IRL_{11}TRL_1 + IRL_{12}TRL_2 + \ldots + IRL_{1n}TRL_n \\ IRL_{21}TRL_1 + IRL_{22}TRL_2 + \ldots + IRL_{2n}TRL_n \\ \ldots \\ IRL_{n1}TRL_1 + IRL_{n2}TRL_2 + \ldots + IRL_{nn}TRL_n \end{bmatrix} \text{ where } IRL_{ij}=IRL_{ji}$$

and

$$SRL = \frac{\left(\frac{SRL_1}{n_1} + \frac{SRL_2}{n_2} + \ldots + \frac{SRL_n}{n_n}\right)}{n}$$

where n_i is the number of integrations with technology *i* plus its integration to itself.

The resulting SRL metric can be used to determine the maturity of a system and its status within the developmental lifecycle. Table 3, for example, is a representation of how the SRL scale correlates to a systems engineering lifecycle. These notional values of the SRL scale shown in Table 3 are meant to be organization-generic examples of how the calculated SRL values can be set as a guide by a systems engineer or program manager. That is, in practice the systems engineer or program manager at the outset must determine what values of the SRL correlate to that point where one phase begins and where it ends for that particular system. A calibration of these relevant ranges for each phase of system development will have to be program-specific or, at best, pertinent only to a particular class of systems that share a large degree of similarity. Therefore, the SRL value of a system can only be compared to that of the same system or a very similar system.

Table 3. System Readiness Levels

SRL	Name	Definitions
0.90 to 1.00	*Operations & Support*	Execute a support program that meets materiel readiness and operational support performance requirements and sustains the system in the most cost-effective manner over its total lifecycle.
0.80 to 0.89	*Production & Deployment*	Achieve operational capability that satisfies mission needs.
0.60 to 0.79	*Engineering & Manufacturing Development*	Develop system capability or (increments thereof); reduce integration and manufacturing risk; ensure operational supportability; minimize logistics footprint; implement human systems integration; design for production; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety and utility.
0.40 to 0.59	*Technology Development*	Reduce technology risks and determine and mature appropriate set of technologies to integrate into a full system and demonstrate CTEs on prototypes.
0.10 to 0.39	*Materiel Solution Analysis*	Assess potential materiel solution options

NOTE: These ranges have been derived conceptually and are undergoing field verification and validation under Naval Postgraduate School Contract # N00244-08-0005.

While the TRL has been widely accepted by many government and industry organizations, the IRL and SRL need continued verification and validation; efforts are currently under way. Early results indicate that SRL can institute a robust and repeatable method for assessment and reporting the status of a system’s development. It enables program managers to evaluate system development in real time and take corrective actions. It can also be applied as a predictive tool for technology insertion (Michaud, Forbes, Sauser & Gentile, 2008). In order to firmly establish the validity of SRL, it must be applied to a sufficient number of real complex systems under development.

Nevertheless, a rudimentary SRL calculator has been developed by the Systems Development & Maturity Laboratory (SD&ML) at Stevens Institute of Technology (see http://www.SystemReadinessLevel.com; Tools) and is undergoing refinement. In addition, the SD&ML is in ongoing partnerships to develop tools for system maturity assessment that leverage their continued research in systems maturity.

3. Formulating Optimal Development Plans

System development is pursued based on two generic strategies: minimizing costs or being the first to market/deployment (Laugen, Acur, Boer & Fick, 2005). In order to meet these strategic imperatives, the program manager must have the capability to instruct the project managers about which technologies and integration links must be matured to sufficient levels and when. Leveraging the SRL method previously described, such a development plan can be formulated by relying on constrained optimization techniques. The methodology for cost minimization has been formulated by Magnaye, Sauser, and Ramirez-Marquez (2009) while the first to market/deployment was developed by Sauser and Ramirez-Marquez (2009). These are summarized below.

3.1. Cost-driven Strategy

The cost-driven strategy is becoming more common as political pressure (in government programs) and competitive intensity (in industry) becomes more pronounced in the current and future economic environment characterized by more constrained resources and more demanding customers. In this case, the development strategy is to optimize the allocation of limited resources while attaining a certain level of system maturity or readiness within a specified time. In order to execute the development required to reach a SRL value by a certain time, it is necessary to know how to reach this level at a minimum cost. To address these concerns, Magnaye et al., (2009) proposed an optimization model whose objective is to minimize development cost (a function of TRL and IRL development) under constraints associated with the required SRL value and schedule. This model recognizes that technologies compete for resources and that the optimal allocation of the least amount of resources to reach a certain SRL value is desirable. The general mathematical form of this model called $\text{SCOD}_{\min}$ follows:

Minimize: SCOD (**TRL,IRL**) = SCODfixed + SCODvariable (**TRL,IRL**)

Subject to: SRL(**TRL,IRL**) ≥ λ

R_1 (**TRL,IRL**) ≤ r_1

.

.

.

R_h (**TRL,IRL**) ≤ r_h

In addition to the SRL and time or schedule constraints, other possible constraints could be technical performance parameters such as equivalent mass for space systems, peak load capacities for transportation and so on.

The matrices **IRL** and **TRL** in Model $\text{SCOD}_{\min}$ contain the decision variables. Each variable is integer-valued and bounded by (IRL_i,9) and (TRL_i,9), respectively. That is, the TRL/IRL for the i^{th} component cannot be below its current level or above perfect technology or integration development (IRL or TRL = 9).

To completely characterize the decision variables in Model $\text{SCOD}_{\min}$, it is necessary to introduce the following transformation:

$$y_i^k = \begin{cases} 1 & \text{If } TRL_i = k \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad x_{ij}^k = \begin{cases} 1 & \text{If } IRL_{ij} = k \\ 0 & \text{otherwise} \end{cases} \quad \text{for } k=1,\ldots 9$$

Notice that based on these binary variables, each of the possible normalized TRL and IRL in the system can be obtained as $TRL_i = \frac{\sum_{k=1}^{9} k y_i^k}{9}$ and $IRL_{ij} = \frac{\sum_{k=1}^{9} k x_{ij}^k}{9}$. Based on these binary variables SRL_i is transformed to:

$$SRL_i = \frac{\left(\sum_{k=1}^{9} kx_{i1}^{k}\right)\left(\sum_{k=1}^{9} ky_{1}^{k}\right)}{81} + \frac{\left(\sum_{k=1}^{9} kx_{i2}^{k}\right)\left(\sum_{k=1}^{9} ky_{2}^{k}\right)}{81} + \ldots + \frac{\left(\sum_{k=1}^{9} kx_{ij}^{k}\right)\left(\sum_{k=1}^{9} ky_{j}^{k}\right)}{81} + \ldots + \frac{\left(\sum_{k=1}^{9} kx_{in}^{k}\right)\left(\sum_{k=1}^{9} ky_{n}^{k}\right)}{81}$$

$$= \frac{\sum_{j=1}^{n}\left(\sum_{k=1}^{9} kx_{ij}^{k}\right)\left(\sum_{k=1}^{9} ky_{j}^{k}\right)}{81}$$

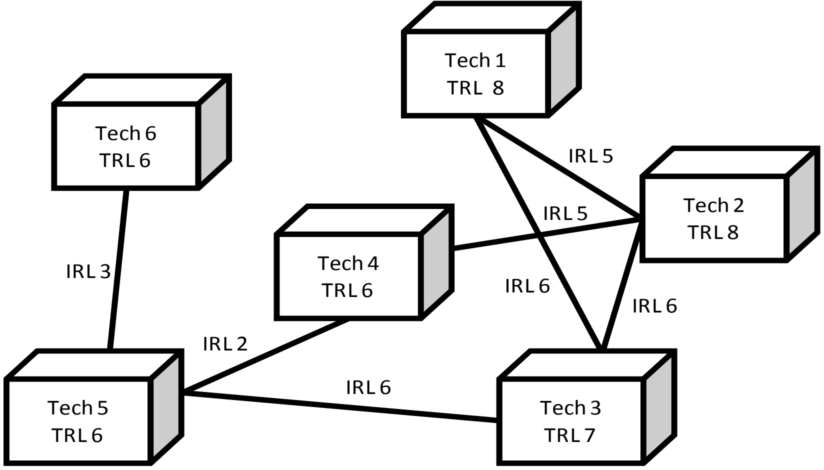
Based on the computation of the SRL with these decision variables, Model SCOD_{min} belongs to the class of binary, integer-valued, non-linear problems. For a system with n technologies containing m ($m \leq (n-1)n/2$) distinct integrations, and assuming all technologies and integrations are at their lowest levels, there are 9^{n+m} potential solutions to Model SCOD_{min}. Evaluating each possible solution is prohibitive, so to generate a more timely optimal solution, a meta-heuristic approach developed by Ramirez-Marquez and Rocco (2008) was applied to the system under development and is described below. This approach, called Probabilistic Solution Discovery Algorithm (PSDA) has the capability of producing quasi-optimal solutions in a relatively short period of time. However, it must be mentioned that the results cannot be proven as the optimal solution because by taking a probabilistic approach, the algorithm can only select subsets of the entire feasible set from which to find a solution. Every time the algorithm is run a different subset is selected. Nevertheless, prior tests have indicated that PSDA results tend to be better than results from alternative meta-heuristic approaches (Ramirez-Marquez & Rocco, 2007).

As used in the solution of the minimization problem, the algorithm follows three inter-related steps:

- Strategy Development—a Monte Carlo simulation is used to identify the potential TRL or IRL levels the technologies and links can advance or mature;
- Analysis—each potential solution is analyzed by calculating its associated cost, schedule and SRL;
- Selection—through an evolutionary optimization technique, a new optimal set of technologies and integration links (with their corresponding TRLs and IRLs are chosen based on the cost, schedule and SRL values).

3.2. Notional Example and Results

Figure 1. System Concept Diagram



Tech 1: Remote Manipulator System (RMS); Tech 2: Special Purpose Dexterous Manipulator (SPDM); Tech 3: Electronic Control Unit (ECU); Tech 4: Autonomous Grappling (AG); Tech 5: Autonomous Proximity Operations (APO); and Tech 6: Laser Image Detection and Radar (LIDAR).

The following notional example will use a simple system of six technologies and seven integrations (see Figure 1 above) to demonstrate the steps involved in calculating the SRL value and minimizing the cost subject to constraints on system maturity and schedule. By evaluating the SRL of this system, an estimate of its actual readiness can be obtained before being deployed. In year 1 (current year), when reviewing the SRL for this system in its current state, the calculations yielded an SRL of 0.48. Referring to Table 3, this value indicates that this system should be in the Technology Development phase, with the technologies close to maturity (lowest TRL is 6) while integration elements are behind, one as low as level 2 only. For the system used in this example, Tables 4 and 5 present the *incremental* budgetary and time requirements to mature each technology and integration element from its current level to the next. For example, to mature Technology 1 from its current TRL of 8 to 9 will require another $900,000 and 349 labor-hours. In order to fully mature all the technologies and integration elements, an additional $26.574 million and 19,122 labor-hours are required.

Table 4. Estimated *Incremental* Cost (x1000) and Time for Each Technology Effort

Technology	1		2		3		4		5		6	
TRL Level	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time
1												
2												
3												
4												
5												
6												
7							$876	127	$467	280	$780	450
8					$689	476	$421	341	$531	236	$123	21
9	$900	349	$765	432	$734	299	$853	568	$189	48	$389	300

Table 5. Estimated *Incremental* Cost (x1000) and Time for Each Integration Effort

Integration	1,2		1,3		2,3		2,4		3,5		4,5		5,6	
IRL Level	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time
1														
2														
3											$453	200	$123	80
4											$581	400	$219	380
5											$721	658	$595	532
6	$100	140					$275	164			$900	700	$700	621
7	$175	180	$200	93	$50	25	$540	320	$345	324	$1,200	954	$808	862
8	$400	300	$400	165	$450	320	$632	432	$457	400	$1,432	1021	$1,003	997
9	$600	500	$650	389	$550	465	$745	690	$678	500	$1,765	1238	$1,110	1145

If, for example, management wants to increase maturity from the current value of 0.48 (Technology Development stage) to 0.69 (Engineering & Manufacturing Development stage), using a maximum of 40% of the remaining time (7,649 labor-hours), the PSDA cost minimization model calculated a minimum additional development cost of $5.914 million and would require 3,797 labor-hours.

In addition, the development plan that can achieve this desired SRL value of 0.69 with the least cost will be attained if the subsystems that are based on each technology element reach the maturity levels listed in Table 6. The latter shows that of the six subsystems, two are ahead ($SRL_{1,3,}$), two are behind ($SRL_{4,5}$) and two are close to the same level ($SRL_{2,6}$) as the whole system. This insight can become useful when the maturity levels are associated with systems engineering activities. That is, the spectrum of SRL_i's can indicate levels of variation in the systems engineering activities, which are needed to mature the entire system.

Table 6. Subsystem and Composite SRLs

SRL1	SRL2	SRL3	SRL4	SRL5	SRL6	∑	Composite SRL = ∑/6
0.856	0.707	0.815	0.461	0.593	0.722	4.154	0.692

Table 7 summarizes the additional results for the targeted SRL values and Table 9 indicates the development plan for each improvement scenario.

Table 7. Best Solutions for Desired SRL Values

Year	SRL		Time (man-hrs)		Computed Minimum Cost ($ x1000)
	Targeted	Computed	Targeted	Computed	
1	0.48	0.48	NA	NA	NA
2	0.58	0.587	3,824	1,654	2,203
3	0.69	0.692	7,649	3,797	5,914
4	0.79	0.794	11,473	7,667	11,065
5	0.89	0.896	15,298	11,309	16,888
6	1.00	1.00	19,122	19,122	26,574

Table 8. Development Plan

Year	Target SRL	TRL						IRL						
		1	2	3	4	5	6	1,2	1,3	2,3	2,4	3,5	4,5	5,6
6	1.000	9	9	9	9	9	9	9	9	9	9	9	9	9
5	0.89	9	9	9	8	9	9	9	9	9	8	8	5	7
4	0.79	8	9	9	6	9	9	9	9	9	5	8	4	6
3	0.69	8	8	9	6	9	9	8	8	7	5	7	2	4
2	0.58	8	8	8	6	7	6	7	7	7	5	6	2	4
1	0.48	8	8	7	6	6	6	5	6	6	5	6	2	2

It must be noted that the algorithm can only work if the management objectives are inherently feasible. If a prescribed objective is impossible to achieve—as when too little time or labor-hours are available—the algorithm will not produce a solution.

3.3 First-to-Market/Deployment Strategy

A very similar optimization procedure can be designed to determine how fast a system can reach a certain stage in the development lifecycle or how quickly it can be deployed. In this case, there may be a need to launch an experimental system in favor of maximum current and short-term effectiveness while disregarding long-term reliability. The objective may be to meet pressing needs in a war theater or commercial market as quickly as possible.

For example, there is currently a necessity to deliver Operationally Responsive Space (ORS) systems to meet shortfalls in tactical space capabilities (e.g., communications and imagery) that the warfighter needs in Iraq and Afghanistan. These are being satisfied through the development of small experimental satellites called TacSats (average cost=$87 million) as well as improvements in the capabilities of small launch vehicles (GAO, 2008). In the private sector, the first company to develop commercially viable autonomous-recharging powertrain battery systems will enjoy first-mover advantages in the defense and commercial motor vehicle industry. Such a company will be able to create and sustain barriers to entry through control of the technology (property rights), brand recognition and so on.

In such instances, the primary objective is to maximize the readiness of the system utilizing a given amount of limited resources. Sauser and Ramirez-Marquez (2009) developed an SRL maximization model—SRL$_{max}$—for such an application. As with the SCOD$_{min}$ model, this model recognizes that the technologies as well as the integration elements that form the system compete for resources and that in order to reach the highest level of readiness, a program manager must be able to allocate the limited resources optimally. Just as what had to be done in the SCOD$_{min}$ model, the program manager must be able to decide which technologies and integrations can be advanced to which levels of readiness at a certain point in time in order to reach the highest level of readiness for the system. The general mathematical form of SRL$_{max}$ follows:

$$\text{Maximize: SRL } (\mathbf{TRL,IRL})$$

$$\text{Subject to: } R_1\,(\mathbf{TRL,IRL}) \le r_1$$

$$\vdots$$

$$R_h\,(\mathbf{TRL,IRL}) \le r_h$$

As with the minimization model above, SRL$_{max}$ belongs to the class of integer-valued, non-linear problems.

Using the same data for the notional example above, the maximization algorithm indicated that to get to the Engineering & Manufacturing Development phase of the lifecycle with an SRL value of 0.73, $7.724 million and 5,081 labor-hours will be required. For comparison purposes, the optimal development plans to get to the Engineering & Manufacturing Development stage, albeit at different SRL values (0.69 for cost minimization and 0.73 for SRL maximization) are presented in Table 9 below.

Table 9. Comparable Development Plans

Model	SRL	TRL						IRL						
		1	2	3	4	5	6	1,2	1,3	2,3	2,4	3,5	4,5	5,6
SCOD$_{min}$	0.69	8	***8***	9	6	9	9	8	8	***7***	5	7	2	***4***
SRL$_{max}$	0.73	8	***9***	9	6	9	9	8	8	***8***	5	7	2	***5***

The cost minimization strategy will reach this stage by year 3. On the other hand, when the objective is to deploy as quickly as possible, the system can be in production as soon as the prescribed resources are applied, provided the process and product technologies are amenable to accelerating the schedule. This assumes constant productivity that represents an ideal situation. In reality, there is more likely to be "process congestion," which can lead to increased coordination and communication expenses, among other things. Therefore, for the maximization model, the estimated incremental costs for each TRL and IRL level must be adjusted upwards in order to reflect the cost implications of "crashing" the schedule. Depending upon these CTE- and integration link-specific cost increases, the formulated development plan is likely to be different from the one obtained from the minimization model.

The results must be carefully examined by the program manager and adjusted according to a proper understanding of the technologies involved and the context for the system. For example, in the previous illustration, some of the integration links have to be examined more closely and compared to a pre-determined minimum acceptable readiness values. If the minimum IRL values of, say, 5 are required in order to proceed to production within acceptable risk limits, then, additional resources must be allocated to mature integration links (4,5) and (5,6) to this level. This threshold IRL value may be higher for a cost minimization strategy (whereas long-term reliability is an important lifecycle variable) and lower for the first-to-deployment experimental strategy that characterizes the TacSats program in which long-term reliability is not quite as important as delivering the capability sooner rather than later.

It must also be noted that the solution is driven by the estimates of cost and labor inputs. The effectiveness of the optimization models are very dependent on the accuracy of the estimates of the resources required to proceed from one readiness level to the next. If these values are unrealistic, sub-optimal solutions will be generated.

Furthermore, given the high levels of uncertainty associated with complex systems that are under development, estimates of costs which are farther into the future may be less reliable than those which are closer to the current period. Thus, estimates have to be continually refined and reapplied to the optimization algorithm in order to fine-tune the development plan accordingly.

4. Monitoring Progress

The metrics that measure readiness together with the development plans generated by the appropriate optimization model serve as the foundation for a mechanism that can measure and communicate accomplishments during the development of complex systems. As a general principle, EVM may be retained as the preferred tool for project managers tasked with developing each of the critical technology and integration elements. To consider all the projects that an enterprise has to manage, Project Portfolio Management (PPM) has been suggested by De Reyck et al. (2005) and Martinsuo and Lehtonen (2007). In between, to manage the development of a system, which is a set of projects that are related because they share a common objective or client—a program management tool is required. Developing such a tool, which we refer to as System Earned Readiness Management (SERM), is one of the activities we intend to pursue next. SERM is intended to be very similar to EVM. It must answer the following questions:

- What amount of readiness is expected from the tasks planned?
- What level of readiness was accomplished by the tasks completed?
- How many resources did the accomplished level of readiness cost?
- How many resources were allocated to reach this level of readiness?
- What was the total budgeted resources to fully mature the system?
- What are now the expected total resources required to develop the system?

4.1 Work Breakdown Structure for SERM

SERM will require a breakdown of the tasks necessary to define the system, develop the critical technology elements and integrate them into the desired system. The tasks could be oriented towards the phases of the system lifecycle at the highest levels (i.e., Materiel Solution Analysis, Technology Development, Engineering & Manufacturing Development, Production & Deployment, and Operations/Support) and continue to be disaggregated into the TRL and IRL levels that have to be attained and, if necessary, down to the jobs that must be completed to reach the desired readiness for each time period. An abbreviated example is shown in Table 10 below.

Table 10. WBS for SERM

1. SYSTEM A 1.1Materiel Solution Analysis Phase 1.1.1 Materiel Solution Analysis Decision Review 1.1.1.1 Joint Requirements Oversight Council (JROC) recommendations 1.1.1.2 Initial Capabilities Document(ICD) 1.1.1.2.1 Preliminary concept of operations 1.1.1.2.2 Description of needed capability 1.1.1.3 Analysis of Alternatives (AoA) 1.1.1.3.1 Determine acquisition phase of entry 1.1.1.3.2 Identify the initial review milestone 1.1.1.3.3 Designate the lead DoD Component(s) 1.1.1.3.4 Prepare Acquisition Decision Memorandum 1.1.2 Satisfy phase-specific entrance criteria for initial review milestone 1.1.2.1 Proposed materiel solution 1.1.2.2 Secure full funding for Technology Development Phase
1.2. Technology Development Phase 1.2.1 Management 1.2.1Materiel solution 1.2.2Technology/system development strategy 1.2.3 Acquisition decision memorandum 1.2.2 CTE 1 1.2.2.1 TRL =3 1.2.2.2 TRL =4 1.2.2.3 TRL =5 1.2.3 CTE 2 1.2.3.1 TRL =3 1.2.3.2 TRL =4 1.2.3.3 TRL =5 1.2.3.4 TRL =6 1.2.x CTE n……etc.
1.3. Engineering & Manufacturing Phase 1.3.1 Management 1.3.1.1 Key performance parameters … etc. 1.3.2 CTE 1 1.3.2.1 TRL = 6 ... etc
1.4. Production & Deployment Phase
1.5. Operations & Support Phase

4.2 Determining Earned Readiness and Baseline

A readiness-oriented baseline should reflect the cumulative increase in the readiness of the technology and integration elements of the system. Readiness is allocated throughout the system by assigning the TRL and IRL values to the tasks completed *if and only if* they satisfy the definition for that readiness level. Thus, it is possible that under SERM, a planned task may be completed during the specified time frame but if it fails to advance the maturity of that particular technology or integration link, that completed task did not earn any readiness values. By doing this, a program manager can clearly see which activities have failed, in order to identify the sources of cost overruns and find and communicate explanations for exceeding the budget.

This scenario is not unlikely given the high amount of uncertainty involved with developing complex systems. This uncertainty—the result of novelty, high technological content and very long development lifecycles—can lead to late identification of requirements and design flaws, requirements churn (due to inaccurate statements of user needs), delays in integration and testing and the need for significant unplanned work—rework as well as revisions in the system architecture and technology choices (Brownsword & Smith, 2005).

5. Conclusion

This paper suggested the development of a new program assessment and evaluation system that relies on the readiness measurement of a system's critical technology elements (using TRL) and the integrations that link them to each other (using IRL), which are then combined to estimate a System Readiness Level (SRL) in order to determine the readiness of the system as a whole. SRL can then be combined with the prescribed strategy for developing the system (either minimize costs or be the first to deploy the system) and used in an appropriate constrained optimization model to formulate the optimal development plan. Based on this plan, the progress of the system development effort can be monitored and evaluated using System Earned Readiness Management (SERM).

Of the various concepts enumerated here, only TRL has been accepted as a generally valid principle. IRL, SRL and SERM are all new, and thus require substantial efforts to verify and validate. It is necessary to apply them to a sufficient number of programs that have recently been completed or are currently being implemented. It must be noted that EVM for project management became more widely accepted only when the graduate students in the DoD's academic institutions were able to apply it to defense acquisition projects and show its benefits (Abba, 2001). The early anecdotal evidence from the few attempts to apply SRL has been positive and may justify a similar approach to verify and validate it.

Acknowledgements

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Dynamic Multipoint Optimization Application to Corporate Portfolio Management

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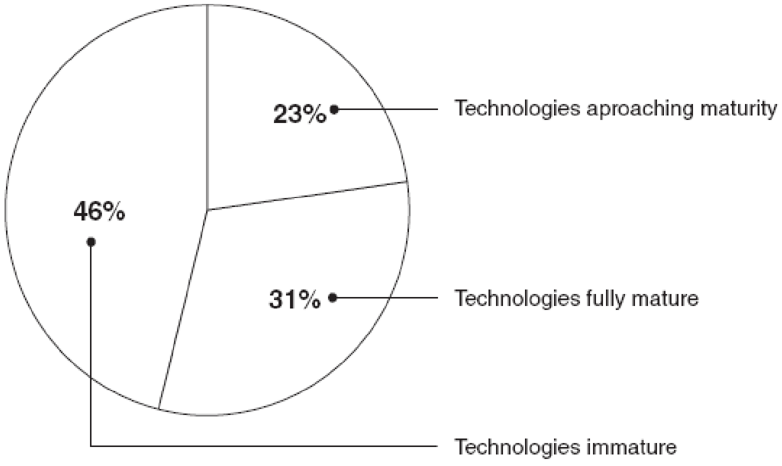
Abstract

There are many challenges facing complex system development in today's environments. Systems have become far more complex, operating in a net-centric environment, with ever increasing threats to system security posing a challenging design and development task for program managers and systems engineers. We have seen an increasing number of major DoD system development programs experiencing difficulties and failing to achieve their intended goals successfully. Reasons for these difficulties and failures include both technical and programmatic type issues. At the top of the list has been the failure to properly assess the technical maturity of complex systems during system development, leading to cost overruns, program delays, program cancellations, and unacceptable system performance. Recently introduced corporate or program portfolio management ideologies supporting system development in the DoD have shown some promise in providing a more dynamic approach to project management. Advantages include the ability to make dynamic changes to the mixture of technology investments in a development program and increased probability of attaining the desired end-state goals at planned cost and on schedule. The programs need to consider external technology shifts and ensure the programs and their technology investments stay ahead of the critical "S-Curve." The dynamics of program management, including effective decision-making, also play an important role in ensuring end-goal success. Missing from corporate portfolio management are good maturity metrics to assess the system development process

throughout the lifecycle. This paper addresses the application of system maturity metrics and decision theory ideologies to a portfolio management framework supporting multi-technology based system development. The application of previous research performed by the Stevens Institute of Technology in the area of system maturity metrics including "systems readiness levels" will be leveraged and applied to existing problem sets resulting in a dynamic decision-making process.

Introduction

As we look at current lifecycle system development, we see an increasing number of major Department of Defense (DoD) system development programs experiencing difficulties and failing to achieve their intended goals successfully. Reasons for these difficulties include both technical and programmatic type issues that are experienced throughout the system development lifecycle. At the top of the list has been the failure to properly assess the technical maturity of these complex systems during system development, leading to cost overruns, program delays, program cancellations, and unacceptable system performance. Evidence of this is seen in the often cited Government Accountability Office (GAO) report that reviewed and analyzed major defense acquisition programs. This report concluded that the causes and reasons for failure in major defense acquisition programs were due to a majority of programs failing to meet a TRL 7 level before entering the system development phase (1999). These findings were echoed again in a more recent GAO report that showed an increase from the previous year in the number of programs with immature technologies still maturing technologies late into the system development and production lifecycles (2008). It is troubling that nine years after the original report, we are still reporting the same types of problems with these acquisition programs. The evidence is overwhelming and shows that serious attention to the application of lifecycle system maturity metrics is essential to reversing the present trend in major acquisition program failures. Figure 1 below shows the maturity levels of critical technologies for DoD programs.



Source: GAO analysis of DOD data.

Figure 1. Maturity Levels of Critical Technologies for DoD Programs

System Development Challenges

There are many challenges facing system development in today's fast-paced environments. Systems have become more complex, operating in a net-centric environment, with ever increasing threats to system security posing a challenging design and development task for program managers and systems engineers. Complicating this scenario are the added constraints of budget, shorter development lifecycles, and available experienced workers. These demands have further increased the pressure on program managers and systems engineers to achieve expected success in the areas of technical performance, budget, and schedule. Further concerns are the failure of developers to make the necessary decisions to integrate newer technologies, and they continue to invest in existing technologies that produce no added benefits while the rapidly changing technological world moves on. This is known as the "S Curve" effect and is illustrated in Figure 2 below. These developers face the risk and unintended consequences of becoming irrelevant quickly by not reacting fast enough to these external forces (Christensen, 2003).

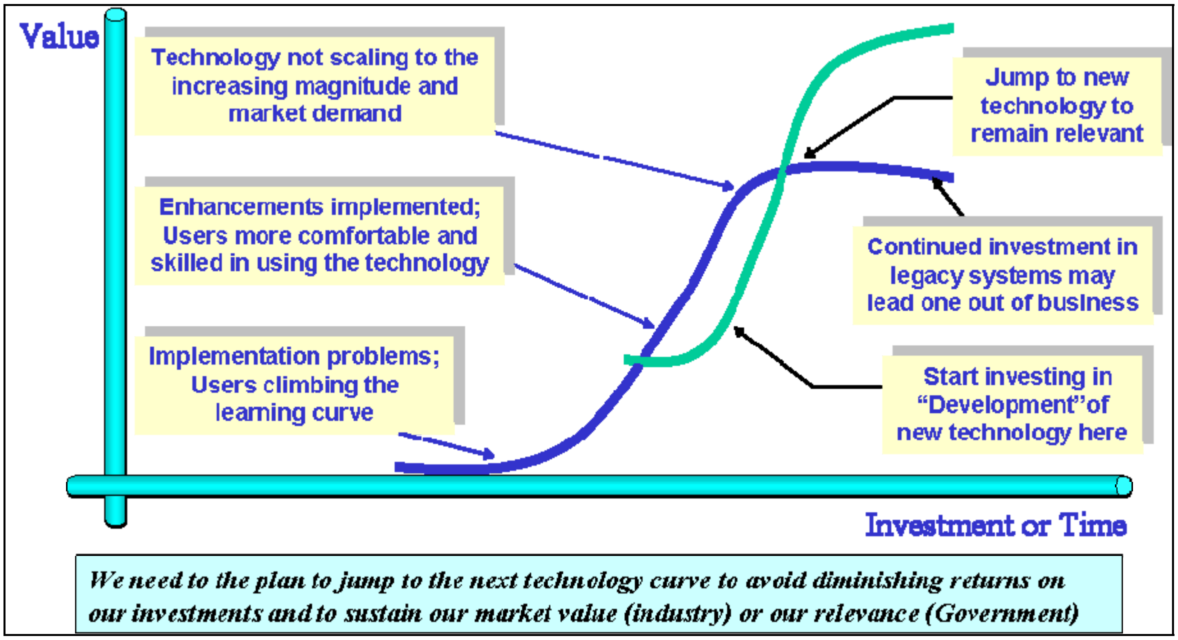


Figure 2. Technology S-Curve

Need for an Integrated Environment

For success in today's accelerated, system acquisition development programs, we need to ensure the existence of an integrated environment that consists of a management process that is guided by a defined lifecycle framework and at the same time, a maturity metric process that maps to this same lifecycle framework and supports the management process. This integrated environment allows for maximum interaction between these domains to support the manager's decision-making process, whether the organization is small, medium, or large. This integrated environment will consists of the following three components: a defined accepted lifecycle framework, a realistic portfolio management process, and metrics to include financial, technical, and technology maturation. Since this paper is looking at DoD based programs, we will refer to the *DoD 5000.2* lifecycle framework. For the system maturity metrics, we can apply the System Readiness Level

(SRL) model, developed by Stevens Institute of Technology, to a portfolio management based environment, which is becoming more popular in DoD programs.

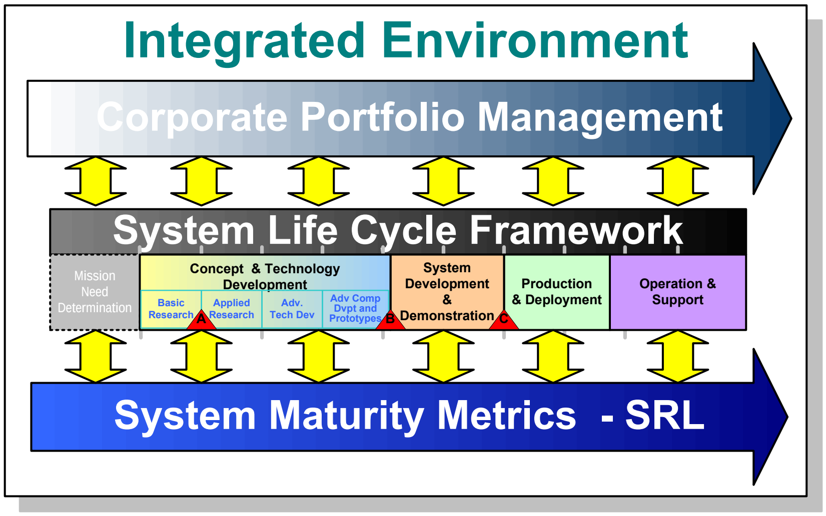


Figure 3. Integrated Environment

What is a Lifecycle Framework?

A lifecycle is an inherent part of all system development and encompasses a framework that that defines all the necessary systems engineering phases and lifecycle activities that are necessary to support system development production and post development activities. Within the lifecycle are decision points or milestones when technology, performance, and schedule are assessed (INCOSE, 2006). In its simplest definition, a lifecycle is described as “The system or product evolution beginning with the identification of a perceived customer need, addressing development, test, manufacturing, operation, support, and training activities, continuing through various upgrades or evolutions, until the product and its related processes are disposed of” (Kossiakoff & Sweet, 2003). Obvious in Kossiokoff and Sweet’s definition is the existence of least three stages, the conceptual development, engineering development, and post development. Within each stage are the activities described in Kossiakoff and Sweet’s lifecycle definition. In the real world, there are some subtle variations in the comparison of lifecycle models across the different system development domains. This paper will focus on the DoD’s “DoD 5000 Acquisition Lifecycle Framework” model, which has benefited DoD acquisition based programs successfully by provided a basic common system development lifecycle framework describing all the necessary processes and activities needed to support system acquisition.

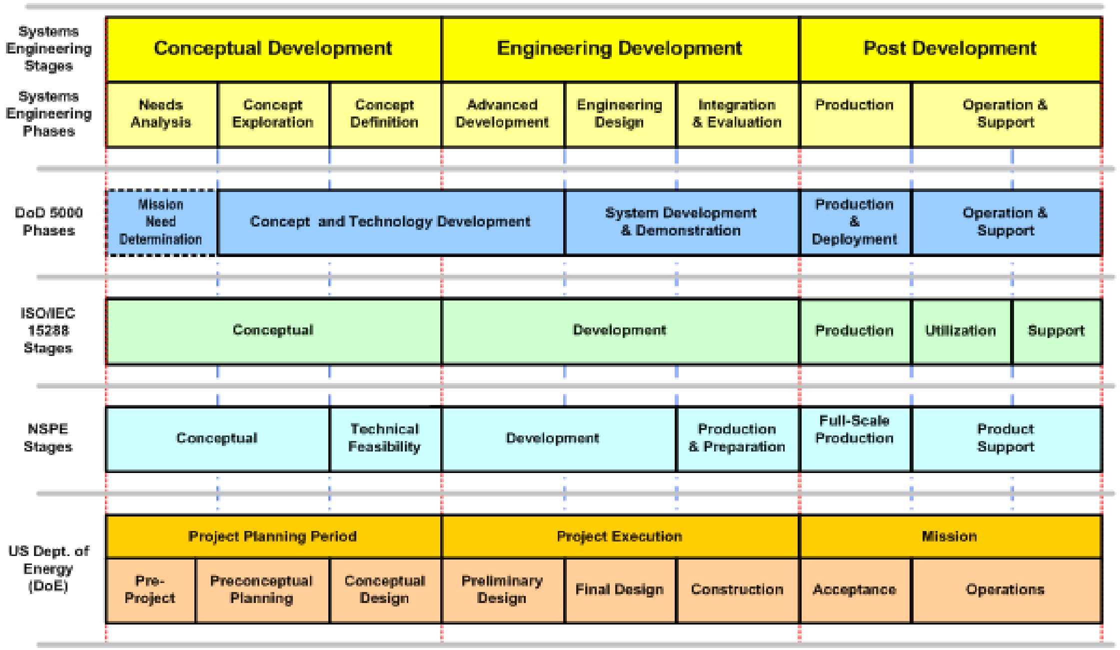


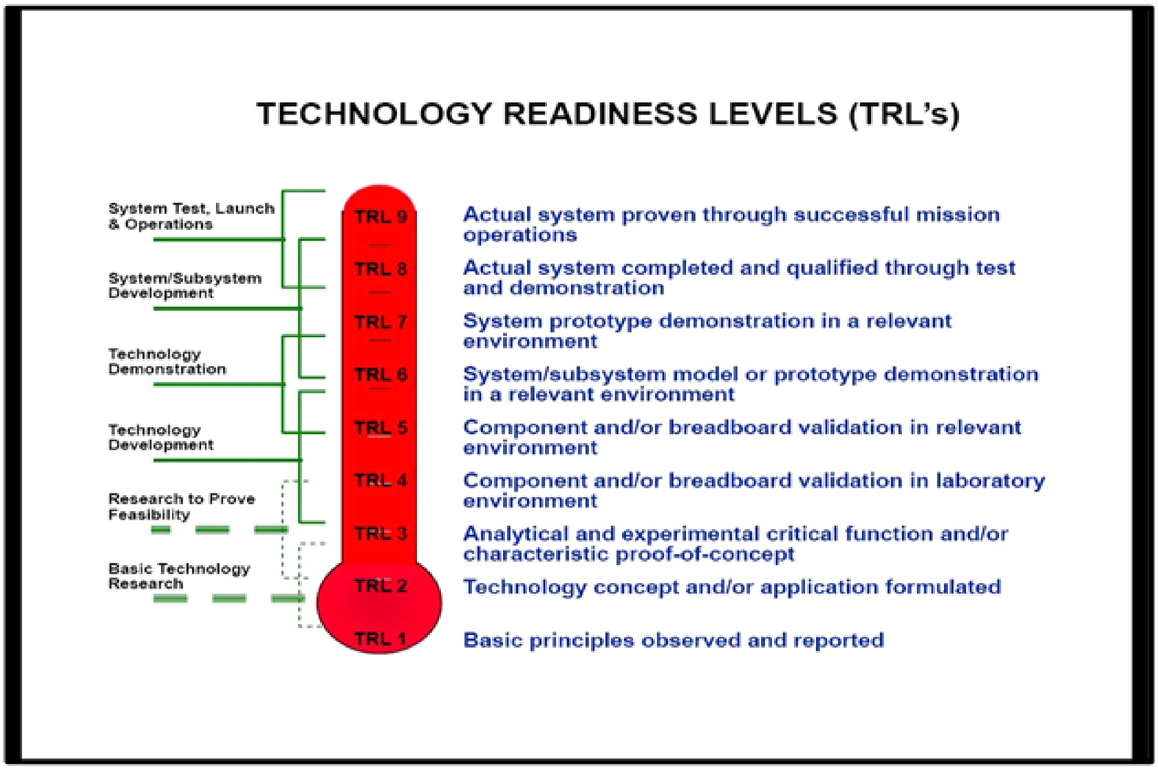
Figure 4. Lifecycle Model Comparisons

What are Maturity Metrics?

In the past, we have made considerable improvements in the tracking and monitoring of program metrics focusing on the financial status through improved software IT systems. We have also done well in metrics associated with performance testing of systems. Missing is the lack of better metrics supporting support the lifecycle assessment of system maturity. Technology maturity is a main area of concern among developers as many system development efforts have failed because of the inability to assess the system technology's state of progress or development. This can often lead to failure of a technology to perform in a system or be integrated into a system. The need to assess the maturity level of the technologies and systems in the development process becomes a critical factor in the decision-making process throughout the system development lifecycle.

What Maturity Metrics Do We Have?—Technology Readiness Level (TRL)

The need to assess the maturity level of the technologies and systems in the development process becomes a critical factor in the decision-making process throughout the system development lifecycle. This has led to the introduction of a metrics assessment process supporting the assessment of maturity of different types of technologies used in a system development program. One of these metrics, the Technology Readiness Level (TRL) was originally introduced by the National Aeronautics and Space Administration (NASA) for the development and support of their space mission programs and later adapted for use by other agencies, including the DoD. The TRL describes the maturity level of that technology. There are nine TRL levels used to describe the maturity of a particular technology, starting from a TRL 1, in which basic principles have been observed and reported, and progressing to a maximum of TRL 9, in which the technology has been proven in a successful operational test (Mankins, 1995).



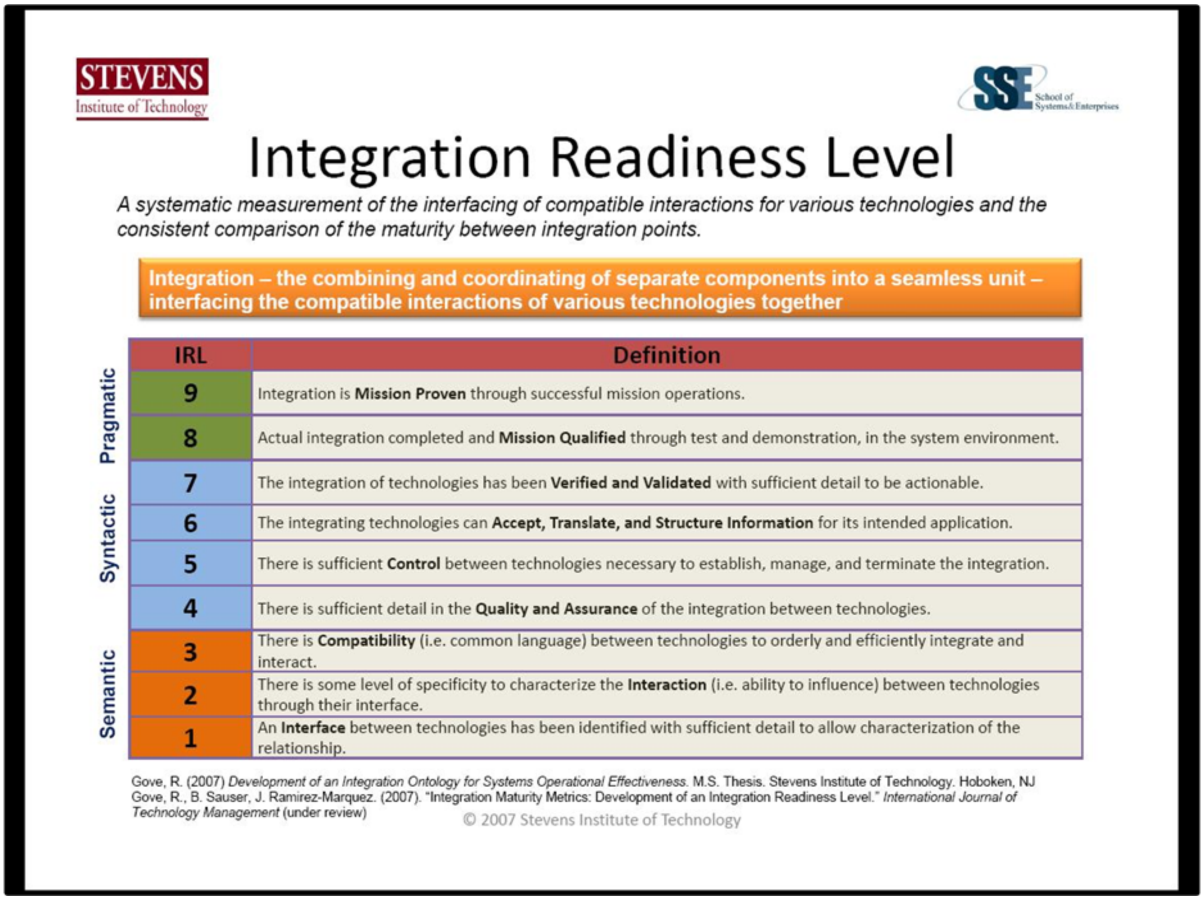
TECHNOLOGY READINESS LEVELS (TRL's)

TRL 9	Actual system proven through successful mission operations
TRL 8	Actual system completed and qualified through test and demonstration
TRL 7	System prototype demonstration in a relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 2	Technology concept and/or application formulated
TRL 1	Basic principles observed and reported

Table 1. NASA's Technology Readiness Levels Summary

What's New in Maturity Metrics—System Readiness Level (SRL)

While the Technology Readiness Level (TRL) works well in providing a common maturity assessment metric in system development involving individual technologies, it does not address those projects with systems involving multiple technologies. The introduction and application of the System Readiness Level (SRL) provides a potential solution to this problem (Sauser, Verma, Ramirez-Marquez & Gove, 2006). The SRL metric indicates the systems maturity level of a system composed of multiple technologies undergoing a lifecycle system development effort. It is a system maturity index that can provide a "snapshot" view of the system maturity throughout a system development lifecycle. The SRL is formulated by incorporating the currently used TRL index along with a newly introduced index, Integration Readiness Level (IRL). The IRL describes the level of integration maturity between any two system components that are integrated. Applying the IRL methodology for a particular system yields a unique IRL matrix reflecting that system's physical architecture.



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Integration Readiness Level

A systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points.

Integration – the combining and coordinating of separate components into a seamless unit – interfacing the compatible interactions of various technologies together

	IRL	Definition
Pragmatic	9	Integration is **Mission Proven** through successful mission operations.
	8	Actual integration completed and **Mission Qualified** through test and demonstration, in the system environment.
Syntactic	7	The integration of technologies has been **Verified and Validated** with sufficient detail to be actionable.
	6	The integrating technologies can **Accept, Translate, and Structure Information** for its intended application.
	5	There is sufficient **Control** between technologies necessary to establish, manage, and terminate the integration.
	4	There is sufficient detail in the **Quality and Assurance** of the integration between technologies.
Semantic	3	There is **Compatibility** (i.e. common language) between technologies to orderly and efficiently integrate and interact.
	2	There is some level of specificity to characterize the **Interaction** (i.e. ability to influence) between technologies through their interface.
	1	An **Interface** between technologies has been identified with sufficient detail to allow characterization of the relationship.

Gove, R. (2007) *Development of an Integration Ontology for Systems Operational Effectiveness*. M.S. Thesis. Stevens Institute of Technology. Hoboken, NJ
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Table 2. Integration Readiness Levels

Though the SRL concept is not fully mature or accepted universally, it provides the beginnings of an effective system maturity assessment process framework that can support and improve the decision-making process throughout the system development lifecycle by reducing uncertainty and risk. The SRL metric provides the following benefits:

- Common metric methodology that is easy to apply
- Integrates well into system lifecycle framework
- Supports the management decision-making process.
- Provide a more precise "system level" maturity assessment

Calculating the SRL

This excerpt for Sauser, Verma, Ramirez-Marquez, DiMarzio, and Devanandham (2008) describes the SRL computation as follows:

The computation of the SRL is a function of two matrices:

1. Matrix **TRL** provides a blueprint of the state of the system with respect to the readiness of its technologies. That is, **TRL** is defined as a vector with *n* entries for which the i^{th} entry defines the TRL of the i^{th} technology.

2. Matrix **IRL** illustrates how the different technologies are integrated with each other from a system perspective. **IRL** defined as an $n \times n$ matrix for which the element IRL_{ij} represents the maturity of integration between the i^{th} and j^{th} technologies.

In these matrices, the standard TRL and IRL levels corresponding to values from 1 through 9 should be normalized. Also, it has been assumed that on the one hand, a value of 0 for element IRL_{ij} defines that the i^{th} and j^{th} technologies are impossible to integrate. On the other hand, a value of 1 for element IRL_{ij} can be understood as one of the following with respect to the i^{th} and j^{th} technologies: 1) completely compatible within the total system, 2) do not interfere with each others functions, 3) require no modification of the individual technologies, and 4) require no integration linkage development. Also it is important to note that IRL_{ii} may have a value lower than 1, illustrating that the technology may be a composite of different sub-technologies that are not absolutely mature.

In any system, each of the constituent technologies is connected to a minimum of one other technology through a bi-directional integration. How each technology is integrated with other technologies is used to formulate an equation for calculating SRL that is a function of the TRL and IRL values of the technologies and the interactions that form the system. In order to estimate a value of SRL from the TRL and IRL values we propose a normalized matrix of pair-wise comparison of TRL and IRL indices. That is, for a system with *n* technologies, we first formulate a TRL matrix, labeled [TRL]. This matrix is a single column matrix containing the values of the TRL of each technology in the system. In this respect, [TRL] is defined in Equation 1, where TRL_i is the TRL of technology *i*.

$$(1) \qquad [TRL]_{n \times 1} = \begin{bmatrix} TRL_1 \\ TRL_2 \\ \ldots \\ TRL_n \end{bmatrix}$$

Second, an IRL matrix is created as a symmetric square matrix (of size $n \times n$) of all possible integrations between any two technologies in the system. For a system with *n* technologies, [IRL] is defined in Equation 2, where IRL_{ij} is the IRL between technologies *i* and *j*. It is important to note that whenever two technologies are not planned for integration, the IRL value assumed for these specific technologies is the hypothetical integration of a technology *i* to itself; therefore, it is given the maximum level of 9 and is denoted by IRL_i

$$(2) \qquad [IRL]_{n \times n} = \begin{bmatrix} IRL_{11} & IRL_{12} & \ldots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \ldots & IRL_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ IRL_{n1} & IRL_{n2} & \ldots & IRL_{nn} \end{bmatrix}$$

Although the original values for both TRL and IRL can be used, the use of normalized values allows a more accurate comparison when comparing the use of competing technologies. Thus, the values used in [TRL] and [IRL] are normalized (0,1) from the original (1,9) levels. Based on these two matrices, an SRL matrix is obtained by obtaining the product of the TRL and IRL matrices, as shown in Equation 3.

$$(3) \qquad [SRL]_{n \times 1} = [IRL]_{n \times n} \times [TRL]_{n \times 1}$$

The SRL matrix consists of one element for each of the constituent technologies and from an integration perspective, quantifies the readiness level of a specific technology with respect to every other technology in the system while also accounting for the development state of each technology through TRL. Mathematically, for a system with *n* technologies, [SRL] is as shown in DoD (2005).

$$(4) \qquad [SRL] = \begin{bmatrix} SRL_1 \\ SRL_2 \\ \ldots \\ SRL_n \end{bmatrix} = \begin{bmatrix} IRL_{11}TRL_1 + IRL_{12}TRL_2 + \ldots + IRL_{1n}TRL_n \\ IRL_{21}TRL_1 + IRL_{22}TRL_2 + \ldots + IRL_{2n}TRL_n \\ \ldots \\ IRL_{n1}TRL_1 + IRL_{n2}TRL_2 + \ldots + IRL_{nn}TRL_n \end{bmatrix}$$

where $IRL_{ij}=IRL_{ji}$.

Each of the SRL values obtained in DoD (2005) would fall within the interval (0,n). For consistency, these values of SRL should be divided by “n” to obtain the normalized value between (0,1). Notice that [SRL] itself can be used as a decision-making tool since its elements provide a prioritization guide of the system’s technologies and integrations. Thus, [SRL] can point out deficiencies in the maturation process.

The SRL for the complete system is the average of all such normalized SRL values, as shown in Equation 5. Equal weights are given to each technology and hence a simple average is estimated. A standard deviation can also be calculated to indicate the variation in the system maturity and parity in subsystem development.

$$(5) \qquad SRL = \frac{\left(\frac{SRL_1}{n_1} + \frac{SRL_2}{n_2} + \ldots + \frac{SRL_n}{n_n} \right)}{n}$$

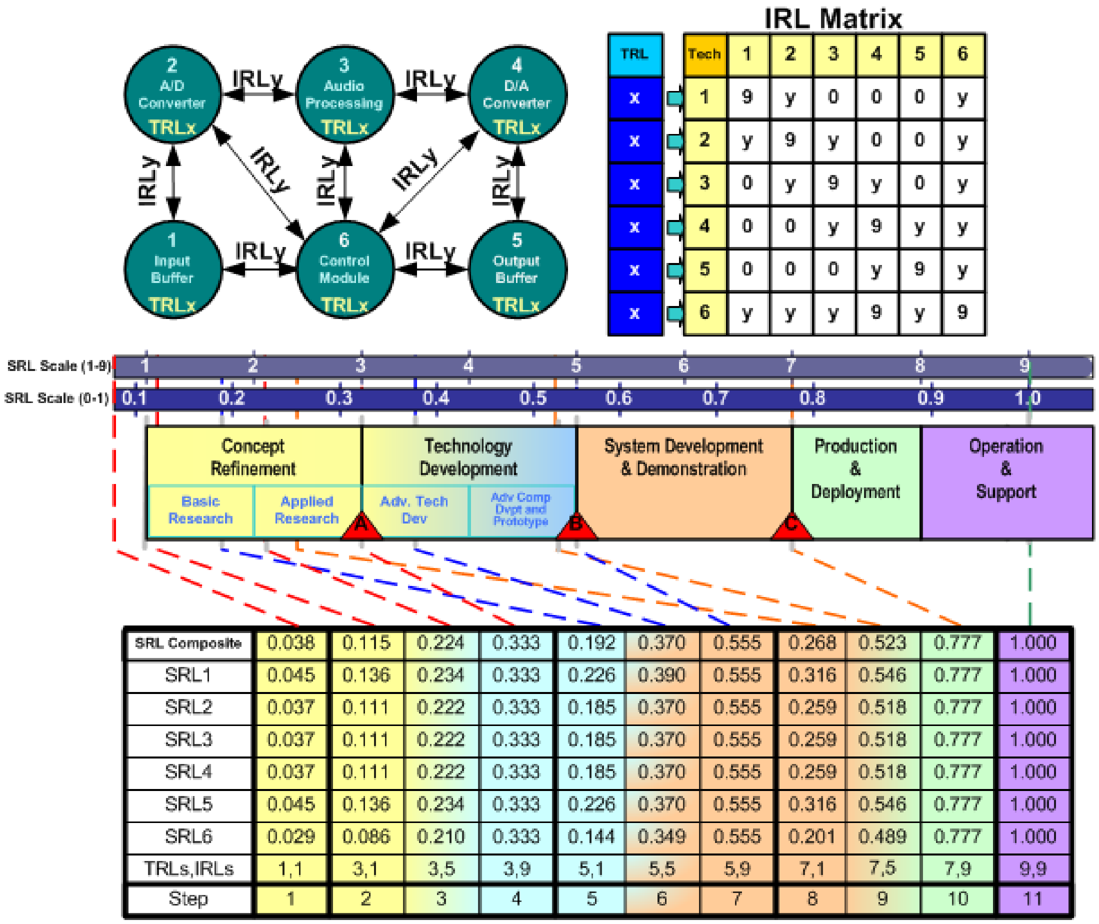
where n_i is the number of integrations with technology *i*.

The SRL metric can be used to determine the maturity of a system and its status within a developmental lifecycle.

Applying the SRL Methodology

In the following SRL examples, we take two different system architectures, each consisting of six technologies, and track the System Readiness Level metrics through the system development lifecycle, calculating the SRL metrics at each program decision point. We also look at the effects of IRL maturity on the composite SRL position along the system lifecycle by calculating the SRL for IRLs = 1, 5, and 9. This information can support the decision-making process by providing us with valuable information about the maturity of the system undergoing development and the status of the system’s individual components. The two examples shown in the following sections illustrate the SRL composites mapped across the entire system lifecycle. One can derive some interesting points by reviewing the data in these tables. For example, using the traditional TRL methodology and looking at Milestone C, we see that all the TRLs are equal to TRL 7. If we look at the SRL composite value for a maximum IRL value set equal to 9, we see that the table data shows the system maturity aligned with Milestone C, which in the traditional sense means we have a TRL equal to 7. Introducing the new SRL methodology, we can show that for a TRL 7, and a lower Integration Readiness Level of IRL 5, the SRL composite value then drops the SRL of the system to a point close to Milestone B. This point could perhaps shed some light in the area of COTS applications where developers have assumed their COTS components to be at a high TRL level, assuming easy and straightforward integration, and find themselves with great difficulty in the integration process.

SRL Example 1



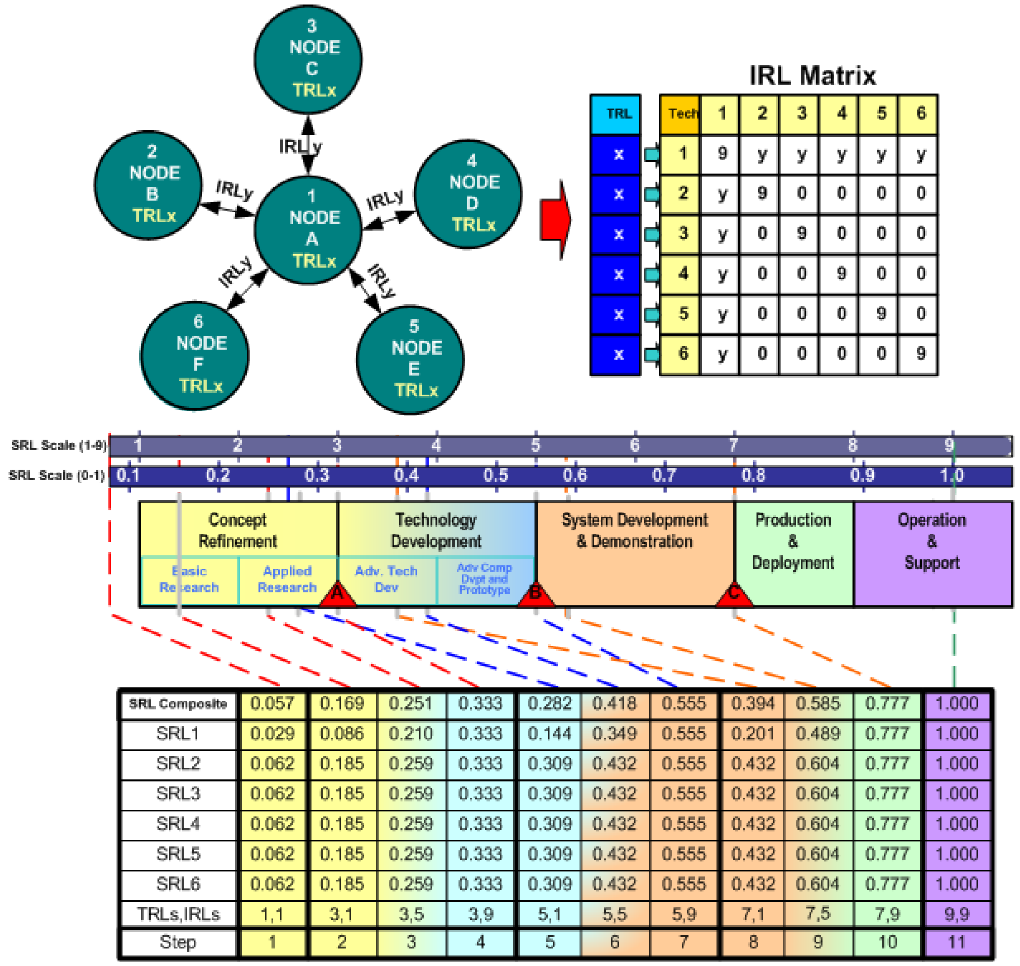
IRL Matrix

TRL	Tech	1	2	3	4	5	6
x	1	9	y	0	0	0	y
x	2	y	9	y	0	0	y
x	3	0	y	9	y	0	y
x	4	0	0	y	9	y	y
x	5	0	0	0	y	9	y
x	6	y	y	y	9	y	9

SRL Composite	0.038	0.115	0.224	0.333	0.192	0.370	0.555	0.268	0.523	0.777	1.000
SRL1	0.045	0.136	0.234	0.333	0.226	0.390	0.555	0.316	0.546	0.777	1.000
SRL2	0.037	0.111	0.222	0.333	0.185	0.370	0.555	0.259	0.518	0.777	1.000
SRL3	0.037	0.111	0.222	0.333	0.185	0.370	0.555	0.259	0.518	0.777	1.000
SRL4	0.037	0.111	0.222	0.333	0.185	0.370	0.555	0.259	0.518	0.777	1.000
SRL5	0.045	0.136	0.234	0.333	0.226	0.370	0.555	0.316	0.546	0.777	1.000
SRL6	0.029	0.086	0.210	0.333	0.144	0.349	0.555	0.201	0.489	0.777	1.000
TRLs,IRLs	1,1	3,1	3,5	3,9	5,1	5,5	5,9	7,1	7,5	7,9	9,9
Step	1	2	3	4	5	6	7	8	9	10	11

Table 3. SRL Example 1 Mapping to System Lifecycle

SRL Example 2



TRL	Tech	1	2	3	4	5	6
x	1	9	y	y	y	y	y
x	2	y	9	0	0	0	0
x	3	y	0	9	0	0	0
x	4	y	0	0	9	0	0
x	5	y	0	0	0	9	0
x	6	y	0	0	0	0	9

SRL Composite	0.057	0.169	0.251	0.333	0.282	0.418	0.555	0.394	0.585	0.777	1.000
SRL1	0.029	0.086	0.210	0.333	0.144	0.349	0.555	0.201	0.489	0.777	1.000
SRL2	0.062	0.185	0.259	0.333	0.309	0.432	0.555	0.432	0.604	0.777	1.000
SRL3	0.062	0.185	0.259	0.333	0.309	0.432	0.555	0.432	0.604	0.777	1.000
SRL4	0.062	0.185	0.259	0.333	0.309	0.432	0.555	0.432	0.604	0.777	1.000
SRL5	0.062	0.185	0.259	0.333	0.309	0.432	0.555	0.432	0.604	0.777	1.000
SRL6	0.062	0.185	0.259	0.333	0.309	0.432	0.555	0.432	0.604	0.777	1.000
TRLs,IRLs	1,1	3,1	3,5	3,9	5,1	5,5	5,9	7,1	7,5	7,9	9,9
Step	1	2	3	4	5	6	7	8	9	10	11

Table 4. SRL Example 2 Mapping to System Lifecycle

Push for Portfolio Management

As systems become more complex, management of their development efforts become more difficult. The management environment has become a critical focus for many organizations seeking to ensure the success of their programs and projects. The quest for new innovative approaches supporting the management decision-making process, including new software management tools, are at the top of the list. Portfolio management is defined as the management of an optimized group of projects aligned towards a central goal, theme, or strategy—sharing common resources within an organization. Portfolio management principles can be applied on the corporate level as well as the program or project level. In order to corporate portfolio management principles to be effective in an organization, that organizational behavior and process must be aligned towards a common goal or strategy (Sanwal, 2007). Though, the application of portfolio management strategies to different domains are evident from the many coined references like “corporate portfolio management,” “project portfolio management,” and “enterprise portfolio management,” their basic approaches are the same. Recently introduced corporate portfolio management (CPM) ideologies supporting system development in the DoD have shown some promise in providing a more dynamic approach to project management. The DoD’s Joint Net-Centric

Operations (JNO) group has adopted a capability portfolio management process to ensure that the portfolio is aligned with strategic objectives, the capability mix is synchronized, integrated, and optimized to meet warfighter needs, while being delivered more rapidly and efficiently. The overall goal of applying joint capability portfolio management is to help manage groups of similar and like capabilities across the DoD enterprise to improve interoperability, minimize capability redundancies and gaps, and maximize capability effectiveness (JNO, 2007, April).

Developing a CPM Strategy

The portfolio management process begins with a vision or desired capability that defines the strategic focus of the organization. This can be driven by internal corporate goals and/or by external customer/stakeholder requirements or needs. These requirements or needs are then translated to high-level, long-term research development goals and objectives, which can then be developed and achieved through a well defined, executed program. The final deliverable to the customer will be a technological capability, which is delivered to the customer through a technology transfer process. These high level principles are highlighted in a recent INCOSE paper titled, “A Systems Approach to the Transition of Emergent Technologies into Operational Systems—Herding the Cats, the Road to Euphoria and Planning for Success,” which discusses the critical elements needed to support and enable successful technology transition through the lifecycle development process (Austin, Zakar, York, Pettersen & Duff, 2008).

Four Key Questions Driving CPM Strategy

1. **What are we trying to Accomplish?** (Euphoria)

This question asks “”Where do you want to be?” and drives an end-state vision and goal based on high-level corporate strategy and stakeholder requirements.

2. **What can we do now?** (Herding the Cats)

Here, we must determine “Where are we now?,” “What can we do now?,” “What are our technical assets, past accomplishments, and available resources?” and “Can they be aligned with the desired end-state goals?

3. **What is our plan to get there?** (the Road to Euphoria)

Based on the answers to the first two questions, identify the technology gaps, and develop a roadmap or plan to reach the desired goals.

4. **How are we doing?** (the Metrics)

Here, we need to determine how well the system lifecycle development is maturing so that corrections and modifications can be implemented if necessary.

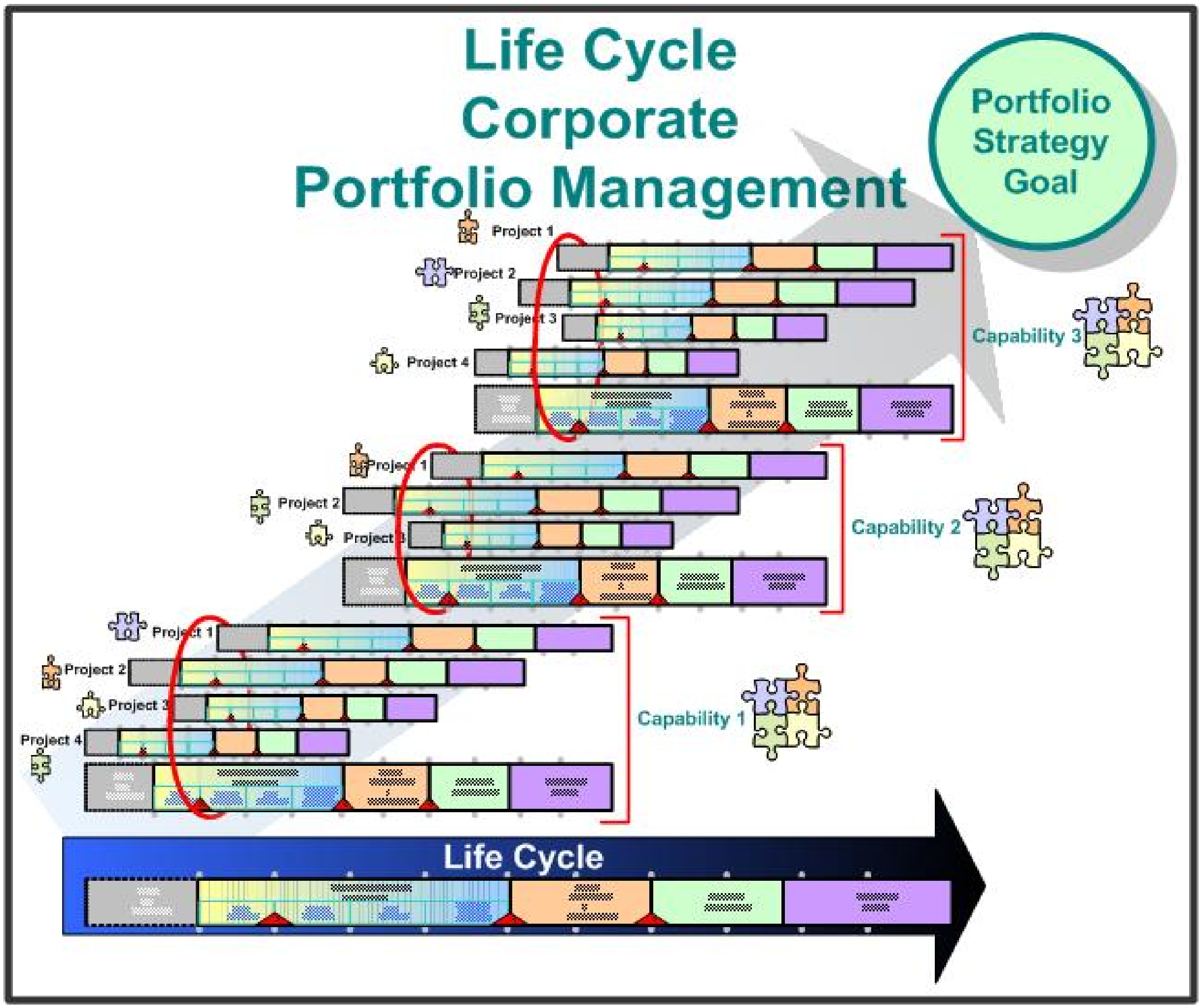


Figure 5. Lifecycle Corporate Portfolio Management

Portfolio Enterprise View

Based on the answers to the “Four Key Questions Driving CPM Strategy” discussed in the previous section, the selection of projects is based on their alignment to the desired capabilities and sub-objectives as well as available resources, including funding and available manpower.

Implementation of the portfolio management approach to project management eliminates the traditional approaches that led to multiple concurrent, often duplicative and “stove-piped” solutions that were inefficient, often subjected to irrational, “below the line” and “salami slice” budget cuts. These cuts can result in key capabilities being lost, leading to programs not being able to meet their objectives. Portfolio management presents an “enterprise” approach, providing for synchronized investments to deliver maximum capability through the prioritization of your investments by maintaining an optimal mix of investments in objectives aligned to your strategy.

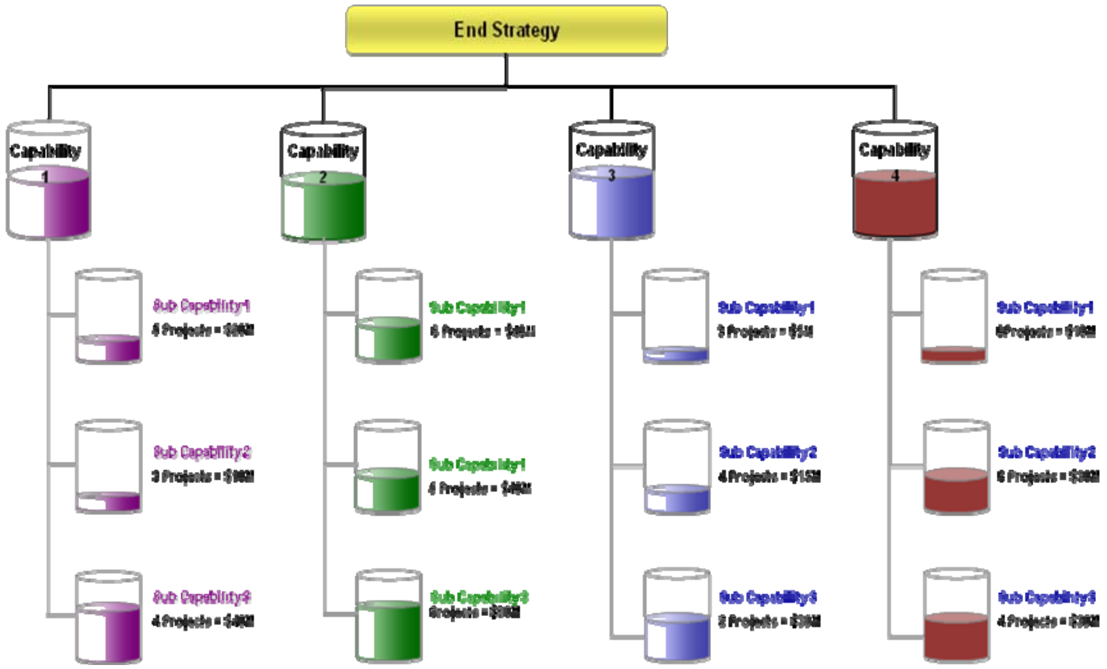
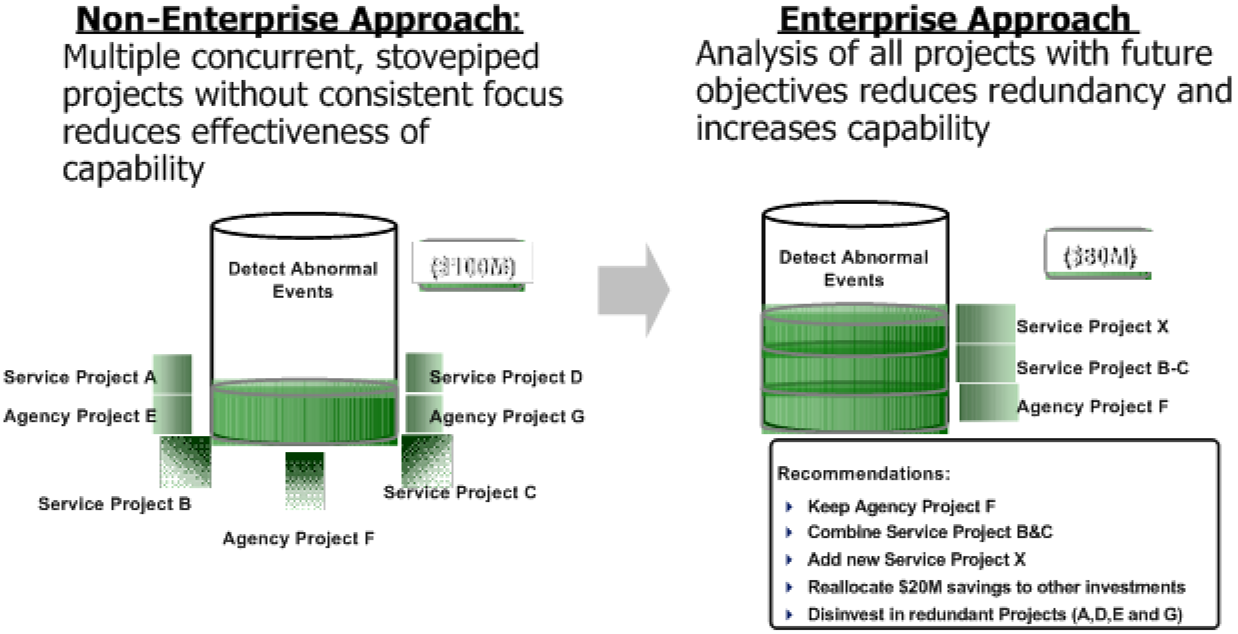


Figure 6. Portfolio Project Enterprise View


Non-Enterprise Approach:
Multiple concurrent, stovepiped projects without consistent focus reduces effectiveness of capability

Enterprise Approach
Analysis of all projects with future objectives reduces redundancy and increases capability

Recommendations:

- Keep Agency Project F
- Combine Service Project B&C
- Add new Service Project X
- Reallocate $20M savings to other investments
- Disinvest in redundant Projects (A,D,E and G)

Figure 7. Historical/Enterprise Approaches

Lifecycle Portfolio Management

Lifecycle portfolio management includes the capture of a variety of metrics (financial, performance, and maturity metrics) that are analyzed and the results support some type of decision-making process. At this point, optimization is considered a way to keep the portfolio better aligned to meet it strategic goals.

Metrics Assessments

The strength of portfolio management lies in the capture of metrics that measure the vital functions of a development effort and how well the development process is going. These metrics provide input to the optimization and decision-making process. These metrics can be captured on a quarterly basis and/or tied to key, program-specific development milestones. Progress against these milestones can provide key insight to the user regarding current program status, risk and progress. After the initial strategy development phase, a proposed approach for applying the maturity metrics to the portfolio management process would include performing the following:

- Initial assessment of selected technologies in portfolio mix, which includes the initial assessment TRL/IRL/SRL data, resource data.
- Quarterly cycle assessments of TRL/IRL, SRL, and funding and at milestones A, B, C of the DoD 5000.2 system lifecycle framework.
- Ongoing, search for new and viable technologies that may be available now or in the near future for possible integration or substitution into existing portfolio mix.
- Analysis of data to see if optimization opportunity is available.

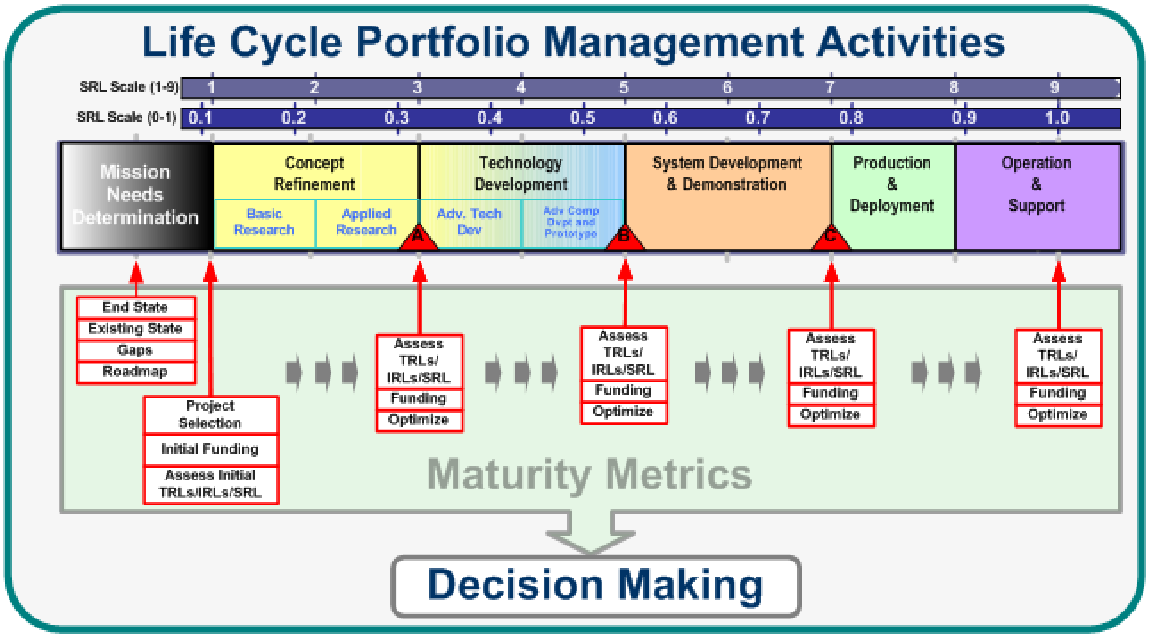


Figure 8. CPM Lifecycle Activities

Optimization

One of the key focuses of successful portfolio management is trying to maintain an optimal mix of technology development efforts aligned with the organizations strategic vision or goals. In addition, we need to understand how well or how fast these individual technologies are maturing relative to each other or if any new external technologies have been developed and can be immediately substituted, allowing for more dynamic changes to the portfolio mix. How do you decide between competing system design alternatives or which individual TRL or IRL to improve? The use of optimization modeling techniques can provide great insight and support to trade-off analysis and decision-making throughout the system development lifecycle.

Two recently developed optimization models, **System Cost of Development (SCOD) Minimization** and **SRL Maximization** are examples of using optimization techniques to help provide better decision-making, control-based resource constraints. The first model, **SCOD Minimization,** considers minimizing the development cost associated to increasing SRL to some predefined user level, λ. This model's objective is to minimize development cost (a function of TRL and IRL development) under constraints associated with schedule and the required SRL value (Magnaye, Sauser, Ramirez-Marquez & Tan, 2008). The second model, **SRL Maximization,** maximizes the SRL (a function of TRL and IRL) under constraints associated with resources. This model recognizes that the technologies compete for resources and that benefits can result in an improved SRL via the optimal allocation of such resources (Sauser & Ramirez-Marquez, 2009). In summary, optimization modeling should help provide the decision-maker, whether it is the program manager or the systems engineer with the best balance between the SRL and all the associated resources to help achieve the desired end-state goals. We must remember that optimization should be considered only a tool used along with other inputs, like metrics, to help provide depth to the decision-making process.

Decision-making

CPM decision-making is a complex undertaking as there are many elements and events that need to be understood and analyzed in a real-time manner. The pressures of schedule, cost and performance hold true along with an associated more real-time element. Adherence to the DoD 5000 acquisition framework's critical decision point assessments at milestones A, B, and C affects the optimization process.

1. **Optimal mix of research development investments to achieve capability goals based on maturation, cost, etc.**
2. **Allocation of resources to investments (Funding/Manpower)**
3. **Corrections to mix of research investments in reaction to the introduction of new technologies**

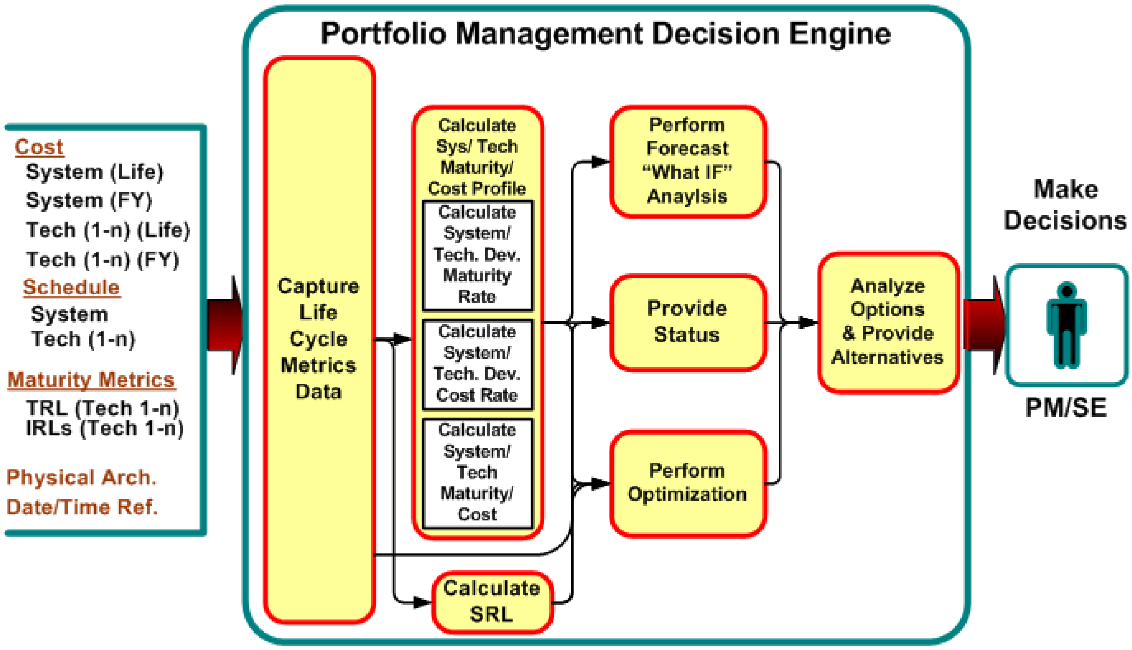


Figure 9. Portfolio Management Decision Engine

Summary and Conclusion

The purpose of this paper was to introduce the concepts of SRL metrics to multi-technology based system development environment in a portfolio management environment. The proposed application of these concepts and ideologies presents a new, potentially viable alternative to previously methodologies using TRL metrics. Stressed in this paper was the belief that you must consider an integrated approach to ensure that the portfolio management process and system maturity metric assessment process are synchronized closely to a lifecycle framework in order to meet your strategic goals. Looking ahead, research in the following areas would further contribute to the body of knowledge in System Maturity Metrics:

- SRL software tools to implement a combined SE, CPM and Road Mapping.
- Application of SRL metrics to support CPM environment.
- What additional maturity metric variables are needed to support the decision-making process?—security readiness
- Application of SRL model to other lifecycles outside the DoD.
- Robustness of SRL to variety of differing physical architectures.
- Impacts of disruptive technologies on systems maturity forecasting.
- SRL applications to COTS environment and lifecycle development

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Implementation of a Methodology Supporting a Comprehensive System-of-systems Maturity Analysis for Use by the Littoral Combat Ship Mission Module Program

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Mr. Peter Gentile is an Associate Systems Engineering Fellow for the Northrop Grumman Corporation currently working as the Technical Director and Chief Engineer for the Littoral Combat Ship Mission Package Integrator program. His 40 years of engineering includes wide involvement in the design of electronics, computers, software, and systems for platforms covering sea to space. Gentile earned a Bachelor's degree in Electronics Technology from NY Institute of Technology and a Master's in Systems Engineering from The Stevens Institute of Technology in Hoboken, NJ.

Mr. Ken Michaud assumed his current responsibilities as Acquisition Manager for Littoral Combat Ship (LCS) Mission Modules Program Office (PMS 420) under the Program Executive Officer for Littoral and Mine Warfare in January 2008. Prior to that, he was the Anti-Submarine Warfare (ASW) Assistant Program Manager (APM) within PMS 420 for over four years. He has served in the ASW community for over 20 years. As the Acquisition Manager, Michaud is responsible for a full range of acquisition and business planning tasks, including financial planning, program control, production and manufacturing coordination, and lifecycle planning. He provides leadership in the areas of acquisition through policy development, performance measurement and training.

Abstract

A core tenet of spiral development and evolutionary acquisition concepts is the ability to insert new technologies into an existing system on an as-needed basis, as they mature, in order to minimize risk and maximize affordability. Through this continual rolling in of evolving components the system continues to offer more advanced capability. This creates an elaborate tradeoff scenario in which dissimilar attributes must be examined, weighted, and analyzed for best value and applicability to user needs and requirements, including timing. A further complication for system-of-systems is added by the need to give equal consideration and analysis to each technology's ability to be integrated with existing system components

in a functional architecture as well as any impact on current and interconnected capabilities. To address this need for a multi-attribute decision-making tool, NAVSEA and the Northrop Grumman Corporation, along with partners at the Stevens Institute of Technology and SPAWARSYSCEN Pacific, have collaborated to define a holistic approach for evaluating technology insertion options from a complex system-of-systems integration perspective. Through this paper, we will discuss the tool's potential to aid the decision-maker in the selection of best value technologies and its potential utility as a critical piece of the unified system engineering and acquisition process.

Overview of the Current System-of-systems (SoS) Acquisition Environment

Current Department of Defense (DoD) acquisition activities continue to push the integration envelope with the development of larger and more complex systems-of-systems. In many ways, this development paradigm invalidates many of the models, historical databases, and even engineering expertise that have been used for decades in the development of stand-alone systems. Similarly, the system-of-systems revolution has made management of acquisition programs more difficult, as keeping accurate and current control of the countless moving parts of systems development is nearly impossible due to the exponential growth of technologies and integrations being incorporated under a common system-of-systems banner. This fact necessitates the development of a new set of tools and best practices in order to manage the many unique aspects of development associated with system-of-systems.

Unique SoS monitoring, assessment, and management needs

Nowhere is the need for enhanced monitoring capabilities more visible than in the SoS development maturity. For the better part of two decades, the Technology Readiness Level (TRL) methodology has been key in gauging the current maturity status of a given piece of technology within the DoD. By monitoring capability development from concept definition through operations and support using the TRL series of nine levels of maturity, the readiness of a technology for integration into a system has been adjudicated. In countless development efforts, TRL has been key in indicating progress and has aided dramatically in keeping numerous programs on track. Indeed, it has been incorporated as a critical tollgate criterion in the Defense Acquisition Milestone process. However, when TRL is applied to components within a system-of-systems, the model of using individual technology maturity as a measure of readiness to integrate into system development quickly breaks down. TRLs do not account for integration maturity or the complexity of bringing together any number of independent technologies to function as a common system. Similar problems also become apparent with many other technology development tools when applied in a system-of-systems context. This lack of adequate system-of-systems level development monitoring tools and methodologies has resulted in a rash of complex development and acquisition projects going astray. The General Accounting Office (GAO) noted that a lack of insight into the technical maturity of complex systems during development has contributed to an environment of significant cost overruns, schedules slips leading to program delays, canceled acquisition efforts, and reduced system performance at fielding (2006). In case after case, failure is not commonly found at the technology development level, but rather at the point of combination of two or more elements.

In order to mitigate this identified risk, PMS 420, the Littoral Combat Ship Mission Module Program Office has previously implemented an emerging concept known as the System Readiness Level (SRL). By pairing the traditional TRL scale with a new series of criteria known as the Integration Readiness Level (IRL), a more complete look at true system maturity can be obtained (Sauser, Ramirez-Marques, Magnaye & Tan, 2008). Under this methodology the readiness of each technology is still considered, but instead of being a stand-alone metric for determining readiness for incorporation, it is analyzed in concert with both its integration requirements and the maturity of other technologies with which it interfaces. The SRL methodology has been highly successful on the program and has paid dividends in terms of both increasing decision-maker visibility into true system status and allowing for pre-emptive actions to be taken to mitigate potential developmental issues. PMS 420 is looking to expand upon the foundation of system readiness monitoring laid by the SRL concept and expand it to new uses in both guiding technology selection, insertion and tradeoffs as well as for use in cost modeling in order to understand the impacts of implementing technology options.

Initial Step—Understanding the Current System

A core tenet of systems engineering is to fully understand and capture the architectures of the system being developed. This includes obtaining a comprehensive background on the individual components and technologies as well as the ramifications of their proposed integration or networking. In case after case, however, it can be seen that programs have entered acquisition with incomplete or inaccurate mappings of these most basic of considerations. The SRL concept enforces a degree of accountability by requiring consideration be given to mapping of an architecture and the maturity of the individual pieces being brought together prior to action being taken.

Upon the start of the Mission Module Program, the ability to pull together and assess a wide variety of components at numerous developmental maturity states was a necessity. As the provider of a set of interchangeable and standards-based mission modules for the Littoral Combat Ship, PMS 420 was tasked to leverage a considerable amount of technology from existing programs of record in a “come as you are” development effort. This was done to facilitate quick fielding of desperately needed capability in the areas of mine countermeasures, anti-submarine warfare, and surface warfare. This rapid development environment resulted in the selection of technologies from a considerable mix of existing GOTS and COTS products along with new development efforts. Initially, integration of the capabilities was not an objective, but it rapidly became a necessity. Thus, the Mission Module Program needed to track not only the widely varying maturity status of the technologies but also the various integrations activities between them as a critical function of management control. The SRL methodology was used to capture this complex and diverse acquisition effort and provide snapshots of program status, technology maturity and integration risks and issues.

SRL Concept

Since being introduced by NASA in the early 1990’s, the TRL has steady gained widespread acceptance as a powerful tool for its use in assessing technology maturity. In order to build upon the successes of this tool, the SRL methodology leverages the traditional TRL scale as its core for assessing the maturity of individual technologies within the system-of-systems. The TRL scale is then paired with a parallel evaluation scale, known as the IRL, to capture integration status between individual components. Much like the TRL, IRL is a nine-level scale capturing evolving levels of maturity for two components. Though it is natural for integration to slightly lag technology maturity, the IRL closes follows the TRL scale as it tracks integration maturity development from concept to operational system. Table 1 provides a high-level definition of the IRLs (Gove, Sauser & Ramirez-Marquez, 2009). The development of SRL has been led by a joint team of researchers from the Stevens Institute of Technology, Northrop Grumman Corporation, SPAWARSYSCEN Pacific, and PMS 420. Full reports on the creation and validation of the SRL concept have been provided in a series of academic papers and presentations. The concept has powerfully displayed insight into complex system-of-systems development maturity.

Table 1. Integration Readiness Level Definitions

IRL	Definition
9	Integration is Mission Proven through successful mission operations.
8	Actual integration completed and Mission Qualified through test and demonstration, in the system environment.
7	The integration of technologies has been Verified and Validated with sufficient detail to be actionable.
6	The integrating technologies can Accept, Translate, and Structure Information for its intended application.
5	There is sufficient Control between technologies necessary to establish, manage, and terminate the integration.
4	There is sufficient detail in the Quality and Assurance of the integration between technologies.
3	There is Compatibility (i.e., common language) between technologies to orderly and efficiently integrate and interact.
2	There is some level of specificity to characterize the Interaction (i.e., ability to influence) between technologies through their interface.
1	An Interface between technologies has been identified with sufficient detail to allow characterization of the relationship.

One of the most commonly recognized shortcomings of readiness scales is their inherent subjectivity in evaluation due to the fact that ratings are often determined by individual assessors using qualitative data. The SRL methodology implements an analytical approach to help to mitigate some of these concerns. Steps have also been taken to enhance the quality of the TRL and IRL evaluations that feed it by creating detailed evaluation criteria to minimize the opportunity for subjective interpretation. In order to assess the SRL of a given system, each component of the end capability (i.e., single system or a system-of-systems) is rated with respect to its TRL or IRL. These are then combined into a TRL and IRL matrix as shown in Figure 1.

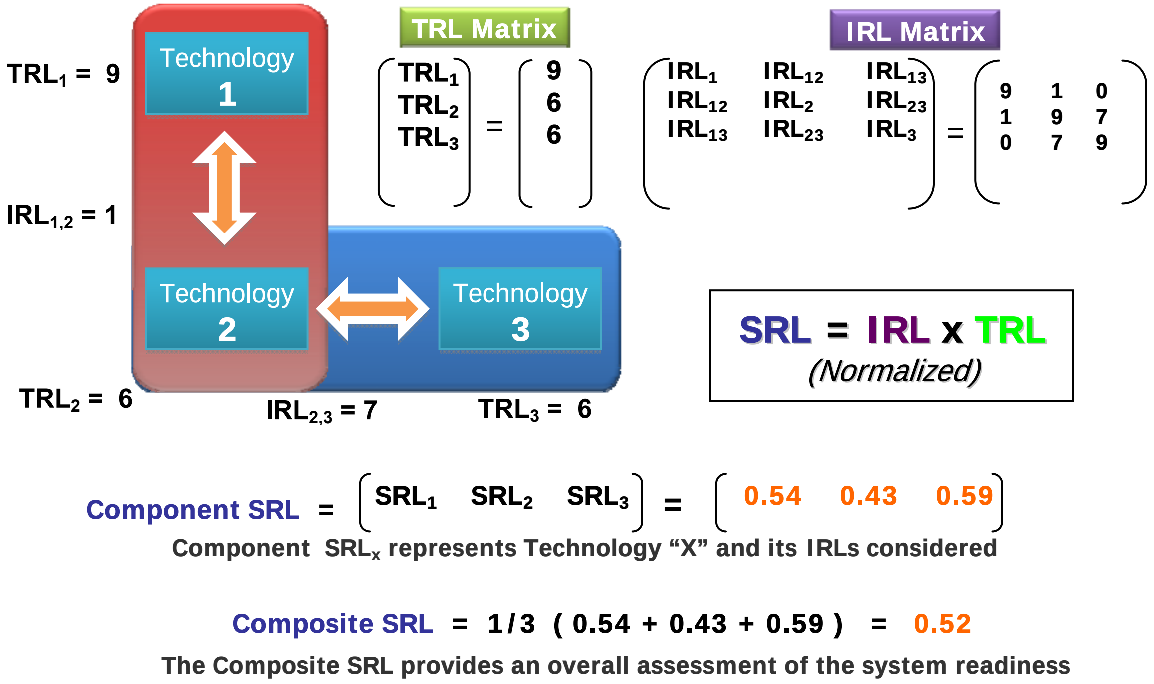
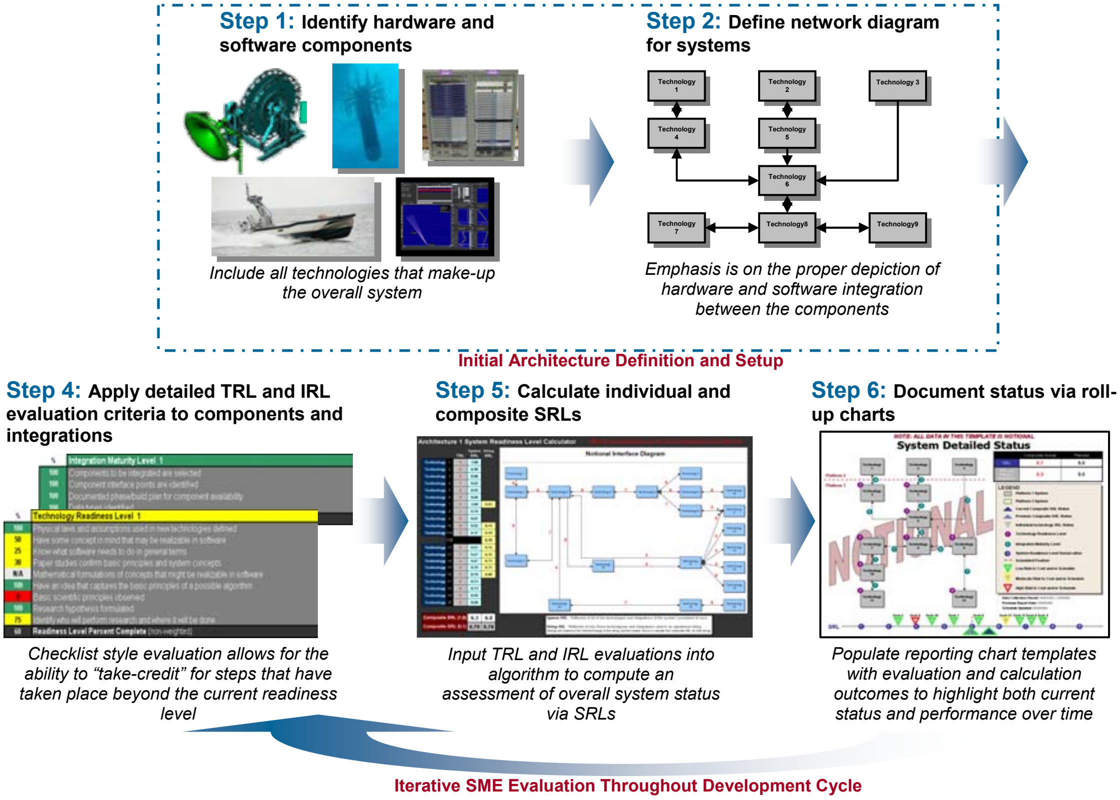


Figure 1. SRL Calculation

After normalizing, the matrices are multiplied forming a SRL vector. This vector is known as “component SRL” and represents each of the technologies within the system, considering all its integrations. These individual technology SRL assessments provide powerful insight into the maturity and integration status of each technology from an end capability perspective. Additionally, they offer an indication of which elements are lagging and which are ahead in development within the system. The individual SRL scales can also be averaged to provide an overall SRL rating for total system-of-systems capability. This single score is known as a “composite SRL” and functions as a roll-up of the individual component SRLs, providing insight into the level of maturity and integration of the total capability. It is important to note that each assessment is critical to assessing the state of the overall system. Simply examining an overall SRL score does little without understanding the impact of maturity and integration status of each individual component. In a large system, a single immature piece could easily be masked in a composite SRL number but such an act would be evident when assessed at a component SRL level. Likewise, composite SRL provides a good indication of overall development status and the magnitude of remaining work, but it could mask the inability of the system to function due to a single capability with low levels of maturity or integration at a key juncture within the overall system-of-systems.

An overview of the overall SRL assessment is provided in Figure 2. It is important to note that the actual SRL calculation is one part of a larger exercise in defining and evaluating the overall system architecture.



Step 1: Identify hardware and software components

Include all technologies that make-up the overall system

Step 2: Define network diagram for systems

Emphasis is on the proper depiction of hardware and software integration between the components

Step 4: Apply detailed TRL and IRL evaluation criteria to components and integrations

Checklist style evaluation allows for the ability to "take-credit" for steps that have taken place beyond the current readiness level

Step 5: Calculate individual and composite SRLs

Input TRL and IRL evaluations into algorithm to compute an assessment of overall system status via SRLs

Step 6: Document status via roll-up charts

Populate reporting chart templates with evaluation and calculation outcomes to highlight both current status and performance over time

Figure 2. SRL Analysis Process

SRL Applications in Decision-making

The SRL methodology has proven to be of tremendous use and utility in evaluating current status and then providing the needed insight in order to determine the appropriate course of action. In a complex SoS environment, it is not always immediately clear where resources should be applied for most efficient application in order to maximize system maturity and minimize risk. By allowing for trade-off analysis and "what-if" scenarios, the SRL lends itself to analysis of overall system impact, which allows for a wide variety of combinations to be tried before dollars are ever spent. In this way, a new technology or development option can be inserted into the architecture and its impact on overall maturity analyzed. An example of this trade-off analysis as applied on the Mission Module program can be found in Figures 3 and 4.

The figures represent the architecture of one SoS on the Mission Modules Program. Technologies are located in blue boxes while the lines between them denote integrations. The assessed TRL and IRL ratings can be found in teal and purple boxes, respectively. The component SRL ratings are denoted by small triangles across the top of the development scale at the bottom of the figure, while the overall composite SRL readiness number appears underneath the scale. The overall system maturity is exceeding the scheduled development position, which is indicated by the dotted red line and is determined via an SRL to program Integrated Master Schedule mapping. However, one of the system technologies, the MVCS (RMMV), has fallen significantly behind in planned development. This technology serves as a vital communication link in the command-and-control chain between the ship and an unmanned vehicle. With a risk item in the system development identified, mitigation options were generated, including increasing development resources or inserting an alternate technology. After examining projected performance, cost, and schedule numbers for each option as well the impact on overall system maturity, it was determined that a more mature technology would be inserted for initial spirals. While this option offered less capability in the near-term, it ensured performance requirements were met while enhancing overall system maturity and reducing risk.

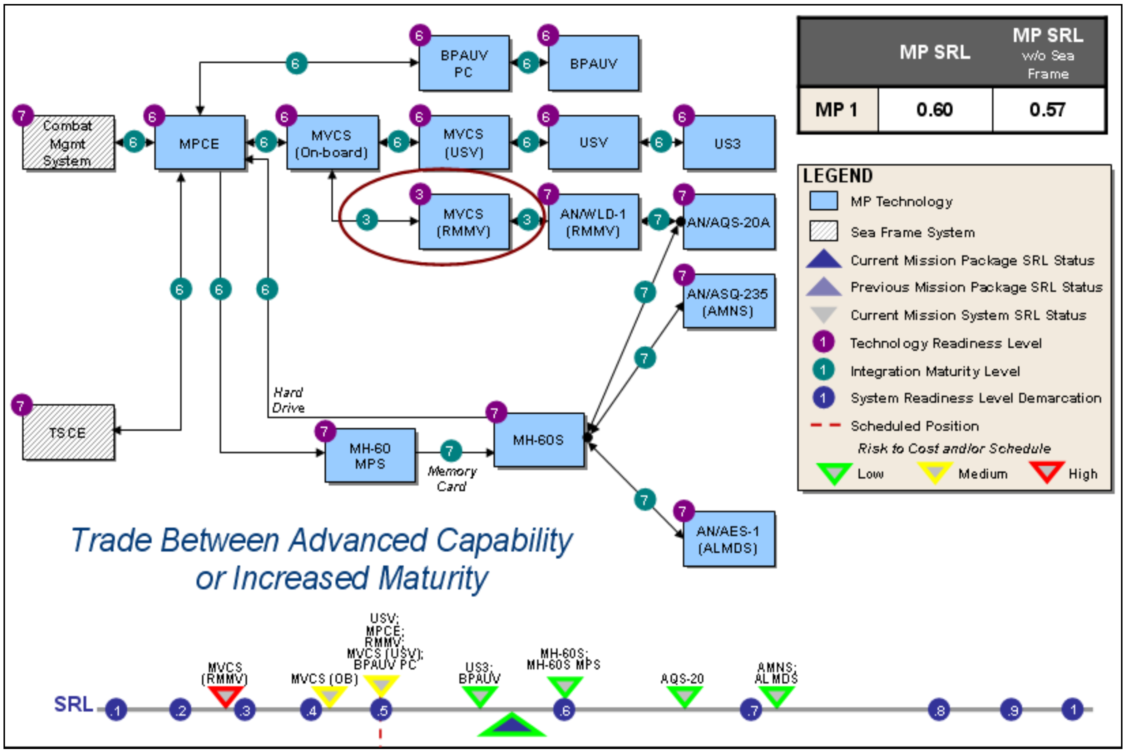


Figure 3. Initial System Readiness with Lagging Technology

The SRL assessment incorporating the insertion of the more mature technology is shown in Figure 4. By inserting this more mature technology, the component SRL of that element has risen above the scheduled development point along with the component SRLs of all of the technologies with which it integrates. Previously, these levels were determined to be held lower although they were mature because they were interfacing with a lower maturity component. Additionally, the overall composite SRL has seen a dramatic increase as indicated by the advancement of the indicator below the SRL development scale. Cleary this example indicates an instance in which the insight provided by both component and composite SRL was critical to identifying and assessing areas of system development risk.

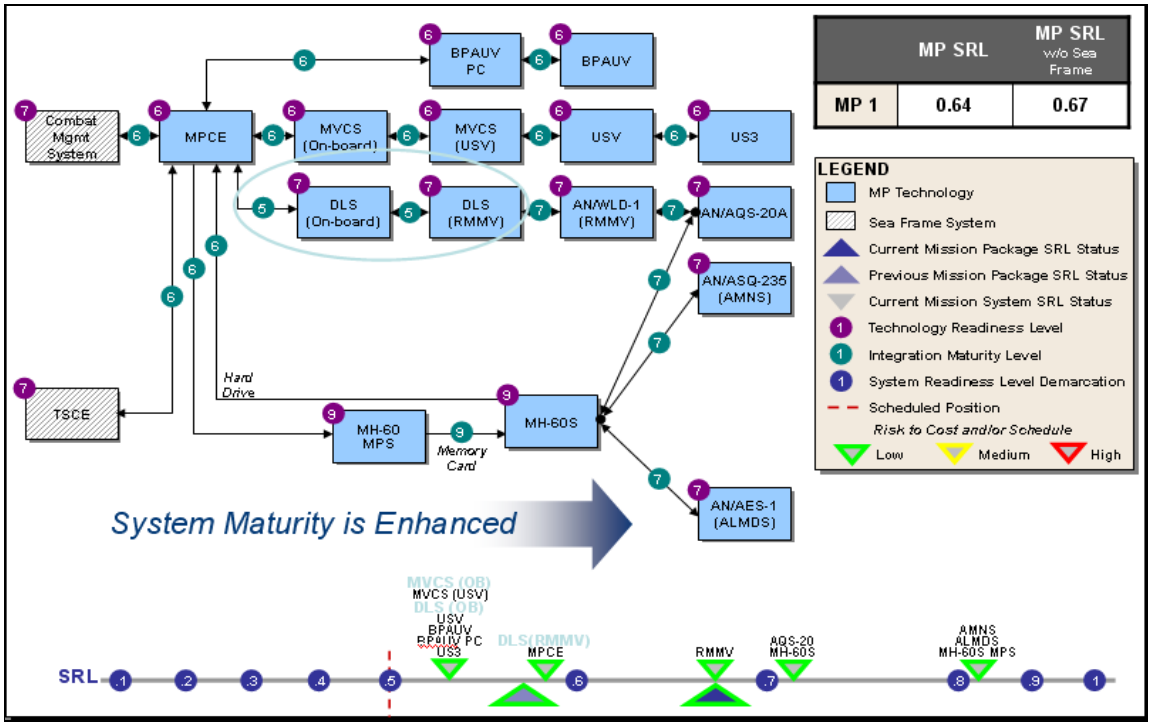


Figure 4. Enhanced Readiness via Capability Trade

Technology Insertion/Integration Challenge for Systems-of-systems

There are many reasons for the insertion of new technologies into existing systems-of-systems. Activities can range in scope from simple obsolescence work focused merely on keeping system functionality at a given level all the way to incremental elements of continued development. The latter case represents an opportunity for not only replacement of an element, but also potential changes to the existing architecture that is currently completely functional. The impacts of such insertion can be equally varied. Ideally, the new technology or set of technologies fit seamlessly with that of the old while increasing performance. However, this is seldom the case and, in some cases, the addition can cause a reduction in the current state of the system. Other impacts include forcing its functionality and performance to vary widely with impacts ranging from cost to reliability, maintainability, and availability. In most cases, failure of technology insertion can be traced back to a common failure cause—integration. This can include not giving proper consideration to the original requirements of the functional system or how the requirements have evolved due to the realities of operational use. Consideration must be given early and often to how original systems had been designed and what modifications must be made to allow the integration to proceed. It is also important to note that two mature (TRL 9), even operational technologies, will no longer be at an equivalent level of maturity when combined. Simply put, significant risk exists when two mature products are brought together as the combination often does not result in a product of equivalent maturity.

Instances in which integration of mature, proven technologies can produce unintended consequences are numerous both inside and outside of DoD acquisition. A perfect example of this occurred with the Massachusetts Bay Transit Authority (MBTA) in the mid 1990’s and took a full eight years to resolve (Fraser, Leary & Pellegrini, 2003). MBTA operates the oldest light rail system in North America with sections dating back over 100 years. In order to enhance handicapped accessibility it was determined that a new series of railcars would be needed. A competitive bid was sent out and the winner leveraged completely mature and well understood component technologies integrated into a new design. A prototype was constructed and entered into testing in 1998, less than three years after contract award. Testing proceeded as planned and the design entered revenue service in early 1999. However, this entry into service marked the beginning of a four-year period in which braking performance issues and derailments caused repeated withdrawal from service. During this time an extensive investigation into the performance issues was conducted.

The investigation noted many areas where integration of the well-proven technologies with each other and into the existing system infrastructure introduced unintended issues. These included difficulties in matching dynamic car acceleration and braking performance to those cars already in the fleet as well as the integration of the new wheel design to existing rails. In both cases the new car design met requirements, but failure to properly identify and account for the complexities involved with the integration of technologies, even well understood technologies, caused significant issues. In this case, the application of SRL could have been a significant aid as it would have allowed for the tracking of the technologies in the new design and their integration with one another as well as the overall integration to the existing system and operational environment. It cannot be sufficiently emphasized that performance of technology in a stand-alone environment does not mean that the technology can be inserted at a system level without significant planning, monitoring, and assessment.

Impact of Degree of "Design for Integratability" Inherent in Individual Systems (i.e., standards-based, common elements, non-planned, etc.)

In the command-and-control world, an approach to mitigate unplanned integration has been developed and is commonly referred to as Service-oriented Architecture. In this manner, a common set of standards are used to define interfaces and data types allowing a variety of elements from different developers to be quickly integrated into a common whole.

Depending on the system, the degree to which standards are applied and designed inherently brings about different levels of integratability. Two development projects beginning simultaneously can have drastically different trajectories based on the degree to which the technologies were designed to integrate. This difference can be seen by either enhanced IRL scoring or a far more rapid rise through the TRL maturation process due to significant amount of “pre-work” done via standards incorporation.

Another important consideration when it comes to integration is its multiple aspects. Depending on someone’s background, talk of integrating an avionics box into an airframe can have drastically different meanings. To a software engineer, integration means getting the box to exchange data with the countless other computers, sensors and control mechanisms on the pan. To an aerospace engineer, integration means the accounting of the systems weight in the overall performance of the plane. To a mechanical engineer, integration means ensuring the box fits in the rack; to an electrical engineer, integration means the type and amount of power required. Even to a human-factors expert, integration will mean balancing functionality with the pre-existing cockpit workflow. While these examples are relatively simplistic, it very rapidly becomes clear that integration is not just a single attribute that can be tracked as such; instead, it must be tracked at countless levels and, indeed, even the influence of the different types of integration must be taken into consideration.

In a real-life example of the above situation, the Army's canceled Aerial Common Sensor (ACS) program can be examined. In this instance, a highly capable intelligence gathering system was to be integrated onto an existing airframe design. Early focus on the intelligence system design and architecture produced a cutting-edge solution that met or exceeded customer requirements. However, it quickly became apparent that the design would be too heavy for the selected airframe, and the program was subsequently canceled after other mitigation attempts failed. In this case, it was not the integration of emerging technologies that posed a problem but rather the simple matter of vehicle payload, further underscoring the need for a comprehensive architecture analysis and integration monitoring methodology at all levels of systems design.

Consideration of Integration Types

In cases such as these, it is important to note that a single view of the previously discussed network diagram and SRL assessment may not be enough. In the PMS 420 program, IRL criteria have been broken into different types to account for software and hardware, in addition to physical aspects such as weight and clearances.

In essence, it looks at internal and external integration to a SoS. These can be considered individually for greater detail or summed up in a roll-up chart to appease management. In this way, countless implications and variations of integration can be tracked in a single place.

Reduction of Integration Risk in a System-of-systems

As discussed above, integration of components is one of the key areas of risk for developmental and production activities. While the SRL methodology will provide insight into the potential risk for mangers to understand, it does not inherently provide methods for reducing the risk. One way PMS 420 is seeking to reduce that risk is through the increased use of common components across the SoS in order to drive down integration uncertainty. Basically, an expansion of the open architecture concept, PMS 420 is seeking to define and manage the interfaces to be used by concepts seeking evaluation for insertion while allowing the technical capability to mature/change internally to the externally defined interfaces. An example of this process is how all mission package services were devised to operate upon a common operating system on common hardware. Within an individual mission package this capability was further allocated to individual mission systems, thereby providing processing and storage capabilities while requiring they support a minimal level of integration for use of common core capabilities. The drive towards Service Oriented Architectures for software base capabilities is another example of how integration risk can be minimized by increasing the use of common capabilities vice having each system try to provide an end-to-end solution.

Future Planned Expansion of the SRL Methodology

While the use of the present SRL methodology described above has helped the Mission Modules Program in terms of effectively managing system-of-systems procurement by providing additional insight into the technical and integration risks associated with the incremental acquisition or spiral development of capabilities, the efforts to date are just beginning to scratch the surface of providing management with the information required to make informed decisions and to apply these decisions in a predictive method for selecting technologies for future increments and spirals. Several areas have been identified as areas of investigation designed to further increase management insight in helping to resolve these deficiencies. These focus areas include the incorporation of methodologies designed to allow for the program office to gain better insight on the impact of inserting a new technology across the spectrum of the SoS's existing performance capabilities, the inclusion of cost factors and monitoring into the tool to allow for both predictive determination of "should cost" factors, and the use of the tool to provide insight into cost versus performance status monitoring. Additionally, for the Mission Module Program there is a desire to increase the use of common components across the warfare areas. This drive for commonality could impact performance and a method of analyzing the cost benefits versus performance risks prior to implementation is needed. All these focus areas are areas of growth for the methodology and will be discussed in the following paragraphs.

Technology Insertion/Integration Focus Area

One of the challenges of managing technology insertion into spiral or incremental programs is determining the value added and understanding the potential of a capability lost by inserting a new capability. Historically, technology insertion into a stand-alone system has only focused on the cost versus capability gained determination. In a system-of-systems, especially a constrained system-of-systems design such as the mission packages, the value of the capability gained on a individual system has to be assessed in terms of the impact and cost to that system as well as to the entire system of system. For example, Figure 4 is an example of how technology blocks for the MVCS control the present limitation on how far an unmanned surface vehicle (USV) can be from the LCS. A new manufacturer may devise a new communications capability that can greatly enhance the USV's operational range without increasing its cost or weight. While initially a great potential for improvement, the effectiveness of implementing the change is only beneficial if the greater range can be utilized and the impact of incorporating it does not impact the ability of the package to conduct all of its assigned missions. Thus, the impacts and limitations imposed by the directly linked components of the USV need to be understood but, more importantly, the total Mission Package impacts need to be understood. If the new capability added sufficient weight to the USV string, shown in Figure 4, it might create a condition in which the total weight of the package exceeded limitations, and a sensor might have to be removed from the helicopter to remain within the weight constraint. The loss of the sensor might mean that the Mission Package could no longer complete all assigned missions—so what appeared to be an improved capability at the start can turn into a negative if the impacts are not understood early enough to enable informed decision-making. One method that PMS420 is investigating for asserting this determination is using reliability block diagrams developed by the mission packages to predict end-to-end mission capability reliability, shown in Figure 5, and overlaying the TRL's and IRL's development through the SRL methodology to increase the understanding of the risk areas involved across a package when deciding to implement changes.

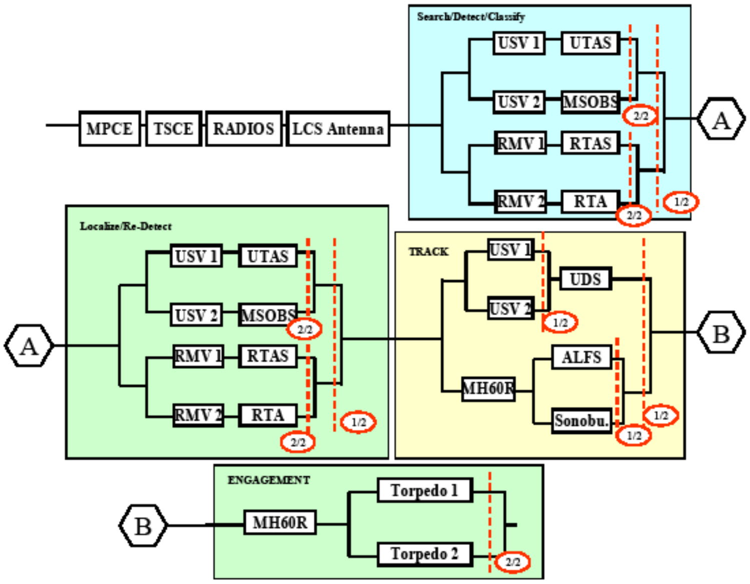


Figure 5. PMS 420 Reliability Block Diagram

Cost Prediction and Monitoring

Up until now we have been talking about the engineering implications of integration. As well all know, however, the real world is about more than just technical development. In order to have a successful system development effort, it is imperative that the design not only function, but also be built at the price that is affordable to the buyer. This is especially critical at a time when acquisition costs have soared, and it seems that even the most well-understood jobs cannot be completed on time or within budget. A fundamental failure in this area again relates to integration. Though the unique art and science that is cost estimation has been steadily expanding in experience for decades, the knowledge available for appropriately modeling and estimating the level of effort required to integrate various pieces of technology into a holistic capability is limited.

Degree of "Design for Integratability" Dramatically Impacts Cost Estimates

As with the previous examples of integration maturity being at different levels based on the degree to which technologies have been designed to integrate, cost is a similar and, in some sense, even more complicated operation. While there is a significant amount of data available to determine the cost of a new ship based on its displacement or on a new piece of software based on its lines of code, the understanding of how these two elements connect is far less understood. From the perspective of a cost estimator, who in many cases is outside the bounds of the program, the degree of work it takes to modify a pair of technologies to work together is somewhat of a mystery. The systems that have been designed with a standards-based approach may require little more than being brought together whereas other systems may require significant modification and extension of existing documents.

Cost Estimation Relationship Plans

In order to better capture this and estimate it for the PMS 420 effort, steps are being taken to categorize the integration at hand. In this way, a standards-based approach can be costed based on similar historical efforts while a dramatic revamping can be costed entirely differently. This information is being combined with technical status data to form an overarching assessment tool known as a System Maturity Model. In this effort, inputs on both technical development and factors impacting cost are collected side-by-side with cost and technical development information. Care is taken to specify the data types requested and examples are provided to ensure that the responses received are the type and quality requested. This requirement for data is then forwarded to subject matter experts for input. The data is then collected and used to populate algorithms that produce cost and technical assessments for the program. In the near-term, these assessments take the form of the CARD, PLCCE, and Milestone B documentation, but over the life of the program they will also form the foundation of program status reports and monitoring tools. By combining this information together from a system-of-systems perspective, the interdependencies of cost and technical development from a holistic perspective can be most accurately captured. As outlined above, the technical and integration maturity of the components are used to form the basis of cost estimates for development. From there, a variety of other information can be applied to expand that initial acquisition cost model into an estimate of total program lifecycle cost. Key elements include the operations and maintenance, CONOPS, as well as the technology insertion and obsolescence pans. By leveraging the architecture diagrams of how future technologies will be applied to the system over the course of time, a more accurate assessment can be obtained. A significant amount of unknowns and guess work can be reduced since detailed plans for what technologies may be inserted and in what manner that may happen. This eliminates surprise modernization service life extension efforts later in the program from running wildly out of control.

Conclusion

System-of-systems development is here to stay and will undoubtedly only grow more complex as the technologies that make up the systems continue to evolve, expand, and push the leading and often bleeding edge of technology. With this evolution, complex systems integration begins to require a paradigm shift in how assessment, analysis, and management techniques must be used and what tools are applicable. No longer can the development of individual technologies be considered in isolation; rather, these developments and their integration with one another must be defined and analyzed in new and enhanced ways. It is only by considering the impacts of all technologies and integrations as a whole that the acquisition approach can be improved. As discussed above, the implementation of a methodology that combines assessment of the technology maturity of component pieces with the assessment of their integration level has been shown to add value. The next step in improving this technique is to continue to expand its use in assisting in technology insertion assessments by using it as a predictive tool. Beyond that, the goal is to incorporate cost inputs into the tool to provide further insight to management on the existing risks thereby being accepted in the selection of technologies for incorporation into mature systems-of-systems.

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Panel 6 - Resourcing Strategies in System Lifecycle Management

Wednesday, May 13, 2009 **1:45 p.m. – 3:15 p.m.**	Panel 6 - Resourcing Strategies in System Lifecycle Management
	Chair: Lorna Estep, Executive Director, Air Force Global Logistics Support Center, Air Force Materiel Command **Discussant: Stan Soloway**, President, Professional Services Council; former Deputy Under Secretary of Defense (Acquisition Reform) ***Achieving Performance-based Lifecycle Management*** **Louis Kratz** and **Bradd Buckingham**, Lockheed Martin Corporation ***The Logistics Support Resource Strategy Map: A Design and Assessment Tool*** **John Dillard**, Naval Postgraduate School, and **David Ford**, Texas A&M University

Chair: Lorna B. Estep, a member of the Senior Executive Service, recently assumed the position of Executive Director, Air Force Global Logistics Support Center, Air Force Materiel Command.

As Deputy Director for Supply, Directorate of Logistics, Headquarters Air Force Materiel Command, Wright-Patterson Air Force Base, OH, Estep was responsible for the Materiel Support Division of the Supply Management Activity Group, a stock fund with annual sales of $7 billion. She directed a wide range of logistics services in support of Air Force managed spare parts, to include transformation programs, requirements determination, budgeting, acquisition, provisioning, cataloging, distribution and data management policy. She also provided supply chain management policy, guidance and direction in support of headquarters, air logistics centers, and US Air Force worldwide customers.

Estep started her career as a Navy logistics management intern. She has directed the Joint Center for Flexible Computer Integrated Manufacturing, was the first program manager for Rapid Acquisition of Manufactured Parts, and has served as Technical Director of Information Technology Initiatives at the Naval Supply Systems Command. In these positions, she has developed logistics programs for the Department of Defense, implemented one of the first integrated and agile data-driven manufacturing systems, and directed the development of complex technical data systems for the Navy.

As the Director of Joint Logistics Systems Center, Estep had the duties of a commanding officer for a major subordinate command. In addition, she acted as the Logistics Community Manager, an emerging organization to coordinate and implement the revised Defense Department logistics strategy for achieving *Joint Vision 2010* through modern information techniques and processes. She has also served as Chief Information Officer for the Naval Sea Systems Command in Arlington, VA, and Executive Director of Headquarters Materiel Systems Group at Wright-Patterson AFB. Prior to her current assignment, she served as Deputy Director for Logistics Readiness at the Pentagon, where she developed combat support concepts, doctrine, and sustainment policy with the Office of the Secretary of Defense, defense agencies, the Joint Chiefs of Staff and combatant commanders.

Discussant: Stan Z. Soloway is President and CEO of the Professional Services Council, the principal national trade association of the government professional and technical services industry. PSC is widely known for its leadership on the full range of government acquisition/procurement and outsourcing and privatization issues. Soloway assumed the presidency in January 2001. PSC has a membership of over 325 companies of all sizes, performing services of all kinds for virtually every agency of the government.

In addition to serving as President of PSC, Soloway was confirmed by the Senate in June 2007 as a member of the Board of Directors of the Corporation for National and Community Service. He writes a monthly column in Washington Technology magazine and was a member of the congressionally mandated, national panel on the future of government outsourcing chaired by the Comptroller General of the US. Soloway is also a Principal of the Council for Excellence in Government, where he also serves as a charter member of the Council's "Senior Advisors to Government Executives" program. He is a member of the Board of Advisors of the National Contract Management Association and received the prestigious Federal 100 Award in 2005. He also serves as an advisor to the Missile Defense Agency for the MDA's upcoming "MiDAESS" procurement for SETA support.

Prior to joining PSC, Soloway served as the Deputy Under Secretary of Defense (Acquisition Reform) and concurrently as Director of Secretary of Defense William Cohen's Defense Reform Initiative. As Deputy Under Secretary, he was the department's senior official responsible for the development and implementation of far-reaching reforms to DoD's acquisition processes and policies and for the oversight of the training, education and career development of the 200,000-member defense acquisition workforce. As director, DRI, Soloway led significant department-wide re-engineering and reform initiatives in areas as diverse as privatization and outsourcing, electronic commerce, financial management reform, logistics transformation, and the quality of life for American troops.

In recognition of his leadership at the DoD, Soloway was awarded both the Secretary of Defense Medal for Outstanding Public Service and the Secretary of Defense Medal for Distinguished Public Service.

Before his appointment to the DoD, Soloway was a public policy and public affairs consultant for more than 20 years and a highly regarded expert on acquisition, privatization, and outsourcing issues. He also co-produced the critically acclaimed "Great Confrontations at the Oxford Union," a series of prime-time specials that aired nationally on public television. He earned a degree in political science from Denison University, where he was elected to the National Men's Journalism, National Men's Leadership, and National Political Science honorary societies.

Achieving Performance-based Lifecycle Management

Presenter: Mr. Louis A. Kratz is the Vice President and Managing Director for Logistics and Sustainment, Lockheed Martin Corporation. Kratz is responsible for coordinating Lockheed Martin's logistics and weapon system sustainment efforts. He leads Lockheed Martin's Automatic Identification Technology implemtation, including RFID and UID. After successfully completing eight pilot projects, Kratz is now guiding Lockheed Martin's enterprise implementation of RFID. He also guides Lockheed Martin's logistics strategic planning, performance-based logistics efforts, logistics technology development, logistics human capital development, and cross-corporate logistics business initiatives. Previously, Kratz served as the Assistant Deputy Under Secretary of Defense (Logistics Plans and Programs) within the Office of the Deputy Under Secretary of Defense (Logistics and Materiel Readiness). As such, he was responsible for guiding the DoD's logistics transformation to meet the operational requirements of the 21st Century. Kratz oversaw the DoD's long-range logistics planning to meet the requirements of the *Quadrennial Defense Review* (*QDR*) and *Joint Vision 2020*.

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Author: Mr. Bradd A. Buckingham is an analyst for Lockheed Martin Corporate Engineering and Technology, Logistics and Sustainment. He holds a Bachelor of Liberal Studies degree in Conflict, Politics, and National Policy from the University of Mary Washington. Buckingham currently provides research and analytic support in theater opening and sustainment, and in support of Army, USMC, and Defense Logistics Agency Depot management. His prior experience includes supporting the Army Manufacturing and Technology Program at Fort Belvoir, Virginia, as well as providing support to the Joint Defense Manufacturing and Technology Program's (JDMTP) Warfighter Brochure, and serving as a subject-matter expert for Army ManTech Small Business Innovative Research (SBIR) program. Buckingham was also the acting Army representative for the JDMTP SBIR Working Group.

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Abstract

In July of 2008, Mr. John J. Young, Jr., Under Secretary of Defense for Acquisition, Technology and Logistics, issued a memorandum titled *Implementing Lifecycle Management Framework.* The memorandum addresses the need for Performance-based Lifecycle Management and is the Department of Defense's (DoD) most recent effort to improve weapon system readiness while reducing costs and cycle-times.

Since the end of the Second World War, the United States DoD developed and refined an acquisition process focused on responding to a predictable, monolithic threat. The process built upon several underlying principles, including a desire for US technological superiority, a competitive industrial base, and a relatively long planning and requirements horizon. Over the course of 60 years, the DoD attempted to improve its acquisition and lifecycle process through a series of incremental changes to address requirements creep, cost growth, funding instability, and technical risk.

Currently, the US faces significant economic and national security threats from near-peer competitors, rogue states, and transnational terrorist organizations. This multiplicity of threats requires an agile, cost-efficient process to mature and sustain military capabilities. A fundamental change to DoD lifecycle management is required to achieve that necessary agility.

This paper explores fundamental changes within government and industry to evolve a highly agile and responsive lifecycle process. Such a process would include effects-based requirements to enable effective cost/performance trades, a commercially driven research and development model to instill technology and requirements discipline, and industry provided lifecycle product support based on best-in-class performance. This paper summarizes those changes to enable and enhanced readiness.

"The only thing harder than getting a new idea into the military mind
is getting an old one out."
—B. H. Liddell Hart

Background

The Department of Defense (DoD) acquisition and sustainment processes are straining under the demands of the Global War on Terror, an increase in Congressional oversight, and an emerging shortage of skilled acquisition and sustainment professionals. Significant cost and schedule growth, extended development cycles, schedule delays, elongated logistics response times, and increasing backorders are evidence of those strains. The Government Accountability Office (GAO) documented a 36% percent cost growth for major defense acquisition programs and characterized DoD logistics as high risk (GAO, 2008a). Additionally, the DoD continues to struggle to keep pace with and develop new technologies and is no longer the catalyst driving the development of new revolutionary technology (Hagar, 2008).

In July 2008, the Defense Science Board (DSB) issued its report, "Creating an Effective National Security Industrial Base for the 21st Century: An Action Plan to Address the Coming Crisis." The report provided several specific recommendations to enable the DoD to achieve lower costs, field capabilities faster, and improve logistics support. The DoD also recently issued revised guidance on implementing a lifecycle management framework that focuses on lifecycle metrics, aligning resources and readiness, and implementing performance-based lifecycle product support (Young, 2008).

Our current national security posture and federal budget dictate that the DoD and industry continue to explore and refine new acquisition and sustainment processes to enable greater agility and capability at reduced costs. Capitalizing on market forces as an alternative to government regulations will permit the DoD to achieve the desired agility. In order to comprehend the challenges the DoD faces in achieving that agility, one must first review the path that the DoD and industry have traveled since World War II.

The World War II Acquisition and Logistics Environment

The acquisition process during the Second World War focused on mass production of weapon and support systems, as the American economy served as the heart of the Allied war effort. The United States produced over 2.4 million vehicles, 88,000 tanks, and 303,000 aircraft during the war with the lend-lease program exporting $57.4 billion worth of equipment to its allies. The US industrial complex was beyond the range of enemy attack, resulting in production numbers that exceeded that of the Allies and the enemy combined (Dana, 1998). The ability of US industrial base to rapidly transition from civilian to defense production enabled the Allied victory in World War II (Dana, 1998).

Acquisition and Logistics during the Cold War

In 1945, as Americans celebrated the end of World War II, US industrial capacity transitioned from a wartime footing to a commercial market burgeoning with pent-up demand. Commonality in manufacturing processes, similarity in products, and a dramatic increase in demand for consumer durables made for a relatively smooth transition to a peacetime, consumer-driven economy.

The subsequent emergence of the Soviet Union as a peer competitor gave birth to a dedicated defense industry that focused on developing and manufacturing the increasingly complex systems needed for deterrence (Defense Science Board, 2006). Weapons system acquisition during this period displayed several critical market characteristics:

1. A monolithic threat enabled the US to concentrate on relatively stable and predictable requirements

2. A national decision to capitalize on technology to seize and maintain qualitative superiority led the DoD and industry to concentrate on equipment performance

3. A robust set of industrial competitors enabled the DoD to experiment, develop, and prototype needed technologies while capitalizing on competitive market forces

4. A national decision to forward deploy forces in Europe and Korea encouraged large logistics footprints of supplies, personnel, and maintenance facilities to also be forward deployed

5. A national will that supported DoD efforts and provided funding at approximately 5-15% of the GDP (Center for Strategic and Budgetary Assessments, 2006)

6. A supportive environment of exploratory technology that tolerated test failures and allowed new data findings

The DoD and industry became increasingly governed by unique government practices—first in engineering and manufacturing, then in finance and business, with the

DoD specifications and standards numbering 30,000 by 1980 (Poston, 2003). These specifications and standards drove a wedge between defense and commercial industries and served as significant barriers for non-defense firms trying to enter the defense market.

By the early 1980s, the need to improve DoD acquisition was apparent. Numerous studies and academic research efforts documented DoD challenges with requirements stability, technical/risk management, funding stability, and schedule adherence (GAO, 1982). After nearly three decades of Cold War, the national will was shifting to demand more efficiency and accountability within defense acquisition.

The Reagan Era

Beginning in the early 1980s, a series of incremental policy directives attempted to address skyrocketing weapons costs and increasing development schedules. In April 1981, Deputy Secretary of Defense Frank Carlucci presented thirty-two initiatives for reducing weapons systems costs, shortening development time and improving weapons readiness and support.(Carlucci, 1981). One goal of the initiatives was to control cost growth by attempting to achieve realism in cost estimating.

Secretary Carlucci introduced the concept of Preplanned Product Improvement (P3I), a means to deploy systems and sequentially upgrade them over time (Carlucci, 1981). This strategy was intended to minimize technological risk, and quicken the pace of modernization of the nation’s armed forces. Other recommendations included the production of weapons systems at more efficient rates, reduction in the number of DoD directives, more advantageous use of competition, and greater use of standardized subsystems and support equipment. These initiatives represented a comprehensive list of measures with the potential to lower costs, but did not address the major causes of cost growth in weapons systems such as technical risk, requirements creep, and cost-plus business arrangements (Foelber, 1982).

During this period, Congress also took steps to curb the rising cost of weapons systems including the introduction of more rigorous DoD reporting requirements, the establishment of audit procedures for acquisition activities, and wider use of multi-year contracts (Lockwood, 1983).

The Packard Commission

President Reagan established the Packard Commission in 1986 to reduce the inefficiencies in the defense procurement system, with an emphasis on the acquisition process. The Commission’s conclusions supported the results of numerous prior studies, reporting that the acquisition process suffered from schedule delays, cost overruns, and inefficient performance (Blue Ribbon Commission on Defense Management, 1986). The Commission recommended streamlining the acquisition process, increasing the amount of tests and prototypes, and improving planning.

A subsequent review of 269 completed defense contracts found that the Packard Commission’s recommendations were ineffective in reducing cost overruns. Despite implementing over two dozen initiatives, there was no considerable progress in defense program cost performance for over 30 years (Christensen Searle &Vickery, 1992). The recommendations did little to fundamentally change the DoD reward mechanisms that favored expensive, long programs. (See Table 1.)

Table 1. The Effect of Packard Commission Recommendations on Defense Cost Performance
(Christensen, Searle & Vickery, 1992)

	All Contracts	Contract Phase		Managing Services		
		Development Contracts	Production Contracts	Air Force	Navy	Army
Number of Contracts (n)	269	8	188	113	134	22
Final overrun before implementation (%)	5.6	4.1	6.2	2.8	7.6	8.1
Final overrun after implementation (%)	9.5	15.3	7.2	12.7	6.1	17.0
Difference (%)	3.9	11.2	1.0	9.9	-1.5	8.9
Statistical significance (p)	0.055	0.014	0.294	0.003	0.206	0.110

The End of the Cold War

By the end of the Cold War, an industrial structure, an acquisition process, and a logistics system existed that were mismatched with the priorities of the American people and the global environment. The DoD had honed an acquisition process that focused on providing technologically superior systems with industry geared up to produce those systems in large quantities. With the dissolution of Soviet Union, the American public shifted its priorities to domestic issues. Multiple administrations through the 1990s responded to this shift in focus through force reductions, base closures, and industrial consolidation (GlobalSecurity.org, 2003).

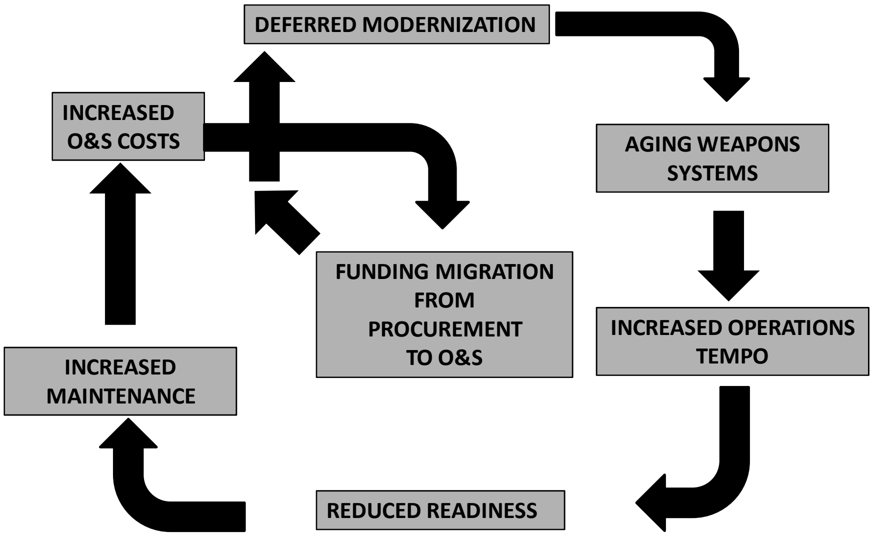
Specifications and Standards Reform

In 1994, Secretary of Defense William Perry issued DoD policy to increase access to state-of-the-art technology and adopt the same business practices as world-class commercial suppliers. The directive attempted to reduce the complexity and costs that the DoD incurred when purchasing major weapon systems and their numerous maintenance requirements.

Secretary Perry chartered a detailed cost analysis allowing the DoD to determine the most important cost drivers in the quest for standards reform. The study concluded that, on average, the DoD paid a regulatory cost premium of approximately 18 percent. The study also indicated that significant cost savings were achievable through reductions in DoD regulation and oversight (Coopers & Lybrand/TASC Inc., 1994). Since Secretary Perry introduced his plan to reform the acquisition process, over 1200 commercial standards have been adopted by the DoD; however, the DoD has not fully capitalized on commercially available solutions (OSD(PA), 1994).

The procurement accounts declined in the late1990s, with fewer new systems under development and existing weapons platforms aging and continuing service past their intended lifecycles. This extended use resulted in increasing operations and maintenance (O&M) costs, which contributed to a lifecycle “death spiral” of further deferred modernization, as shown in Figure 1 (Gansler, 1998).

Figure 1. The DoD "Death Spiral"



(Source: Dr. Jacques S. Gansler, USD(A&T), Acquisition Reform Update, January 1999)

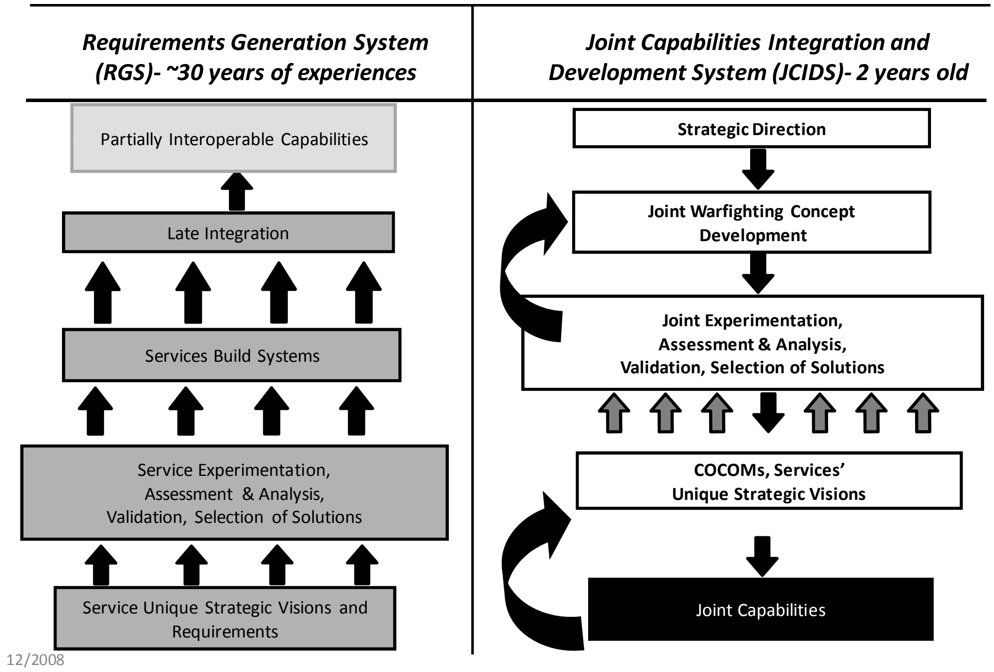
To attack this "death spiral," the Under Secretary launched an aggressive acquisition and logistics reform effort. Key initiatives included increased use of commercial items, evolutionary acquisition, streamlined acquisition documentation, and performance-based logistics. These initiatives emphasized greater civil-military integration and were directed towards increasing acquisition and logistics agility.

Joint Capabilities Integration Development System (JCIDS)

Joint Capabilities Integration Development System (JCIDS) is the DoD's procedure to define acquisition requirements and evaluation criteria for future defense programs. JCIDS was created in 2003 to address shortfalls in the DoD requirements generation system identified by the US Joint Chiefs of Staff, including not considering new programs in the context of other programs, not sufficiently considering combined service requirements, not effectively prioritizing joint service requirements, and not accomplishing sufficient analysis.

The JCIDS process codifies a DoD policy shift away from threat-based assessments to capabilities-based assessments of Warfighter needs. As a replacement for developing, producing and fielding systems based on perceived threats to the nation, JCIDS policy enables the development of capabilities based on strategic direction and priorities defined in the National Military Strategy and National Defense Strategy (Chadwick, 2007). (See Table 2.)

Table 2. Threat vs. Capability-based Planning
(Bromberg, 2006)

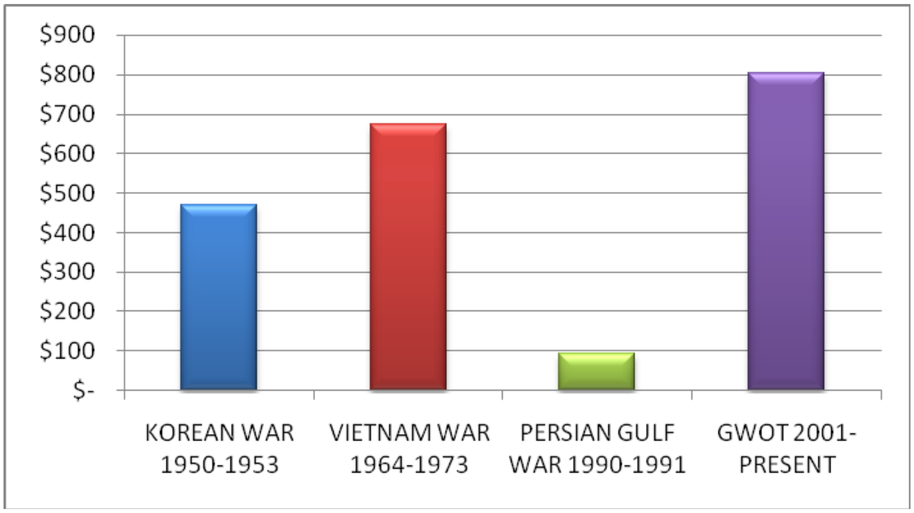


The Global War on Terror

Despite the perceived “peace dividend,” the migration from a bi-polar world to a multi-polar world proved more challenging than anticipated. The DoD continued to rely on acquisition processes, organizations and infrastructure largely developed in the years following World War II. Technical superiority had proven successful against a peer competitor; however, rapid advancement in commercially available computing and telecommunications gave rise to multiple new threats: e.g., transnational terrorism and rogue state actors. This multiplicity of threats demanded greater agility and innovation at the same time DoD acquisition and its associated industrial base were contracting. September 11, 2001, proved these threats very real, initiating the ongoing Global War on Terror (GWOT).

Executing the GWOT is an expensive endeavor. The total amount of GWOT funding provided over the past seven years is approximately $804 billion. This makes the GWOT more expensive than both the Korean ($460 billion) and the Vietnam ($650 billion) wars (Serafino, 2001). (See Table 3.)

Table 3. Cost of Selected Wars (in billions of $2007)
(National Priorities Project, 2007)



The GWOT to date has provided the United States with lessons directly related to DoD acquisition and sustainment. These lessons include:

- Our requirements process is slow to react to a rapidly adaptive adversary.
- Our acquisition process consumes billions of dollars against threats generated at a fraction of that cost.
- Our mass logistics structure is insufficient to support rapid, dispersed forces.

In September 2008, Secretary Robert Gates spoke at the National Defense University and addressed these issues:

> The need for the state of the art systems—particularly longer range capabilities—will never go away, as we strive to offset the countermeasures being developed by other nations. But at a certain point, given the types of situations we are likely to face—and given, for example, the struggles to field up-armored HUMVEES, MRAPs, and ISR in Iraq—**it begs the question whether specialized, often relatively low-tech equipment for stability and counterinsurgency missions is also needed.**

Secretary Gates continued:

> And how do we institutionalize procurement of such capabilities—and the ability to get them fielded quickly? Why did we have to go outside the normal bureaucratic process to develop counter-IED technologies, to build MRAPs, and to quickly expand our ISR capability? **In short, why did we have to bypass existing institutions and procedures to get the capabilities we need to protect our troops and pursue the wars we are in?** Our conventional modernization programs seek a 99 percent solution in years. Stability and counterinsurgency missions—the wars we are in—require 75 percent solutions in months. The challenge is whether in our bureaucracy and in our minds these two different paradigms can be made to coexist.

Time for Change

Since the end of World War II, the United States DoD developed and refined an acquisition process focused on responding to a predictable, monolithic threat. This process built upon several underlying principals including a desire for US technological superiority, a competitive industrial base, and a relatively long planning and requirements horizon. Over the course of 60 years, the DoD attempted to improve its acquisition and lifecycle process through a series of incremental changes to address requirements creep, cost growth, funding instability, and technical risk.

Currently, major weapon system programs within the DoD are taking longer to complete, costing more, and delivering quantities far lower than originally intended. The total acquisition cost of the DoD's 2007 major programs has increased by almost $300 billion over preliminary estimates (GAO, 2008a). Weapon system programs often begin without adequate information pertaining to requirements, technology, and design maturity. Lacking such knowledge, program managers often rely on unrealistic assumptions that increase program risk, cost growth and schedule delays (GAO, 2008a). Finally, the geopolitical environment has changed dramatically over the past 60 years, as summarized in Table 4.

Table 4. Geopolitical Differences

1945 - 1990	Today
Threat: Bipolar threat. Enabled the US to concentrate on relatively stable and predictable requirements (Soviet Union)	**Threat:** Multi-polar threat. Transnational terrorism, near-peer competitors, and rogue state actors
Technology: A national decision to capitalize on technology to seize and maintain qualitative superiority led DoD and industry to concentrate on equipment performance. Military technology as the driving force	**Technology:** DoD no longer the catalyst driving the development of new revolutionary technology. Commercial technology the driving force
Requirements: Concentrated on relatively stable and predictable requirements. Match or counter Soviet weapons systems	**Requirements:** Unpredictable and unstable with the multiplicity of threats and behavior adversaries with current events driving requirements
Acquisition & Sustainment: A robust set of conventional industrial competitors enabled DoD to experiment, develop, and prototype needed technologies while capitalizing on competitive market forces. Incremental change	**Acquisition & Sustainment:** Systems and cost demands of the Global War of Terror, increasing Congressional oversight, and a shortage of skilled acquisition and sustainment professionals. Significant cost and scheduled growth of major defense programs, extended development cycles, schedule slips, elongated logistics response times, and increasing backorders
National Will: A national will that supported DoD efforts and provided funding at approximately 5-15% of the GDP	**National Will:** National will skeptical and increasingly unwilling to accept continued rampant defense spending

The United States DoD can no longer afford to follow the path of incremental change to its acquisition and logistics process and must fundamentally transform its current acquisition practice. The acquisition and logistics environment of the 21st century needs a course of action that will decisively enable greater agility and efficiency through effects-based requirements; commercially driven research and development; and industry-provided lifecycle product support processes.

Becoming Highly Agile and Responsive

Effects-based Requirements

"Requirements creep" has been a persistent problem within defense acquisition since World War II. This "creep" is driven by the DoD focus on technological superiority and the military services historic bias towards unique requirements. The JCIDS process (and subsequent portfolio management) was intended to correct these problems; however, the Joint Staff was never fully resourced to develop capstone and integrating concepts. As a result, the JCIDS process continues to be dominated by Service-driven requirements.

To compensate, DoD is implementing an increasing number of common critical performance parameters to enhance system inter-operability and "jointness." These requirements tend to be overlaid on top of Service-driven performance requirements. Requirements packages for major systems continue to be large, complex, and, in many cases, contradictory.

In order for the DoD to enhance agility, it must begin with a requirements process that is appropriately focused on the military effort that is required. Requirements would be characterized based upon desired effect or outcome, rather than as a specific system. Such an approach would make maximum use of Joint Staff resources for integrated "Concepts of Operation," while fostering innovation within the Services and industry to develop competing solutions. Industry would be empowered to provide a specific capability rapidly, within the constraints of the "Concept of Operations."

The Joint Mine Resistant Ambush Protected (MRAP) Vehicle Program (JMVP) currently offers a good example of what an innovative and agile DoD acquisition process could look like. The MRAP program is the largest and fastest military acquisition buildup since World War II, with the DOD utilizing an acquisition strategy to rapidly acquire and field MRAP vehicles. The MRAP acquisition program established minimal operational requirements and relied heavily on commercially available products (GAO, 2008b).

The DoD designated the MRAP program as DoD's highest priority acquisition, which helped contractors and other industry partners to rapidly respond to the urgent need and meet production requirements with industry partners. This facilitated rapid fielding by generally meeting or exceeding planned production rates. This agile and responsive acquisition process saved lives and made an exponential contribution to warfighter readiness (GAO, 2008b).

Industry-driven Research and Development

The DoD acquisition process reinforces unique solutions via built in bias for large, long cost-plus development programs. These programs inherently embody incentives for cost and schedule growth and limited incentives for efficiency. The DoD and the Congress have attempted to regulate efficiency for 20 years via increased oversight and reporting, but the overall process seems impervious to incremental change.

Advances in technology research and development (R&D) are currently led by the commercial world, where R&D has increased steadily at a rate of about 5% per year for more than 20 years. During this same 20-year period, DoD and government R&D spending dropped 2.5% per year (Gansler, 2000). In order for the DoD to capitalize on commercial investment, it must actively engage the commercial market.

The “new normal” of persistent conflict and stabilization engagement demands a “new normal” research and development business model. Such a model would be more akin to the commercial development process, where industry manages product R&D (and is fully responsible for technology maturation of that product). The DoD would continue to invest in basic research within the 6.1 and 6.2 accounts and in test and evaluation of competing prototypes.

This approach would incentivize industry to control requirements creep, select mature technologies for product integration, and develop solutions in an incremental, timely fashion. Such a system would inherently incentivize industry, since industry would be funding the development (versus the cost-plus development of today) and provide a meaningful business driven mechanism to moderate technical risk and ensure technical maturity (versus the technology readiness levels used today).

Such on approach may not be applicable for complex, high-risk defense items (aircraft carriers, as an example); however, it should be appropriate for a growing number of items required for “persistent presence.” In addition, this approach will require fundamental change within the DoD to accept industry-natured technologies and equipment built to commercial standards.

Industry Provided Lifecycle Product Support

The DoD has recently embraced an innovative approach for procuring logistics support for its weapons systems. In the 2001 *Quadrennial Defense Review*, the DoD mandated the implementation of Performance-based Logistics with the goal to gain the most efficient and effective performance of weapons systems throughout their lifecycles, and to build successful business partnerships that align with the goals of all involved parties for the duration of these programs (Berkowitz, 2005). PBL is a business partnership model designed to align the interests of both the DoD and the logistics service provider: creating value and the desired outcomes of both partners. This yields a more cooperative venture than merely achieving service level agreements or getting the lowest price from the provider.

PBLs have demonstrated success by providing superior logistics support for simple parts such as aviation tires, subsystems such as engines, and complete weapon systems (e.g., F-22). PBLs have demonstrated improved weapons systems readiness and equipment availability through the development of incentives for industry investment and partnerships. There are more than 200 PBL efforts DoD-wide that have demonstrated material availability above 95 percent and commercial response times of 2-4 days (versus DoD average of 16 days) (Estevez, 2005). (See Table 5 and 6 for PBL success examples.)

Table 5. Availability, Cycle-time, and Cost Benefits of Performance-based Logistics

(Fowler, 2008)

PROGRAM	AVAILABILITY BENEFITS
F/A-18	+ 23%; 98% RFT
F/A-18 SMS	32%
H-60 Avionics	14%
Tires	17%
AEGIS	30%
F-404 Engine	46%
T-700	35%
CIWS	9%
Mk41 VLS	8%
Sea Sparrow	14%
Navy Spt Equip	32%
Nimrod (UK)	40%
AN/ALQ-126B	50%
AN/USM-638	40%
LANTRIN	17%
EA-6B Flt Cont	47%
F-22	+ 15% MC

PROGRAM	AVAILABILITY BENEFITS
B-2	47.2% MC (Record Level)
E-8	99.5% Lch Rt; 97.6% ME
ALR-67(v)3	97% Avail
Sentinel	95% Avail
Shadow	96%+ OR
TAIS	98%+ Avail
Javelin	99%+ OR
ITAS	99% Avail
CGS	99% Avail
HIMARS	98.7% Avail
C-17	93.5% Dpt Rel ; 85.4%MC
C-17 Engines	70% TOW incr
T56-15 Engines	+ 35% TOW
APS-137	+ 40% TOW
AN/PSS-14	95% Eff Rate
F414 Engine	97% Avail
Patriot	- 99% B/O's

PROGRAM	AVAILABILITY BENEFITS
F/A-18	-74% LRT; -33% RTAT
F/A-18 SMS	- 84% LRT
H-60 Avionics	- 85% LRT
Tires	-92% LRT; -100% B/O's
APUs	- 82%LRT
LANTRIN	- 90% LRT
F-404 Engine	- 25% RTAT
T-700	-74% RTAT; -100% B/O's
AH-64 Apache	- 35% RTAT
Pegasus Engine	- 59% RTAT
CH-47 (UK)	- 44% RTAT
F-22	- 20% RTAT
B-2	- 20% RTAT (Depot)
CIWS	- 99% B/O's
Sea Sparrow	- 90% B/O's
F-404	- 66%B/O's
RFTLTS	- 96% LRT

RFT - Ready for Tasking
MC - Mission Capable
OR - Operational Readiness
ME - Mission Effectiveness

TOW - Time-on-Wing
B/O's - Backorders
LRT - Logistics Response Time
RTAT - Repair Turnaround Time

Table 6. PBL Cost Benefit
(Fowler, 2008)

PROGRAM	Total Cost Benefit ($M)
F-22	$14,000
ALR-67(v)3	$62.7 (40%)
TOW-ITAS	$350
F/A-18	$688
CGS	$10.3 (65%)
MIDs-LVT	$62 (54%)
AN/AAS-44	$31 (25.2%)
APUs	$4 (20.9%)
AEGIS FCS	$8 (19.3%)
F405 Engine	$61 (17.2%)
Cockpit Disp	$71 (16.5%)
F100	$2 (16.3%)
AH-64 & CCAD	$100
CH-47(UK)	$250
Javelin	10%
RFTLTS	$0.50

PROGRAM	Total Cost Benefit ($M)
ARC-210	$5.4 (8.6%)
TH-57	$15.3 (7.9%)
H-60	$41 (6.5%)
Sea Sparrow	$2.2 (6.3%)
AN/WSN-7	$0.88 (1.3%)
AN-PSS14	$17
Sentinel	$301.70
T-45	$85
C-17	$477
Navy Spt Equip	$1
AN/ALQ-126B	$2.10
AN/USM-638	$0.50
C-17	59%
Tornado (UK)	51%
Harrier (UK)	44%
Nimrod (UK)	8%

PROGRAM	Annual Cost Benefit ($M)
F-22	$500 (39%)
CASS CSP	$30 (54%)
TOW-ITAS	$6.3 (34.5%)
ARCI	$4 (24.7%)
MK 41 VLS	$1.1 (16.4%)
F-117	$124 (14.5%)
Navy Tires	$46 (15%)
GBMD	$1.60
TAIS	$0.01
H-46	$0.35
Program	Flying Hour Cost Reduction
LANTIRN	$9.6 (14.6%)
F-404 Engine	$79 (13.4%)
F-414 Engine	$6.40
Patriot	$1 (13.1%)

The wide use of performance-based logistics (PBL) contracts ultimately puts the focus on readiness and rapid, agile support. PBL enables the DoD to select providers based on competitive value, producing partnerships with preferred providers that overtime will improve the DoD's overall support capabilities (Estevez, 2005).

Conclusion

Despite fond memories of past glories, cost and schedule control have been persistent problems within defense acquisition since World War II. The DoD acquisition and lifecycle processes have proven to be impervious to incremental improvements, despite decades of study and recommendations. It is certain that for the foreseeable future we as a Nation will face a severely constrained fiscal environment that will put added downward pressure on defense and other discretionary budget elements. This situation necessitates an enterprise-wide Defense Department application of the proven lifecycle management practices that will ensure greater performance improvements and simultaneous cost savings. These significant savings opportunities in turn can be deployed to address the significant force modernization and recapitalization requirements that we face today and in the future.

The United States cannot be certain of the international security situations it will confront in the next two decades. The world security environment is likely to be dramatically different and more active than the Cold War years, the years following, and the current

GWOT. This uncertainty requires an acquisition process that is agile and efficient, enabling the DoD to rapidly field and sustain capabilities. Such a process would include:

- Effects-based requirements
- Commercially driven product development
- Industry-provided product support

These elements present fundamental change to DoD's lifecycle processes to meet the needs of the 21st century.

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The Logistics Support Resource Strategy Map: A Design and Assessment Tool

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Abstract

Design of a resource strategy for logistics support requires decision-makers to choose to use contracted, blended, or organic support, or a combination thereof, for acquisition products. Non-cost issues have received much less attention than cost in resource strategy design—even though policy requires the incorporation of many non-cost issues. This lack of attention is partially due to the large number of issues that can impact strategy design, the diversity of issue features and impacts, and the diversity of characteristics of programs, their environments, and potential strategies. Although many issues that should be included in logistic planning have been identified, little guidance is provided for how program management teams can incorporate them into logistics support resource strategy design. Tools that facilitate describing logistics requirements and the impacts of resource strategies on program success can potentially improve resource strategy design, assessment, and documentation for review. The structure and use of the Logistics Support Resource Strategy Map for helping program management teams consider a broad range of logistics support resource strategy design issues are described. An example application illustrates the Map’s use. Implications for practice and potential future developments tool are discussed.

Keywords: Logistic support, resource strategy, strategy design and assessment

Introduction

> “‘[The] logistic process is at once the military element in the nation’s economy and the economic element in its military operation.’ […] Logistical conditions and capabilities largely determined what was strategically available and tactically feasible […] logistics is always the indispensible servant of victory, and ‘like any indispensible servant, it is frequently the master’” (S. B. Duncan, as cited in Rose, 2006, p. 191)

The ability to provide effective and efficient logistics support for deployed military systems is a critical part of successful program management. At least two important questions must be addressed to meet this acquisition goal:

1) What types of resources will be used to provide what logistics support? i.e., What is the logistic support resource strategy?

2) Given the logistics support resource strategy selected, how can logistics operations be managed to maximize effectiveness and efficiency?

The Department of Defense has addressed logistics operations (the second question) at length. Logistics support operations can be assessed by both their effectiveness in meeting requirements and their efficiency of use of funds. Performance of logistics support operations in meeting requirements is measured with metrics such as the average response time and other metrics developed through Performance-based Logistics (PBL). These metrics are used to assess the effectiveness of logistics operations. Costs—including monies paid to contracted logistics support providers, government expenses incurred to contract and manage those providers, and funds for organic logistics support—are used with performance measures to assess the efficiency of the use of funds (Defense Acquisition University (DAU), 2005).

In contrast, logistics support resource strategy design (the first question) has received much less attention beyond the preference for the cheapest alternative. As used here, a logistics support resource strategy describes the sources (contracted, organic, or blended) of support provided to meet different logistics support requirements. However, a DoD program’s logistics support resource strategy is important because it profoundly impacts total program performance. Figure 1 describes the relative costs in a product’s lifecycle. As shown, operations and logistics costs are large when compared to Research and Development, Investment, and Disposal costs. Therefore, the effective and efficient design of a program’s logistics support resource strategy is critical to overall program success.

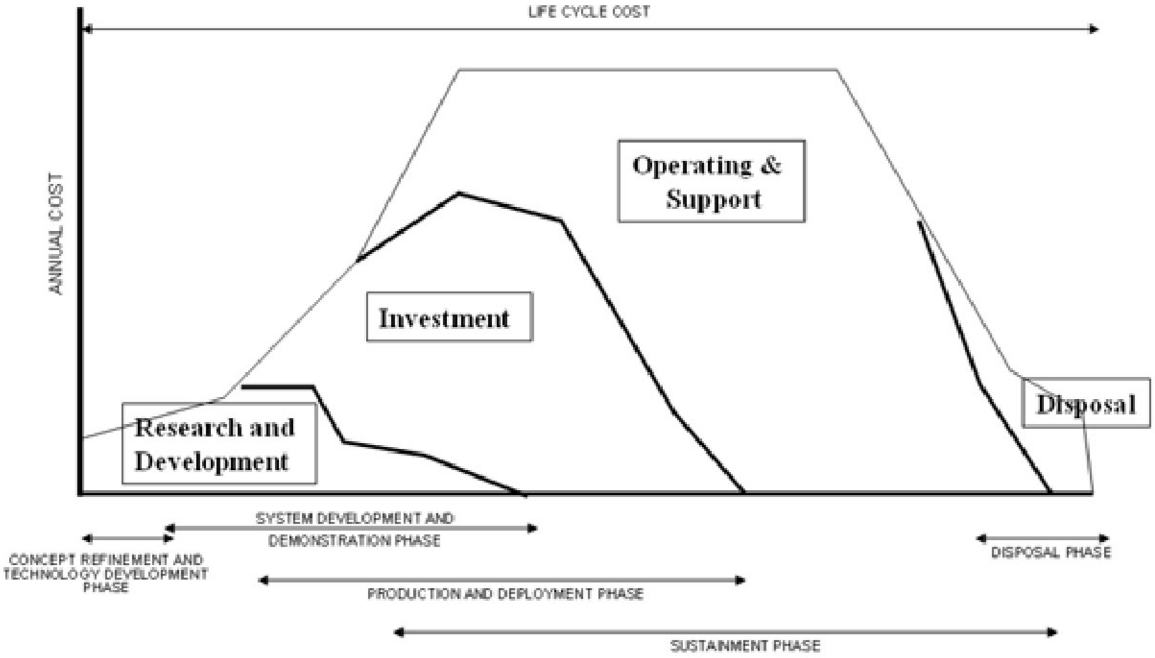


Figure 1. Relative Costs during a Product Lifecycle
(DAU, 2004, November, p. 43)

Most naval logistics support is provided by two types of resources: commercial organizations that contract with the government to provide material, equipment and services (a.k.a., Contractor Logistics Support, CLS) and internal military resources that provide the same material, equipment, and services. These are referred to as “contracted” and “organic” forms of logistics support, respectively. Three logistics support resourcing strategies are commonly considered: 1) contracting for all logistics support, 2) providing all logistics support with organic resources, and 3) providing some support through contracts and the remainder of support from organic resources, referred to as a “blended” strategy.

The three strategies are very different from one another in their characteristics, challenges for the government, and risks. The decision to provide support entirely with contracted resources (CLS) is an outsourcing strategy that often requires significant government contracting effort; it also requires contract management expertise and experience on both the government and contractor sides of the agreement. Contracted logistics introduce challenges to the government that include reduced control of resources and increased sensitivity to the goals of private enterprises. In contrast, by providing all logistics support with organic resources, program managers apply a “make” (versus “buy”) approach to providing logistics. Organic logistics support (OLS) presents challenges of developing and retaining adequate expertise, building the infrastructure of diagnostics, spares, maintenance facilities, etc.; such support also can increase resource allocation risks. Different again is a blended strategy, which can be a disaggregation of meeting the same support requirements between contracted and organic resources, an interdependent allocation of different types of support among different resources, or a combination of the two. Blended logistics resource support strategies bring with them the challenges of comparison between contracted and organic performance and operational interface management. These differences make forecasting the impacts of specific logistics support resource strategies and logistics support performance and cost very difficult. This inability to forecast, in turn, makes logistics support resource strategy design difficult.

Problem Description

The logistical features and characteristics of programs and their environments vary widely. Some impacts on resource strategy design (i.e., the use of CLS, blended, and OLS) can be described and assessed in monetary terms, such as differences in labor costs between contracted and organic personnel. Other aspects may have significant impacts but are intangible, such as reductions in commitment or morale of contracted suppliers due to many large rapid changes in government needs or the introduction of a more lucrative opportunity for using their resources. Many potentially important aspects lie between these two extremes.

Logistics support resource strategies also vary widely. This diversity is partially due to differing abilities of resources to fulfill different logistics requirements. For example, the contractor that develops a critical technology for a new weapons system may be the only organization capable of providing its logistics support. If logistics support is viewed as a single, monolithic set of requirements, then a resource strategy can be described by specifying the resources that fulfill sets of requirements. But different logistics support requirements can often be better met by different support resources. Therefore, total logistics support is often disaggregated into sets of requirements—each potentially with a different logistics support resource strategy or design.

The disaggregation of logistics support can be based on technical knowledge, workforce characteristics, and legal and ownership issues. Contractors may own specific product knowledge, software, facilities, or technical data that are required to provide logistics support, or may have access to necessary or preferred business relationships (e.g., supply chains of critical components). Legal (often proprietary) constraints or extraordinarily high prices for access may require some logistics support requirements to be clustered for supply by specific firms. Clustering based on this third criterion is typically contractor-specific. Therefore, good logistics support resource strategy design includes an analysis of how clustering support requirements for resourcing can impact the attractiveness of specific strategies.

Due to the uniqueness of programs, environments, and strategies, no one logistics support resource strategy is always best for all programs. Each strategy has a different set of features and characteristics that provide different advantages and disadvantages relative to other strategies. Those advantages and disadvantages generate benefits and costs. For example, the contracted logistics support organization may have developed a piece of equipment that is unique to the system being supported and, therefore, would have an intimate knowledge of its design and manufacturing. This provides special expertise in system maintenance and repair that is not available organically. That expertise may reduce repair times, costs, or both. Likewise, organic resources may be fully dedicated to the program and available with zero notice. This allows the organic resources to respond faster to unexpected increases in demands for logistics support, which could reduce response times experienced by warfighters. An example of this type of advantage of organic support is found in Coryell's (2004) case study of logistics support for the Army's Stryker program, in which a change in logistics support resource strategy was driven by the flexibility provided by organic resources. Anecdotal evidence suggests that contracted, blended, and organic strategies each provide a broad and diverse spectrum of advantages and disadvantages. However, selecting the best logistics support resource strategy for a specific program is difficult because of the need to identify the important features and characteristics of the program, its environment, and potential strategies and to assess their impacts on logistics support resource strategy selection. ***Given this multitude of potential drivers of and influences on logistics support, how can acquisition program managers select the best logistics support resource strategy for a specific program?***

DoD Policies Regarding Logistics Support Resource Strategy

Basic DoD logistics policy, as described in the *Acquisition Logistics Guide* (Defense Systems Management College, 1997) suggests six comparison criteria when performing tradeoff studies among alternative system designs and logistics support strategies (pp. 8-10):

- Lifecycle cost comparisons,
- Diagnostic characteristics (e.g., Built-in-Test (BIT)),
- Energy characteristics,
- Battle damage repair characteristics,
- Transportability characteristics, and
- Facilities requirements.

As this list indicates, cost and measurable logistic performance metrics have predominated logistics support resource strategy selection policy. The *Guide* (pp. 8-11) also suggests nine supportability issues for use in logistics strategy design:

- Operations and maintenance personnel and staff-hour constraints,
- Personnel skill-level constraints,
- Lifecycle and Operations and Support (O&S) cost constraints,
- Target percentages of system failures correctable at each maintenance level,
- Mean down time in the operational environment,
- Turn-around time in the operational environment,
- Standardization and interoperability requirements,
- Built-in fault-isolation capability, and
- Transportability requirements (identification of conveyances on which the system and its components are transportable).

Only two of the nine (personnel skill-level constraints and operations and maintenance personnel and staff-hour constraints) reach beyond cost and logistic operations metrics. Acquisition procedures as specified in *DoD 5000.2-R* also emphasizes cost in assessing logistics strategies, saying “Life-cycle costs [...] shall play a key role in the overall [logistics support concept] selection process” (DoD, p. 90).

While cost and logistic operations performance should and will remain a centerpiece of logistics support analysis, more recent DoD policy has shifted to increase the importance of other criteria in logistics support resource strategy design. The Acting Under Secretary of Defense (USD) (AT&L) has promulgated the Performance-based Logistics (PBL) approach (2004, January 23). Later that same year, the USD (AT&L) established the following high-level performance metrics for Performance-based Logistics (2004, August 16):

- Operational Availability,
- Operational Reliability,
- Cost per Unit Usage,
- Logistics Footprint, and
- Logistics Response Time.

Only one of these high-level performance metrics (Cost per Unit Usage) is cost based. The other four metrics address readiness (availability, reliability, and response time) and impacts of logistics (footprint). This ratio clearly shows the importance of integrating non-cost logistics support issues into logistics support design, including resource strategy.

The Performance-based Logistics guidelines (DAU, 2005) also leave no doubt about the importance of non-cost factors in selecting a logistics support resource strategy. The Business Case Analysis requires:

> Consideration of performance and cost risk will explicitly consider contract versus organic risk management, financial accountability, and recovery actions. The risk assessment should address the probability and confidence level of the following events: poor performance, cost growth, extended labor disputes, and changeover in PSI / PSP. (p. 3-30)

The guidelines explicitly describe the resource strategy addressed in the current work as an important logistics support design decision (Figure 2).

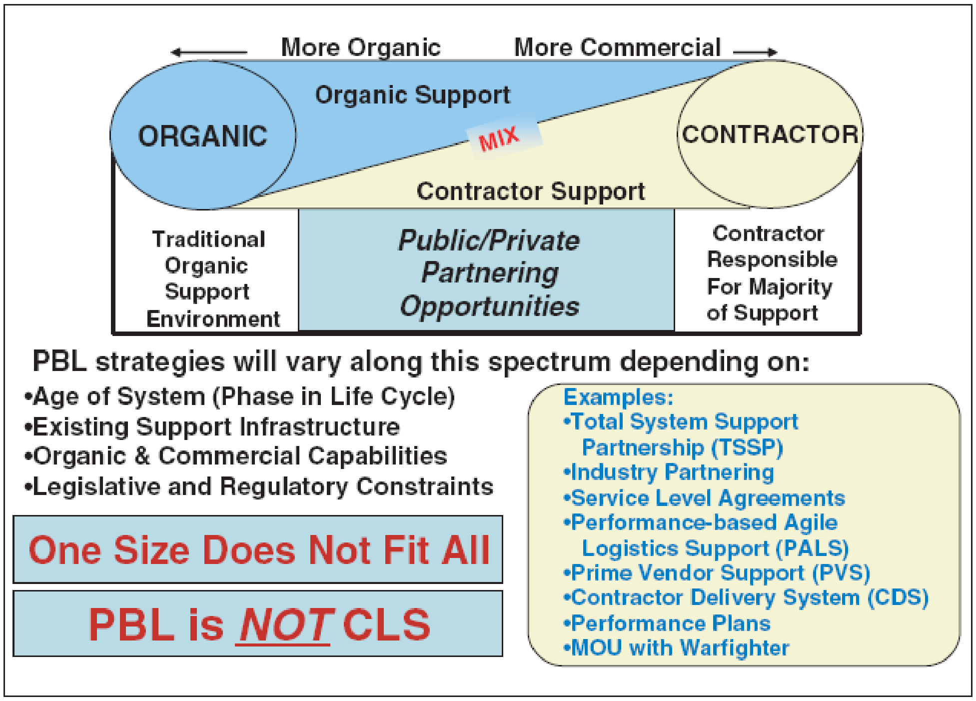
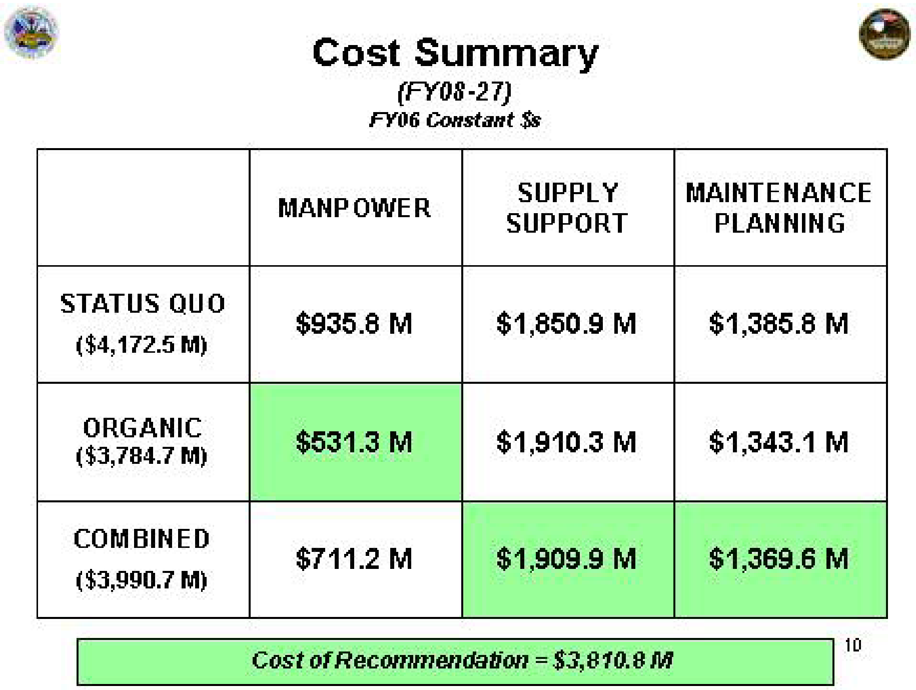


Figure 2. An Illustration of the Role of Logistics Resource Strategy in Performance-based Logistics
(DAU, 2005, p. 2-3)

Coryell's (2004) case study of logistic support in the Army's Stryker program demonstrates the role of non-cost factors in logistic support resource strategy design in implementing the PBL policy. A cost analysis was performed, suggesting the use of purely organic support (Figure 3). However, a different, non-cost issue drove the logistic support resource strategy design. Specifically, the design shifted from a primarily contracted strategy to a more blended strategy based on the differences in the flexibility of logistic support that could be provided by organic and contracted resources.



Cost Summary

(FY08-27)

FY06 Constant $s

	MANPOWER	SUPPLY SUPPORT	MAINTENANCE PLANNING
STATUS QUO ($4,172.5 M)	$935.8 M	$1,850.9 M	$1,385.8 M
ORGANIC ($3,784.7 M)	$531.3 M	$1,910.3 M	$1,343.1 M
COMBINED ($3,990.7 M)	$711.2 M	$1,909.9 M	$1,369.6 M

Cost of Recommendation = $3,810.8 M

10

Figure 3. Cost Analysis Results of Stryker Logistic Support Resource Strategies

(Coryell, 2004, p. 63, Figure 15)

Logistics Support Strategy Improvement Efforts

Several evaluations of DoD logistics support resource strategies have identified areas for improvement. The US Government Accountability Office (GAO) found little data had been collected that could verify the cost effectiveness of logistics strategies (2002). The same report expressed concern over several aspects of logistics support, including:

- Ability to develop and maintain critical technical skills and knowledge,
- Deployment of contractors to the battlefield and how protecting and supporting these contractors may affect their troops' ability to accomplish their missions,
- Ability to shift funds in response to changing conditions, and
- Availability of affordable technical data to develop additional or new sources of repair and maintenance to ensure a competitive market.

Performance-based Logistics (PBL) is a major DoD effort to improve logistics support, including resource strategies. PBL explicitly addresses the resourcing issue.

The Business Case Analysis (BCA) portion of PBL is particularly relevant to the current work. The PBL guide (DAU, 2005) describes the BCA as "an expanded cost/benefit analysis created with the intent of determining a best-value solution for product support" (p. 3-27). The analysis includes much more than traditional economic factors such as cost, including:

- Performance measures,
- Capitalization/asset ownership,
- Size of footprint,
- Reliability growth,
- Lifecycle costs,
- Diminished manufacturing sources management,
- Obsolescence/Obsolescence mitigation plan,
- Technology insertion,
- Risk management,
- Minimum and maximum essential logistics capabilities (peacetime to full mobilization requirement),
- Existing infrastructure,
- Common consumables support,
- Reliability and maintainability forecasts at the major system,
- Supply chain responsiveness, and
- Surge capabilities.

Notice here the shift from a focus on cost (“expanded cost/benefit analysis”) to indentifying the broader “best-value solution.” The factors to be considered include many that are difficult or impossible to measure in monetary terms (surge capabilities) or even quantify (e.g., technology insertion). The PBL BCA provides a useful enumeration of some of the non-cost factors that should be considered in logistics support resource strategy design. However, the guidelines provide little assistance about ***how*** to incorporate those factors into logistics support resource strategy design. The next section describes a tool for this purpose.

A Logistics Support Resource Strategy Map

As described, the features and characteristics of programs, their environments, and specific resource strategies vary widely, as do their impacts on logistics support. The qualitative nature of many important features and characteristics precludes the use of precise mathematical modeling for inclusion in logistics support resource strategy design. However, they can be structured in ways that facilitate objective assessment and inclusion in strategy design. Examples include the different types of flexibility that contracted, blended, and organic strategies provide programs. A useful tool for inclusive resource strategy design will identify and model both qualitative and quantitative features and characteristics and how they impact the attractiveness of different resourcing strategies. The incorporation of qualitative factors in strategy assessment can improve strategy selection by prompting decision-makers to use these factors in decision-making. It is important to note that ***the Logistics Support Resource Strategy Map does not replace critical thinking or analysis by the program management team, but can facilitate that thinking and analysis to improve logistics support resource strategy design.***

An Excel®-based Logistics Support Resource Strategy Map (Map) (Appendix B) has been developed to facilitate logistics support resource strategy design. The Map facilitates five aspects of designing a logistics support resources strategy for a specific set of requirements:

- Identifying and describing logistics support resource strategy <u>criteria</u> that are relevant for meeting specific logistics support requirements;

- Quantifying the relative <u>importance</u> of logistics support resource strategy criteria to meeting specific requirements or sets of requirements;

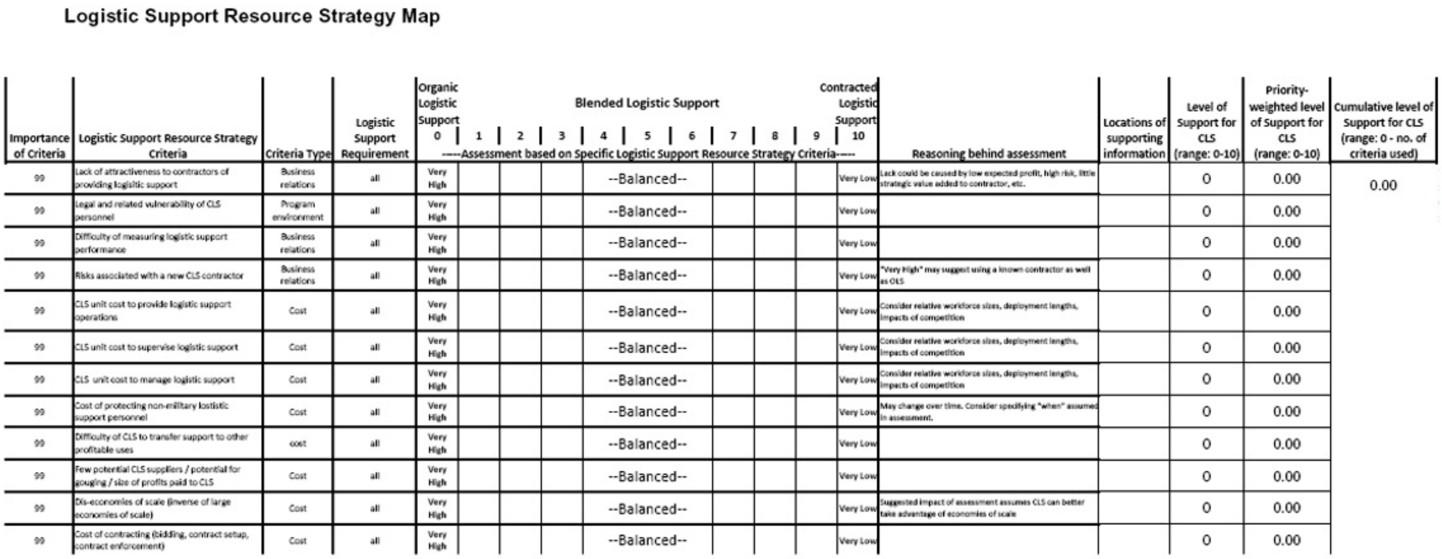
- <u>Qualitative assessment</u> of the degree to which the program and strategy (as they relate to the requirements) favor the use of organic resources, contracted resources, or a blend of organic and contracted resources;

- The <u>quantification of the support</u> for the use of contracted, blended, or organic resources to meet specific criteria and the aggregation of that support for sets of criteria for specific requirements; this can facilitate the grouping of requirements for logistics support acquisition.

- The <u>aggregation</u> of priority-weighted support across criteria for comparison of different program strategies; and

- <u>Documentation</u> and support of logistics support resource strategy decisions for use in program reviews.

The sorting function in Excel® allows the reorganization of the criteria considered to facilitate team discussion and strategy assessment. For example, criteria can be sorted by those that apply to a particular logistics support requirement, by the type of criteria, or in descending order from those most supported by contracted resourcing to those least supported by contracted resourcing (Figure 4).



Logistic Support Resource Strategy Map

Importance of Criteria	Logistic Support Resource Strategy Criteria	Criteria Type	Logistic Support Requirement	Organic Logistic Support	Blended Logistic Support									Contracted Logistic Support	Reasoning behind assessment	Locations of supporting information	Level of Support for CLS (range: 0-10)	Priority-weighted level of Support for CLS (range: 0-10)	Cumulative level of Support for CLS (range: 0 - no. of criteria used)
				0	1	2	3	4	5	6	7	8	9	10					
				-----Assessment based on Specific Logistic Support Resource Strategy Criteria-----															
99	Lack of attractiveness to contractors of providing logisitic support	Business relations	all	Very High				--Balanced--						Very Low	Lack could be caused by low expected profit, high risk, little strategic value added to contractor, etc.		0	0.00	0.00
99	Legal and related vulnerability of CLS personnel	Program environment	all	Very High				--Balanced--						Very Low			0	0.00	
99	Difficulty of measuring logistic support performance	Business relations	all	Very High				--Balanced--						Very Low			0	0.00	
99	Risks associated with a new CLS contractor	Business relations	all	Very High				--Balanced--						Very Low	"Very High" may suggest using a known contractor as well as OLS		0	0.00	
99	CLS unit cost to provide logistic support operations	Cost	all	Very High				--Balanced--						Very Low	Consider relative workforce sizes, deployment lengths, impacts of competition		0	0.00	
99	CLS unit cost to supervise logistic support	Cost	all	Very High				--Balanced--						Very Low	Consider relative workforce sizes, deployment lengths, impacts of competition		0	0.00	
99	CLS unit cost to manage logistic support	Cost	all	Very High				--Balanced--						Very Low	Consider relative workforce sizes, deployment lengths, impacts of competition		0	0.00	
99	Cost of protecting non-military lostistic support personnel	Cost	all	Very High				--Balanced--						Very Low	May change over time. Consider specifying "when" assumed in assessment.		0	0.00	
99	Difficulty of CLS to transfer support to other profitable uses	cost	all	Very High				--Balanced--						Very Low			0	0.00	
99	Few potential CLS suppliers / potential for gouging / size of profits paid to CLS	Cost	all	Very High				--Balanced--						Very Low			0	0.00	
99	Dis-economies of scale (inverse of large economies of scale)	Cost	all	Very High				--Balanced--						Very Low	Suggested impact of assessment assumes CLS can better take advantage of economies of scale		0	0.00	
99	Cost of contracting (bidding, contract setup, contract enforcement)	Cost	all	Very High				--Balanced--						Very Low			0	0.00	

Figure 4. Partial Screenshot of *Logistics Support Resource Strategy Map*

In addition, the Map facilitates the documentation of the strategy modeling. Each row in a Logistics Support Resource Strategy Map represents a specific criterion that may be used to assess a resource strategy to meet one or more support requirements. Each column of the Map describes a characteristic of the criteria, as follows:

- Importance of Criterion,
- Logistic Support Resource Strategy Criterion,
- Criterion Type,
- Logistic Support Requirement,
- Degree of Program & Strategy Support,
- Reasoning behind Assessment,
- Locations of Supporting Information,
- Degree of Support for Contracted Logistics Support,
- Priority-weighted Degree of Support for Contracted Logistic Support, and
- Cumulative Degree of Support for Contracted Logistics Support.

Components of a Logistics Support Resource Strategy Map

Importance of Criterion (Column B in the spreadsheet): This value is the quantified assessment of the relative importance of specific criteria in meeting the requirement named in Column E in the spreadsheet. Consistent with ranking criteria from the most to least important, smaller values indicate more important criteria. Duplicate use of the same importance value and fractional values are accommodated, but values less than one are to be avoided (see “Priority-weighted Degree of Support for CLS” below). All criteria are initially assessed to have essentially no importance (value = 99). This forces the program team to identify and select criteria to be used in assessment by assigning them a smaller importance value. Criteria that are not selected (i.e., value remains 99) are ignored in the quantitative assessments.

Logistics Support Resource Strategy Criterion (Column C in the spreadsheet): In this Map, 51 potential criteria are provided in 8 categories. These suggested criteria were developed based on a review of civilian and military logistics support literature. For example, Fine and Whitney (1996) group the reasons to make (organic support) or buy (contracted support) into issues of capacity and knowledge. They go on to discuss the roles of several factors in the make-buy (organic versus contracted) decision for product support—including the ability of a buyer to provide the support needed (more supports organic), relative costs, the quality of system performance, the criticality of the product to organizational success (more supports organic), the availability of qualified suppliers, product complexity, skill of suppliers, competitive advantages of suppliers, profit for suppliers. Parmigiani (2007) investigates the impact of product specificity (which would increase with product maturity) on firms’ tendency to outsource; her findings suggest increased maturity increases blended support over outsourcing and increases organic support over blended strategies. Military research also provided the basis for potential criteria. For example, Wild (2006) discusses the roles of direct (logistic operations) costs, indirect (logistic supervision and management) costs, transaction (contracting) costs, control (e.g., responsiveness), economies of scale (e.g., fleet size), internal capabilities, profits and competitive advantages (e.g., bargaining power), coordination of the value chain, and information and property rights in outsourcing by the DoD. Several of the criteria suggested by the literature were investigated by others in more depth to assess their applicability to DoD acquisition. For example, Coryell (2004) performs a case study of the shift from predominantly CLS to a more blended logistics support strategy in the Army’s Stryker program. He concludes (p. 61) that the primary reason for the change was not cost, but the need for more flexibility in combat operations.

In the Logistic Support Resource Strategy Map, all criteria are worded so that the more the criterion is met or is true, the stronger support is provided for an organic logistics support resource strategy. Criteria descriptions can be changed and customized to fit program needs; five spaces for new criteria are also provided. For example, one criterion that reflects logistics support costs is “CLS unit cost to provide logistics support operations.” A very high value for this criterion (i.e., CLS costs are very high) supports the use of organic logistics support resources. The opposite is also true. The less the criterion is met (i.e., CLS costs are low), the more the criterion supports the use of contracted logistics support resources.

Criterion Type (Column D in the spreadsheet): Criteria are categorized as being one of eight types:

- Business relations,
- Cost,
- Funding,
- Information and technology,
- Labor resources,
- Logistics operations performance,
- Product characteristics,
- Program characteristics, and
- Program environments.

All criteria of a given type can be grouped to facilitate discussion and assessment by sorting.

Logistics Support Requirement (Column E in the spreadsheet): This cell for each criterion can be used to specify which logistics support requirements are being addressed with the strategy being assessed. This may be useful when a logistics support resource strategy is being assessed that has different requirements that may be addressed with different criteria. Requirement descriptions can be changed as needed to reflect program and strategy characteristics.

Degree of Program and Strategy Support (Columns F through P in the spreadsheet): The Map provides 11 possible degrees of program and strategy support for the use of organic support to meet requirements from "Very high," which supports the use of organic resources, to "Very low," which supports the use of contracted resources. All criteria are worded so that the more or better organic logistics support fills the criteria, the higher the assessment that is given (see "**Logistics Support Resource Strategy Criterion"** above). Therefore, an assessment of "Very High" indicates that using only organic resource strategy can meet the criterion very well; an assessment of "Very Low" indicates that using only contracted resource strategy can meet the criterion very well; and assessments between these extremes indicate the ability of various amounts of blended strategy to meet the criterion best. The degree of support that the strategy provides for filling the criteria with organic resources is indicated by inserting an "X" in the cell that represents the level of support.

Reasoning behind the Assessment (Column Q in the spreadsheet): Space is provided to document the basis for the assessed degree of support provided by the strategy to meet the criteria.

Locations of Supporting Information (Column R in the spreadsheet): Space is provided to document the location of information that supports the assessed degree of support provided by the strategy to meet the criteria with organic resources.

Degree of Support for CLS (Column S in the spreadsheet): The Map quantifies the assessed degree of support provided by the program and strategy to meet the criteria with organic, blended, or contracted resources into integer values from 0 to 10; these reflect the degree of support for contracted resources, with 0 reflecting little support for contracted resources (i.e., strong support for organic resources) and 10 representing strong support for contracted resources. The juxtaposition from increasing qualitative assessment supporting organic resources to increasing quantified support supporting contracted resources (i.e., “Very High” support for organic is assigned the lowest numerical value and vice versa) is purposeful and intended to assist the assessment team in adopting multiple perspectives for improved assessment and logistics support resource strategy planning.

Priority-weighted Degree of Support for CLS (Column T in the spreadsheet): The Map integrates the assessed importance of the criteria and degree of support into a priority-weighted degree of support for the use of contracted resources. Values range from 0 to 10 if the recommendations for assessing each criterion’s importance described above are used,[1] with large values reflecting important criteria that strongly support the use of contracted resources and vice versa (less importance, less support for CLS, or both). These values are generated by dividing the degree of support (range = {0,10}) by the importance of the criteria (range = {1,98}). As an example, if a strategy of contracting all logistics support to a new contractor was being assessed, if the criterion “Risks associated with a new CLS contractor” were considered the most important criterion (Importance of Criteria = 1), and the risks were considered to be very low (“X” in “Very Low” cell, column P), then the Priority-weighted Degree of Support for CLS would be 10 (= 10/1). In contrast, if the assessments for the same criterion for the same strategy were that the criterion was ranked third among criteria (Importance of Criterion = 3), and the risk was assessed to be between that for a balanced blended strategy and a contracted strategy (e.g., 8, “X” in column N) then the Priority-weighted Degree of Support for CLS would be 2.67 (=8/3). Note that the Priority-weighted Degree of Support for CLS directly (linearly) reflects the assessments of criteria importance and the strategies support of organic, blended, or contracted support. Values, or differences in values, are directly proportional to those assessments. For example, the change from a value of 10 to a value of 2.67 in the example above is the product of the reduction in the importance (8/10) and the support degree (1/3). *Users of the Map should not read more meaning or validity into these values than their underlying structure suggest.*

Cumulative Degree of Support for CLS (Column U in the spreadsheet): The Map aggregates the Priority-weighted degrees of Support for CLS into a single quantitative value that represents the strategy’s overall support for CLS. This single value can be useful in comparing different logistics support resource strategies. This value is the sum of the Priority-weighted degrees of support for CLS for all criteria used for strategy assessment (importance < 99) divided by 10.[2] Possible values range from zero to the number of

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[1] Assessments of criteria importance less than one generate Priority-weighted Degree of Support for CLS values that do not accurately reflect the relative positions of criteria due to division by very small values.

[2] The sum is divided by ten solely to keep maximum value equal to the number of criteria used for assessment.

significant criteria. Note that, ceteris paribus (all else equal), a strategy that uses more criteria will have a larger Cumulative Degree of Support for CLS. Therefore, care must be taken in comparing strategies using the Cumulative Degree of Support for CLS to be sure that the strategy assessments use the same number of criteria.

Application Process for the Logistics Support Resource Strategy Map. The following steps can be used to describe and assess a set of logistics support requirements for resource strategy planning.

Phase I: Create Criterion/Requirements Sets for Assessment

1. **Develop a rich description of the logistics support resource strategy to be assessed.**

2. **Identify the logistics support requirements or sets of requirements to be supported by a single resource strategy**. Group requirements into sets that must be or are planned to be supported with the same logistics support resource strategy.

3. **Identify the rows that describe criteria to be used for assessment for each requirement set.** Use the criteria types and specific criteria suggested in the Map in columns C and D as a basis for discussing and indentifying criteria to be used to assess the resource strategy for each requirements set. Enter requirement set names or identifiers in the "Logistics Support Requirement(s)" column (E) of the rows of criteria to be used to assess each requirement set. Copy and insert entire rows of criteria needed for multiple requirement sets. Specify and add assessment criteria if required by altering criteria or entering additional criteria not listed into a row with a column C with the label "blank." To retain the Map’s ability to consistently quantify the characterization of a program and strategy on the criteria, describe the criteria so that more of the criteria supports the use of Organic Logistics Support.

Phase II: Assess Criterion/Requirement Set Needs in Logistics Support Resources

4. **Assess and quantify the importance of each criterion.** Sort the rows of assessments (“Assessments” range) by Logistics Support Requirement (Column E) to gather the criteria being used to assess the resource strategy for different requirement sets. For each criterion/requirement set (i.e., each row), enter a number in the "Importance of Criterion" column (B) that reflects the relative importance of the criterion relative to the other criteria for that requirement set. Although almost all values are allowed,[3] it is suggested to restrict values to the range of 1 to 10—with 1 representing the most important criteria, and 10 representing the least important criteria. The Map can use multiple uses of the same importance value for different criteria and fractional importance values as well as unique integer values, but values less than one are to be avoided (see “Priority-weighted Degree of Support for CLS”).

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[3] The default value of 99 reflects criteria that are not used. Therefore, users must purposefully identify all criteria to be used by changing their importance value.

5. **Qualitatively assess the support provided by different resource strategies.** For each criterion/requirements set (i.e., each row), evaluate how well organic, blended, or contracted logistics support is expected to meet the criterion for the specified requirements set. State the assessment in terms of the ability of organic support to meet the criterion by answering the question, “Based on this criterion, how well do the program and proposed logistic support resource strategy support the use of organic logistics support?” with answers from “Very High” (which strongly supports the use of an organic strategy), “Balanced” (which suggests that there are both advantages and disadvantages to both organic and contracted support), or “Very Low,” (which strongly suggests that a contracted resource strategy can meet the criteria much better than an organic strategy). For example, if the contracted developer of a product to be supported owns critical product information, the assessment for the criterion “Availability/affordability of technical data to the DoD” would be “Low” or “Very Low,” supporting the use of contracted resources (the developer in this case). Assess each criterion in isolation, as if it were the only criterion impacting the logistics support resource strategy design.

6. **Quantify support assessments.** For each criterion/requirements set (i.e., each row), quantify assessments by entering the letter "X" in the appropriate box in Columns F through P. Assessments to the left (closer to “Very High”) indicate that an organic strategy outperforms a blended or contracted resource strategy for the specified criterion and requirements set. Use the letter “X” and only a single assessment for each criterion/requirement set if numerical estimates of support are desired. Upper and lower case “X”s are equivalent. Typing over existing text does not cause problems.

7. **Document assessments.** For each criterion/requirements set (i.e., each row), add notes in the “Reasoning behind assessment” cell that explain the basis for the assessment. Likewise, enter references to data, reports, etc., in the “Locations of supporting information” cell as pointers to support for the assessment.

Phase III: Review, Discuss, and Revise Assessments from Different Perspectives

8. **Review the most important criteria***.* Sort criterion/requirement sets by “Importance of Criterion” in ascending order (select "Assessments" range, then Data/Sort/Column B, Smallest to Largest, no headers) to view the criteria assessed to be most important in logistics support resource strategy design. Review, discuss, and revise as required to reflect criteria importance. For example, criteria reflecting legal constraints that must be met should be assigned a small value (e.g., one).

9. **Review criteria that suggest support for Organic or Contracted Logistics Support** ***.*** Sort criterion/requirement sets by "Degree of Support for CLS (0-10 scale)" in ascending order (select "Assessments" range, then Data/Sort/Column S, Smallest to Largest, no headers) to view the criterion/requirement sets that are most strongly supported by organic

logistics support.[4] Review, discuss, and revise as required. Sort criterion/requirement sets by "Degree of Support for CLS (0-10 scale)" in descending order (select "Assessments" range, then Data/Sort/Column S, Largest to Smallest, no headers) to view the criterion/requirement sets that are most strongly supported by contracted logistics support. Review, discuss, and revise as required.

10. ***Review drivers of a contracted resource strategy.*** Sort criterion/requirement sets by "Priority-weighted degree of Support for CLS " in ascending order (select "Assessments" range, then Data/Sort/Column T, Smallest to Largest, no headers) to view the criterion/requirement sets that are both important and that strongly support a contracted resource strategy.

The Logistics Support Resource Strategy Map is designed primarily for qualitative assessment and the identification of shared and differing impacts of a resource strategy on logistics support. Assessments are based on the perceptions and judgments of program team members about the program, logistics support resource strategy issues and their impacts. Those impacts can suggest information to develop that will improve resource strategy design, groupings of support requirements for effective and efficient acquisition, possible or beneficial evolutionary paths of support that indicate changes in government management needs, or alternative logistic support resource strategies. However, the Map also uses those assessments to calculate degrees of support for Contracted Logistics Support (and, by inference, lack of support for OLS) that can support strategy design choices.

Example Application of the Logistics Support Resource Strategy Map

The use of the Logistics Support Resource Strategy Map will be illustrated with an application to the Predator A Unmanned Aerial Vehicle. See the attached tool as applied to the Predator A case and the following description of the application of the procedure above.

Phase I: Create Criterion/Requirements Sets for Assessment

Drew et al. (2005) provide a rich description of the Predator A program as it relates to logistics support (Step 1 in the Process for the Logistics Support Resource Strategy Map above). A brief summary is included in Appendix A. As described by Drew et al. (2005, p. 74),

> The Predator system consists of three elements—the air vehicle, the Ground Control Station (GCS), and the ground-based mission command and control station (CS). The GCS, which helps land and takeoff the air vehicle, is where the mission pilot is housed. The ground-based mission command and control station oversees the mission plan and its implementation, makes command decisions when needed, collects and disseminates the mission data, and interacts with higher Air Force echelons.

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[4] Hiding rows with values of zero may facilitate viewing and review.

For simplicity and economy, the Logistics Support Resource Strategy Map was applied to the vehicle portion of the Predator system. Note that this choice by the authors implies two potentially important decisions in logistics support resource strategy design: 1) a disaggregation of the logistics support of the system into at least two parts, vehicle support and other support,[5] and 2) the provision of all vehicle support with a single resource strategy (all organic, blended, or all contracted). These choices effectively perform Step 2 in the Process for the Logistics Support Resource Strategy Map above. Therefore, the description of the Logistics Requirements for the example as being for "all," refers only to the Predator A vehicle.

Figure 5. Predator A
(Drew et al., 2005)

Predator A Vehicle Logistics Support Resource Drivers

The Predator A program has a rich history. The portions that most strongly impacted the logistics support resourcing strategy for the vehicle are described here as the basis for illustrating the use of the Logistics Support Resource Strategy Map. See Appendix A of this study and Drew et al. (2005) for a more detailed description and analysis. The acquisition history of Predator A strongly influenced its logistics support resource strategy. Predator A was developed to fill a specific operational need for continuous Intelligence, Surveillance, and Reconnaissance ISR that was not being met. The program had strong support from multiple services, was in a rapid acquisition process (primarily bypassing the advanced development phase), and used accelerated production schedules to get units to the warfighters faster. The accelerated acquisition probably succeeded in delivering the product faster and reduced some oversight compared with traditional acquisition processes. However, it also imprinted the program with characteristics that impacted logistics support. Deployment occurred very quickly after successful testing. At that time, the developer was the only stakeholder knowledgeable enough about the vehicle to provide logistics support. No organic personnel existed with the requisite knowledge and skill sets to provide logistics support. In addition, the developer had paid for most of the development and, therefore, had

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[5] This choice at this point in the logistic support resource strategy design does not preclude adopting the same resource strategy for combinations of the vehicle, GCS, and CS.

a large influence on the amounts and types of information gathered about the vehicle and owned most of the available data on vehicle performance.

Program characteristics also impacted logistics in the Predator A case. Concept of Operations (CONOPS) requirements and mission needs were dynamic during and after first deployment. The developer was generally successful in responding to these changes. But in doing so, the developer became the sole holder of critical product knowledge. In addition, a $5 million-per-vehicle cost limitation required extensive vehicle knowledge to make the retrofits and improvements for the increased capabilities common in high-technology, fast-development products. These could only be performed by the developer.

DoD organizational issues also impacted Predator A logistics support resource strategy design. No Air Force specialty code exists that covers most of the Predator A's needs, limiting the availability of organic logistics support personnel. Training was conducted at Indian Springs Air Force Station in Nevada at a remote location considered unattractive by some military personnel. Training took two years, leaving only one year of productive work in a traditional three-year rotation.

Based on the available information on the program and its logistics, and using Step 3 above, the researchers considered 12 of the suggested possible criteria important in resource strategy design.

- Quantity of OLS logistics support operations labor pool relative to CLS,
- Quality of OLS logistics support operations labor pool relative to CLS,
- OLS ability to provide required skills relative to CLS,
- OLS availability of cross-trained personnel,
- Availability/affordability of reliability and/or maintainability data to the DoD,
- Minimum fleet size & replacement rate required to maintain continuous logistics support,
- Vulnerability of CLS personnel to battlefield threats,
- CLS unit cost to provide logistics support operations,
- OLS speed of deployment relative to CLS,
- Risk of labor disputes,
- Product immaturity (inverse of product maturity), and
- Classification of program and its logistics support as a core competence or mission of the DoD.

However, two important characteristics of the program that impacted logistics were not captured in the 12 criteria. The first was the impact of the $5 million-per-vehicle cap on required knowledge for retrofits and improvements. The second was the flexibility of the developer (but not organic resources) to react quickly to changing CONOPs and missions. Therefore, (in accordance with Step 3 above) two additional criteria were added:

- Ability of OLS vs. CLS to do upgrades within $5 million total-unit-cost cap, and
- Ability of OLS vs. CLS to react quickly to changing CONOPs and missions.

Phase II: Assess Criterion/Requirement Set Needs in Logistics Support Resources

The researchers assessed the importance of each of the resulting 14 criteria for designing the logistics support based on their understanding of the program (Step 4). For simplicity, we decided to use ordinal (integer) values to reflect the relative importance of criteria. Three criteria were considered most important and assigned the value one:

- Quantity of OLS logistics support operations labor pool relative to CLS,
- Quality of OLS logistics support operations labor pool relative to CLS, and
- Product immaturity (inverse of product maturity).

The first two criteria reflect the differences in the knowledge and specialized skills between the developer and the currently available organic logistics support work forces. Drew et al. (2005, p. 46) describe this difference as follows: “The contractor work force comprises mostly skilled mechanics with exceptional knowledge of the air vehicle. By contrast, the Air Force does not hire highly skilled mechanics; it ‘raises’ them,” which is typical of organic support resources. The third criterion reflects the dynamic nature of the product and its requirements. The supporting information about the assessments of these criteria is captured in the “Reasoning behind assessment” cell for each criterion. Interestingly, this criterion and the two that were added are different criteria types—with product immaturity describing a product characteristic and reaction times measuring labor resources. This difference can facilitate identifying different logistics-support and risk-mitigation strategies.

Three of the criteria were assessed to be important but not as important as those above; they are assigned a value of two, followed by supporting notes from their “Reasoning behind assessment” cells:

- Ability of OLS vs. CLS to react quickly to changing CONOPs and missions—NEW CRITERIA ADDED.
- OLS’ ability to provide required skills relative to CLS—No trained OLS staff.
- Program and its logistics support are classified as a core competency or mission of the DoD—Fills critical ISR need. Expanded to strike capability. Strong command support for the program.

Two of the criteria were assessed to be next in importance and assigned a value of three, followed by supporting notes from their “Reasoning behind assessment” cells:

- Ability of OLS vs. CLS to do upgrades within $5 million total-unit-cost cap—Cap hinders retrofits (even to improve capabilities). Requires intimate vehicle knowledge to constrain retrofit cost.
- Availability/affordability of reliability and/or maintainability data to the DoD—Developer paid for most of development. Not developed/available.

Similarly, the remaining criteria were assessed the following importance values, followed by supporting notes:

- Minimum fleet size & replacement rate required to maintain continuous logistics support—4. Current fleet of 100 supports CLS. Fleet expected to grow 12+ vehicles/yr.
- Vulnerability of CLS personnel to battlefield threats—5. Forward sites require logistics support for takeoff, etc.
- OLS speed of deployment relative to CLS—5. None.
- CLS unit cost to provide logistics support operations—6. Slight advantage to CLS, see Drew et al. study (2005)).
- Risk of labor disputes—7. No indication of a risk but could become one.
- OLS availability of cross-trained personnel—8. None.

Each of the 14 criterion were then assessed for the ability of organic support to fulfill the criteria (Step 5) from “Very High” (value=0) to “Very Low” (value=10). Those assessments were then quantified with the selection of a degree in the spreadsheet (Step 6). These assessments were facilitated by the deep reflection of logistics issues required to perform the previous five steps. The quantified assessments were:

- Quantity of OLS logistics support operations labor pool relative to CLS—10.
- Quality of OLS logistics support operations labor pool relative to CLS—10.
- OLS ability to provide required skills relative to CLS—10.
- Ability of OLS vs. CLS to react quickly to changing CONOPs and missions—10.
- OLS availability of cross-trained personnel—9.
- Availability/affordability of reliability and/or maintainability data to the DoD—8.
- Minimum fleet size & replacement rate required to maintain continuous logistics support—8.
- Vulnerability of CLS personnel to battlefield threats—8.

- Ability to OLS vs. CLS to do upgrades within $5 million total-unit-cost cap—8.
- CLS unit cost to provide logistics support operations—6.
- OLS speed of deployment relative to CLS—5.
- Risk of labor disputes—5.
- Product immaturity (inverse of product maturity)—1.
- Program and its logistics support are classified as a core competence or mission of the DoD—1.

The degree of support for each criterion was assessed in isolation, as if the other criteria did not influence the assessment. For example, high product immaturity alone suggests the use of organic support based partially on the reasoning that the many changes require a deep understanding of and sensitivity to requirements and users, which organic support is more likely to be able to provide. But this assessment might shift more toward support of contracted support if the difference in product knowledge of organic and contracted support resources is incorporated into the assessment of the product immaturity.

Phase III: Review, Discuss, and Revise Assessments from Different Perspectives

The researchers then reviewed the assessment using the Map. To review the criteria assessed to be most important (Step 7), we sorted the criteria in ascending order of “Importance of Criteria.” Our review of these criteria indicated that the quantity and quality of logistics support labor available are very important in the assessment, which is consistent with the hard requirement for very knowledgeable and specialized vehicle support. This review provided an opportunity to test the fidelity of the program as described in the Map, improve that fidelity, and build confidence in the Map’s usefulness.

We then reviewed the assessment based on the degree of support for the use of contracted logistics support (Step 8); we did this by sorting the criteria in descending order based on the “Degree of Support for CLS.” This review revealed that two of the three most important criteria and one of the criteria rated with an importance of two were assessed with the maximum degree of support for the use of contracted resources. This suggests that contracted logistics support may be the best strategy for the Predator A vehicle.

Finally, we reviewed the description of the drivers of a contracted strategy (Step 9) by sorting the criteria in descending order based on the “Priority-weighed degree of Support for CLS.” Comparing this review with the previous one revealed that the top four criteria do not change; this consistency suggests that relative influence of the criteria on a design does not alter the suggested design based solely on support for organic or contracted resources. The fifth criterion, if support for CLS is the basis (Vulnerability of CLS personnel to battlefield threats), moves four places lower when importance is included in the assessment—suggesting that although this criterion suggests the use of contracted resources, it should have significantly less influence than other criteria.

Tool Evaluation and Implications for Practice

The Map and its methodology for its use have several advantages as a tool for facilitating logistics support resource strategy design. These include:

- **Provide framework for assessment** by providing structure of criteria and assessment methodology;
- **Provide support for improved assessment criteria identification** due to the extensive list of possible criteria;
- **Provide support for improved assessment quality** due to increased specification of criteria, focusing of assessment on organic, blended, and contracted resources, and signaling (with differing assessments) where more in-depth investigation may be needed;
- **Provide flexibility for adaptation** to many different types of programs and products;
- **Provide high ease of use** due to basis in the widely used Excel® spreadsheet application;
- **Provide high ease of understanding** by users due to its transparency (no hidden or locked cells or complex equations); and
- **provides documentation** of both assessments and reasoning behind those assessments, which can be used to support logistics support resource strategy designs in program reviews.

The Map and the methodology for its use also have weaknesses, including:

- **Illusion of objectivity** based on its use of a computer format, although assessments remain based on the judgments of the program team;
- **Lack of internal checks and balances;** the Map and methodology have no way of identifying if criteria have been overlooked, ignored, or assessed incorrectly.

The use of the Map by program teams can significantly improve logistics support resource strategy design processes through the advantages identified above. The Map can also improve program reviews by providing structured and clear documentation of the evaluation process used to design logistics support resource strategies. This documentation will allow easier and faster review, improvement, and approval of DoD programs. Use of the Map may help program teams to better manage the major acquisition challenge of logistics support resource strategy design.

Conclusions

The current research extends previous research on the costs of logistics support resource strategies by modeling the impacts of programs, environments, and strategies on resourcing with organic, blended, or contracted resources. The structure of the Logistics Support Resource Strategy Map and methodology for its use are designed for ease of understanding and adaptation by users. The Map and methodology were initially tested by application to the vehicle portion of the Predator A unmanned aerial vehicle system. This test indicated that the Map and its methodology can significantly improve logistics support resource strategy design and can facilitate managing program reviews by documenting a program team's assessment of the relative importance of specific program, environment, and strategy features and characteristics as they relate to logistics support resource strategy design and by focusing team assessments on resource design. However, the test also revealed that the successful use of the Map and its methodology is dependent on the deep reflection and evaluation of program team members. Additional validation and verification of the Map is needed to increase the confidence for its use in practice. This can be done by applying the Map to other DoD programs and by improving the Map and its methodology based on those tests.

As discussed above, the Logistics Support Resource Strategy Map is founded on the assessments of the program team. Poor or inadequately supported observations and assessments will generate poor results (i.e., garbage in—garbage out). Sensitivity tests by subject-matter experts can be used to improve user understanding of the impacts of different importance and assessment values on results. The results of such analyses can improve the Map's usefulness.

The Logistics Support Resource Strategy Map may improve DoD acquisition by improving logistics support resource design. In combination with other acquisition tools and methods, the Map can significantly improve program performance and reduce costs. The continued development and use of this and other tools for managing the acquisition process will provide better materiel to warfighters faster for less cost.

Acknowledgements

The authors wish to acknowledge the leaders of the NPS Acquisition Research Program: James B. Greene, RADM, USN, (Ret) and Dr. Keith Snider, as well as the tireless efforts of Karey Shaffer, her assistant David Wood and editorial team, without whose support we could not have conducted this research into the challenges of developing logistic support resource strategies for Defense acquisition.

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Panel 7 - Testing Considerations for Reuse of Weapons System Components

Wednesday, May 13, 2009

1:45 p.m. – 3:15 p.m.

Panel 7 - Testing Considerations for Reuse of Weapons System Components

Chair: William M. Johnson, Principal, WMJ Associates LLC

Discussant: Mark Wessman, CAPT, US Navy (Ret.), President, Wessman Consultancy Group, Inc.

How to Check If It Is Safe Not To Retest a Component

Valdis Berzins and **Paul Dailey**, Naval Postgraduate School

Mathematical Modeling for Optimal System Testing under Fixed-cost Constraint

Karl Pfeiffer, Valery Kanevsky and **Thomas Housel**, Naval Postgraduate School

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Chair: Mr. William M. Johnson is an independent consultant and sole proprietor of WMJ Associates LLC advising government and industry on management and leadership matters involving the acquisition of complex systems. He is recently retired from 37 years of federal government service. Prior to retiring, he was Deputy for Future Combat Systems Open Architecture in the Program Executive Office for Integrated Warfare Systems. Throughout his career, he has developed and successfully pioneered innovative methods for providing the U.S. Navy's fleet with the best possible products in a timely and affordable manner. He has been widely acclaimed as a key leader in business process transformation and is a recipient of the Navy Distinguished Civilian Award, its highest civilian honor.

Mr. Johnson graduated from Cornell University where he received the Bachelor of Science in Electrical Engineering in 1970 and the Master of Engineering (Electrical) in 1975. In addition, he is a graduate of the Program Managers Course at the Defense Systems Management College, Ft. Belvoir, VA in 1989 and the Senior Officials in National Security Program at Harvard University, Cambridge, MA in 1994. He has maintained ties with academia and has been the subject of case studies at both Harvard and the Naval Postgraduate School.

After completion of undergraduate school, Mr. Johnson embarked on his career at the Georgia Institute of Technology Experiment Station, Atlanta, GA where he designed electronic circuitry used in testing of surface ship radar systems. Mr. Johnson subsequently volunteered for active duty in the U.S. Navy where he served three years as an officer in undersea surveillance. As a junior officer, he led efforts related to training and operational readiness that were twice recognized by the Commander Ocean Systems Pacific as the best under his command. After leaving the Navy and completing graduate school, he embarked on a career in engineering and program management with the Department of the Navy. Mr. Johnson is experienced in all aspects of design, development, fielding, support and acquisition of surface ship and submarine combat systems. Since 1980, Mr. Johnson has had significant responsibility for many of the Navy's submarine sonar and combat control systems programs. Most recently, he led business process transformation efforts at the Naval Enterprise level. These efforts aimed to greatly increase the Navy's ability to take advantage of leading edge technologies and innovations. He is most proud of the numerous team awards, including the National Performance Review “Hammer” Award (twice), won by programs which he led. He was awarded the Meritorious Civilian Service Award (twice) and is the recipient of the NDIA Bronze Medal for his leadership in Submarine Combat Systems. In addition, he was presented with the Superior Civilian Service Award by his Fleet sponsor for his pioneering of the highly acclaimed Acoustics Rapid COTS Insertion program which has been the model for technical and business process transformation within the Navy. Based on actual expenditures, this program has been credited with a cost avoidance of $4B over a ten year period.

Discussant: Captain Mark D. Wessman, USN (Ret.), is a 1971 graduate of the University of Utah, graduating with a Bachelor of Science degree in Chemical Engineering. Upon commissioning through the NROTC program, he reported to USS Vancouver (LPD 2) to begin a career as a Surface Warfare Officer that included afloat service in six ships and culminated with his assignment Commanding Officer of USS Mount Hood (AE 29) during Operation Desert Storm. Major shore assignments included Assistant Chief of Staff for Training and Readiness, Combat Logistics Group 1, Head Integrated Logistics Support Policy and Assessment Branch, Staff of the Chief of Naval Operations, and Executive Director for Fleet Logistics Support of the Naval Sea Systems Command. He is an alumnus of the Naval Postgraduate School, graduating in 1983 from the Weapons System Engineering curriculum with a Master of Science degree in Mechanical Engineering. His is also a graduate of the Program Manager's Course of the Defense Systems Management College. Captain Wessman was designated an Acquisition Professional in 1992 and was awarded subspecialties in Weapons System Engineering, Naval Engineering, and Operational Logistics. His personal awards include the Legion of Merit, the Bronze Star Medal, the Meritorious Service Medal (3 awards) and the Navy Achievement Medal.

Following his transfer to the retired list in 1995, Captain Wessman worked for several small and large companies, applying his skills on behalf of customers in both the defense and commercial sector. He founded Wessman Consultancy Group, Inc. in 2003 and has provided logistics, program management and acquisition consulting services to a variety of customers, including the Office of the Secretary of Defense and the US Navy. He currently is a member of the Industry Expert Team supporting the Navy's Director of Open Architecture.

How to Check If It Is Safe Not to Retest a Component

Presenter: Valdis Berzins is a Professor of Computer Science at the Naval Postgraduate School. His research interests include software engineering, software architecture, computer-aided design, and software evolution. His work includes software testing, reuse, automatic software generation, architecture, requirements, prototyping, re-engineering, specification languages, and engineering databases. Berzins received BS, MS, EE, and PhD degrees from MIT and has been on the faculty at the University of Texas and the University of Minnesota. He has developed several specification languages, software tools for computer-aided software design, and fundamental theory of software merging.

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Author: Paul Dailey is a systems engineer for the Office of Naval Intelligence in Washington, DC. He has also recently worked as a systems engineer for the Naval Surface Warfare Center Port Hueneme Division Detachment, Louisville, and has been working for the Department of the Navy for close to seven years. He holds an MS in Systems Engineering from the Naval Postgraduate School and a BS in Electrical and Computer Engineering from the University of Louisville. He is currently pursuing a PhD in Software Engineering from the Naval Postgraduate School, focusing his research on the automated testing of software.

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Abstract[1]

This paper focuses on ways to reduce testing effort and costs associated with technology-advancement upgrades to systems with open architectures. This situation is common in Navy and DoD contexts such as submarine, aircraft carrier, and airframe systems, and accounts for a substantial fraction of the testing effort. This paper describes methods for determining when testing of unmodified components can be reduced or avoided, and it outlines some methods for choosing test cases efficiently to focus retesting where it is needed, given information about past testing of the same component. Changes to the environment of a system can affect its reliability, even if the behavior of the system remains unchanged. The new capabilities added by a technology upgrade can interact with previously existing capabilities, changing the frequency of their usage as well as the range of input values and, hence, changing their effect on overall system reliability.

Keywords: open architecture, reducing regression testing, automated testing, statistical testing, dependency analysis, reuse, technology upgrades.

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Introduction

Current US Navy combat and weapon system test procedures require an integration test event with every change to the software or system configuration to certify that the software-intensive system-of-systems is stable and functional. As more systems are moving to a modular open architecture, software configurations are changing with increased frequency, requiring more testing, which is expensive and time-consuming.

The Navy's open architecture framework is intended to promote reuse and reduce costs. Ongoing research at the Naval Postgraduate School is developing improvements to the test and evaluation procedures that can contribute to these goals. Test and evaluation accounts for a large part of system-development cost, but the impact of open architecture ideas on this part of the process has been relatively modest so far. The purpose of this effort is to provide sound engineering approaches to better realize the potential benefits of Navy open architectures and to provide concrete means that support economical acquisition and effective sustainment of such systems.

The specific goals of this research are to enable: (1) identification of specific testing and checking procedures that do not need to be repeated after given changes to a system, (2) limiting the scope and reducing the cost of retesting when the latter is necessary, and (3) a single analysis to provide assurance that all possible configurations that can be generated in a model-driven architecture will satisfy given dependability requirements. This paper reports some results that address the first two of the goals listed above. A roadmap and technical approach for reaching the third goal are outlined in Berzins, Rodriquez, and Wessman (2007).

Technology upgrades are typically performed on a two-year cycle. They often involve migration to the best hardware and operating system version available at the time, where "best" implies a balanced trade-off between high performance and reliable operation. Typically, only a small fraction of the application code has been changed. However, current certification practices require all of the code to be retested prior to deployment, whether it has been modified or not. Retesting of an unchanged module can be avoided only if we can establish that it has not been adversely impacted by the change. Preliminary results on how to do that have been reported by Berzins (2008). In this paper, we further explore ways to determine whether it is safe not to retest an unchanged component under the assumption that the load characteristics of the component have not changed. We also address the problem of how to most effectively focus retesting for unchanged components in cases where the requirements and behavior of the component have not changed but the load characteristics have changed.

The latter situation has great importance for assuring reliability of reusable components. Many past cases of well-publicized software failures involved reuse of software components in new environments that had different characteristics than the contexts for which the components were originally designed. These components failed in their new environments despite the fact that they were well-tested and found to be reliable in the field under previous deployment conditions. Examples include the Patriot missile failure (Marshall, 1992) and the failure of the European Ariane 5 rocket (Jézéquel & Meyer, 1997, January).

The rest of this paper is organized as follows: Section 2 describes methods for deciding when re-testing of unchanged components can be safely reduced or eliminated entirely; Section 3 presents methods for efficiently retesting reusable components for use in deployment environments with workloads that are different from previous deployments; Section 4 identifies some relevant previous work; and Section 5 presents our conclusions.

Deciding When Retesting Can Be Avoided

Our previous work identified two types of analysis that could enable safe avoidance of retesting unchanged components under certain conditions: program slicing and invariance testing (Berzins, 2008). These techniques are applicable in cases in which the requirements, code, expected workload and available resources of the component are unchanged. This section briefly reviews the approach and then examines in more detail what additional analysis needs to be done to safely reuse such components in the next release without retesting them.

Program slicing is a kind of dependency analysis that is based on the source code. Slicing algorithms are efficient enough to be used on practical, large-scale programs. If two different versions of a program have the same slice with respect to a service it provides, then that service has the same functional behavior in both versions, and retesting can be avoided if having the same functional behavior is sufficient to establish the reliability of the component (Gallagher, 1991, August).

Invariance testing is a kind of statistical, automated testing that is applicable to components whose code has changed but whose specifications and requirements remain the same. The purpose of an invariance test is to confirm that the changes to the code have not changed the behavior of the services it provides. In this kind of a situation, it is easy to implement a test oracle procedure (explained below) that enables affordable checking of large numbers of automatically executed test cases. Invariance testing can increase the number of components that can be certified not to need retesting when combined with program slicing (Berzins, 2008). Invariance testing can also be used to educe the cost of retesting modules that need to be retested, even though their requirements remain unchanged. This includes unchanged components that depend on other modified components, which are identified by program slicing methods, as well as unchanged components whose expected workload has changed (see section 3).

We can omit retesting of a service if slicing and invariance testing confirm that its behavior is unchanged in the new release and that the following additional conditions are met:

1. The same functional behavior is appropriate in the new release, which occurs only if the requirements of the component are unchanged.
2. The same functional behavior is sufficient to meet the requirements only if the requirements do not contain timing constraints. If this is not the case, the timing constraints need to be retested because changes to hardware, systems software, and other components in the system can all affect timing. This can be done by using a kind of invariance testing that measures timing and by the methods described by Qiao, Wang, Luqi, and Berzins (2006, March).
3. Constraints due to shared resources need to be rechecked, which can usually be done via system-level stress testing. Such constraints include:
    a. Sufficient main memory and disk space

    b. Sufficient I/O resources such as number of files that need to be open at the same time, printers, sensors, actuators, or other peripherals.
    c. Sufficient network bandwidth to support worst-case communications load.
    d. Effective access to showed databases and web services, including both timing and freedom from deadlocks.
4. The slicing analysis is only valid under the assumption that the machine code that is actually running corresponds to the source code that was subjected to slicing analysis.
5. The analysis depends on the assumption that the computer correctly translates the source code into machine language.

The fourth assumption is frequently made without explicit acknowledgement in theoretical studies, but it cannot be adopted without verification in serious risk analysis because of the following plausible failure modes:

1. Memory-corrupting bugs—these include out-of-bounds write operations on arrays and through invalid pointers. Such bugs can cause seemingly innocuous statements to overwrite parts of the program itself at runtime, with unpredictable and potentially catastrophic results.
2. Deliberate cyber-attacks—compromise of system security via network or unauthorized insider access to systems can deliberately modify machine code at run-time.

Memory-corrupting bugs are faults in the code that should be detected by test and evaluation processes, and some types can be prevented. One class of memory-corrupting bugs is caused by premature deallocation of dynamically created objects. Garbage-collection algorithms are supposed to prevent this class of problems so that garbage-collected languages such as Java and Lisp should be immune to this type of problem. Software written in languages without garbage collection, such as C, C++ and Ada, needs special quality-assurance methods to look for premature deallocation. There exist a variety of tools that can be used for this task, including Valgrind (2009, April) (see the system commands Memcheck and Ptrcheck) and Insure ++ (2009, April).

We note that in the absence of perfect computer security, which is not likely to be attainable in the near future, no amount of test and evaluation can detect or prevent failures of the second kind because they are not present in the system while it is being tested; they only appear later—after attacks at run-time. We, therefore, recommend adding a design modification that checks at run-time whether component code is still the same as it was in the test load for all mission-critical systems that do not already have such a capability.

This can be done by packaging the machine code in blocks with secure digital signatures and adding a process that periodically checks the signatures while the system is running. To make this secure, the digital signatures have to be cryptographic checksums with strong encryption so that attackers cannot modify a code module and then forge a signature without knowledge of the secret key. The periodic checking process systematically scans the code modules and checks their digital signatures. If it discovers a modified module, it can repair that module and also report the problem to appropriate authorities. Repair can be accomplished by reloading the module from an uncorruptable source such as read-only memory or CD. Failure due to possible physical damage to media can be mitigated by redundant copies. The repair process checks the digital signature of the new copy to verify its integrity and goes to alternative backup copies if there are any discrepancies. We note that this mechanism can be used to compensate for faults due to memory corruption regardless of whether they were caused by attacks or by faults in the code. The state of corrupted modules will usually have to be restored to the most recent, valid date after the corrupted code is repaired. Component designs may have to be augmented to provide this service. There is extensive literature on how to perform rollbacks, particularly in the context of database transitions. A discussion of this problem for object-oriented components can be found in Vandewoude and Berbers (2005).

The mechanism proposed above is similar to a scheme used by a telephone company to keep its software operational, despite the presence of memory-corrupting bugs, which were known to exist but whose source could not be located. This technology has been proven effective in practice and has been used for decades.

The mechanism can also repair faults due to corruption of data if the scanning process understands the data structures and has code to check the invariant constraints associated with them. This can be incorporated into the architecture via a standard interface that every data type must implement for a service that checks all associated data constraints and repairs them if needed.

Technology upgrades typically move to new hardware, which implies the use of new compilers and new versions of the operating system. Presumably, these underlying services are reliable, but, if we are to retest only a subset of the components in the new release, these assumptions need to be verified. This can be done using invariance testing, as explained by Berzins (2008). The correct operation of the new version of the compiler can be checked by combining invariance testing with the approach to testing translators described in Berzins, Auguston, and Luqi (2001, December).

Retesting Unchanged Components under New Load Conditions

The previous section discusses situations in which the following conditions hold:

1. The code of the component is unchanged.
2. The requirements and specifications of the component are unchanged.
3. The expected workload of the component is unchanged.

This section examines what should be done if the first two conditions are met, but the third one is not: the code and requirements of a component are unchanged, but the expected workload is different. This situation is expected when a component is reused in a different context. Such situations will be common when one of the stated objectives of open architectures is achieved: extensive reuse of common components across platforms.

In these cases, some retesting is necessary. We would like to do this efficiently by reusing previous test results and focusing additional testing effort on the system behavior that will be exercised more in the new workload than it was in the previous ones. We, therefore, seek a systematic method to generate new test cases that characterize situations expected in the new deployment context that were not expected in the previous deployment contexts. This informal idea can be made precise in the context of automated statistical testing (Berzins, 2008).

Automated statistical testing is characterized by the following properties:

1. Test cases are automatically generated by random sampling from an *operational profile.* An operational profile is a probability distribution that represents the relative frequency of different input values to the system under test in its expected execution environment.
2. Pass/fail decisions for individual test cases are automated and done by a single *test oracle* procedure that applies to all possible inputs to the service or system under test.
3. If the generated set of test cases runs without detecting any failures, a simple formula gives a lower bound on the mean number of executions with a corresponding statistical confidence level.

The significance of the first two conditions is economic: after the fixed initial cost of implementing the operational profile and the test oracle, the marginal cost of running an additional test case is very small. This is because there is no additional human effort associated with additional test cases; only additional computer resources are needed to run more test cases, and computer time costs much less than human effort.

The consequence is that very large numbers of test cases can be run economically, making it affordable to collect sample sets large enough to provide high statistical confidence levels in the results. Methods for determining the sample size needed to support conclusions of the form “the mean number of executions between failures is at least N with confidence (1- (1/N)” can be found in Berzins (2008). The significance of this is that it can enable practical testing to specified risk-tolerance levels, rather than testing until budget runs out. The latter does not provide high confidence in system reliability, although it occurs commonly in current practices.

Figure 1 shows an example of the situation described above. The distribution g1 represents the operational profile for the initial deployment of a hypothetical reusable component and g2 represents the operational profile characterizing a new environment in which the component is to be reused. Note that a wider range of input values is expected in the new environment. In this example, g1 and g2 are normal distributions; g1 has a standard deviation of 1.0, and g2 has a standard deviation of 2.0.

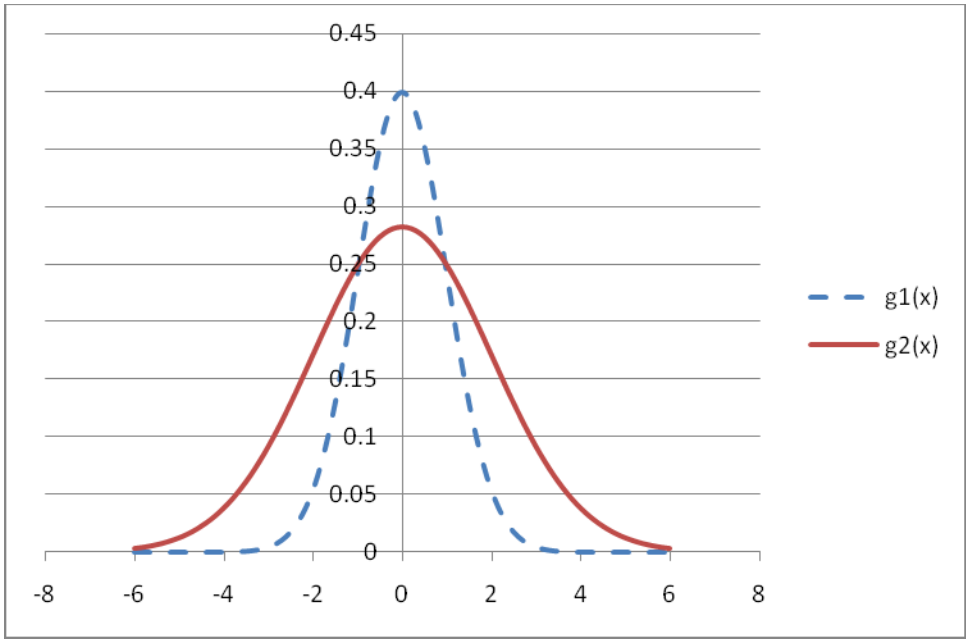

Figure 1. Operational Profiles for Two Different Deployment Environments

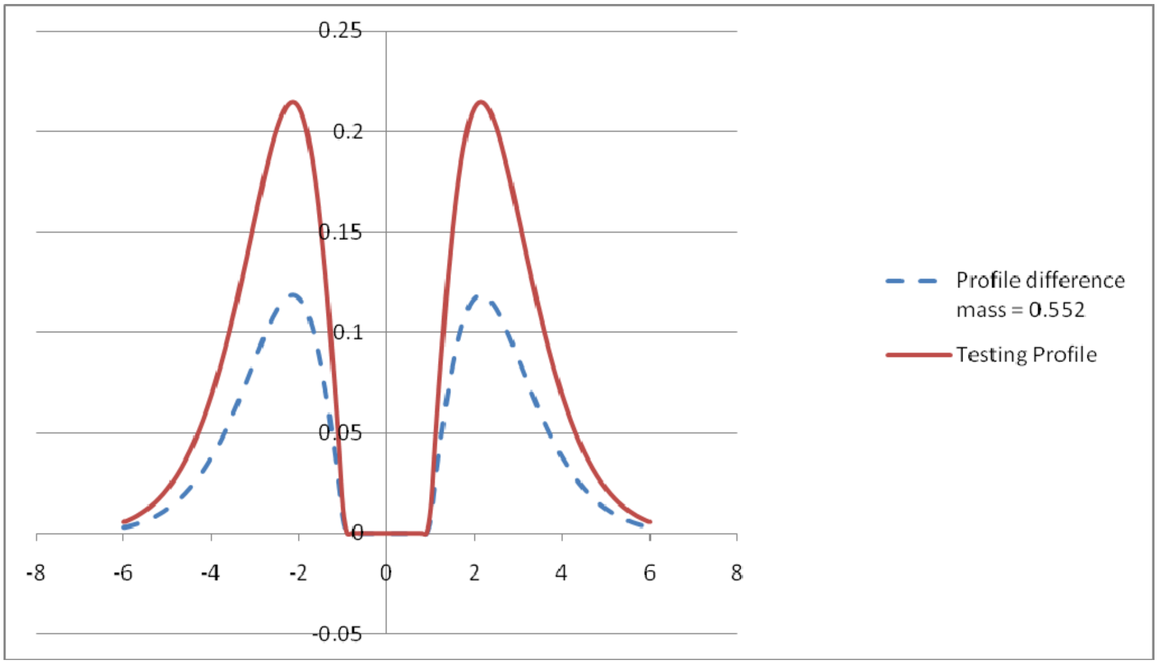

Figure 2. The Derived Testing Profile

Figure 2 shows the profile difference for incremental testing that is derived from the distributions in Figure 1 and the resulting testing profile under the assumption that the number of test cases needed to reach the reliability goals associated with both the previous and the new execution environment are the same.

The profile difference is zero in the region where g1 > g2, and it is equal to the difference g2 – g1 everywhere else. The rationale for these choices is the following:

The region where g1 > g2 has already been adequately tested since the expected number of samples from this region that were checked during prior testing using the profile g1 exceed the expected number of samples from the same region that would be required in testing under the execution profile g2, characterizing the new deployment environment. Therefore, we can avoid this region in the second round of testing, which is accomplished by setting the testing profile to zero in this region.

The remaining region needs more test cases for adequate coverage. If we consider an arbitrary slice of this region, we find that the area under g1 in this slice represents the expected number of test cases that were run in the previous round of testing governed by the profile g1. The area under g2 in the same slice represents the expected number of test cases from the slice that need to be run in the second round of testing. The total area under the profile difference represents the number of test cases needed for the second round of testing as a fraction of the number of test cases required in the first round of testing. In the example, this fraction is calculated to be .552. The testing profile is proportional to the profile difference, which must be normalized by dividing it by the probability mass under the curve to make all of the probabilities add up to 1.

The more general case—in which the reliability goals in the two execution environments differ—has a similar rationale, but the two distributions have to be scaled to account for the differences in the number of test cases needed in each test.

Let N1 be the number of test cases that were needed from profile p1 for the first deployment environment and N2 be the number of cases from a different profile p2, needed for the second environment. Then, in the general case, the profile difference is zero where N1*p1 > N2*p2 and is equal to (N2*p2 – p1* N1)/(N1 +N2) elsewhere.

The testing profile is again the normalized profile difference, obtained by dividing it by the area under the profile difference curve.

We are currently investigating effective methods for modeling operational profiles and for deriving model parameters from historical measurements of actual system loads. Such measurements can come from instrumenting systems to collect data during training exercises or actual missions.

The inputs to the software module must be analyzed to determine dependencies among them. It is also necessary to look for dependencies between the interfaces and other external environmental factors within the context of the operational profile and testing goals. If dependencies exist, they should be characterized.

Once the inputs and the relationship(s) among them are known, the next step is to estimate or specify the distributions that characterize the probabilistic behavior of the inputs. If there are dependencies, the notion of conditional distributions will be considered as a way to handle them. There also may be multiple possible distributions for each input, depending on the state of the environment. This also applies if the goals can vary from testing the normal range of inputs to testing extreme cases, which may be necessary for checking boundary conditions and checking the robustness of the component with respect to unplanned contingencies.

A histogram can be used to represent the new data resulting from the measurements to provide a visual check of the observations. However, it is advisable to fit a distribution based on a theoretical model of the expected distributions for the following reasons:

1. Smoothing—the histogram will show irregularities due to granularity of the random sampling in the measurements. These are not physically significant and are most effectively mitigated by finding the best fit to a smooth curve that interpolates between the samples and smoothes out the gaps.
2. Extrapolation—realistic probability distributions do not cut off suddenly but rather gradually decrease with long tails. Such tails are impossible to accurately estimate based solely on measured data because the number of observed samples is often too small to provide an accurate measurement near the extremes of the expected range of values. If we use the histogram as measured, it is likely that we will set the probability distribution to zero in places where it is actually small, but nonzero. Since this will result in tests that do not cover the full range of possible parameter values, we propose to use a theoretical model in this region and to do the extrapolation by matching the standard deviation of the actual measurements to the standard deviation of the theoretical model. This will smoothly extrapolate the tails out to or beyond the real limits of the input value range. Details about how to choose an appropriate theoretical model for this purpose are still under investigation.

We are also planning to investigate the effectiveness of Bayesian methods for estimating the distributions based on the actual data. This approach will also need a theoretical model of the probability distribution function, which will be used as the prior distribution.

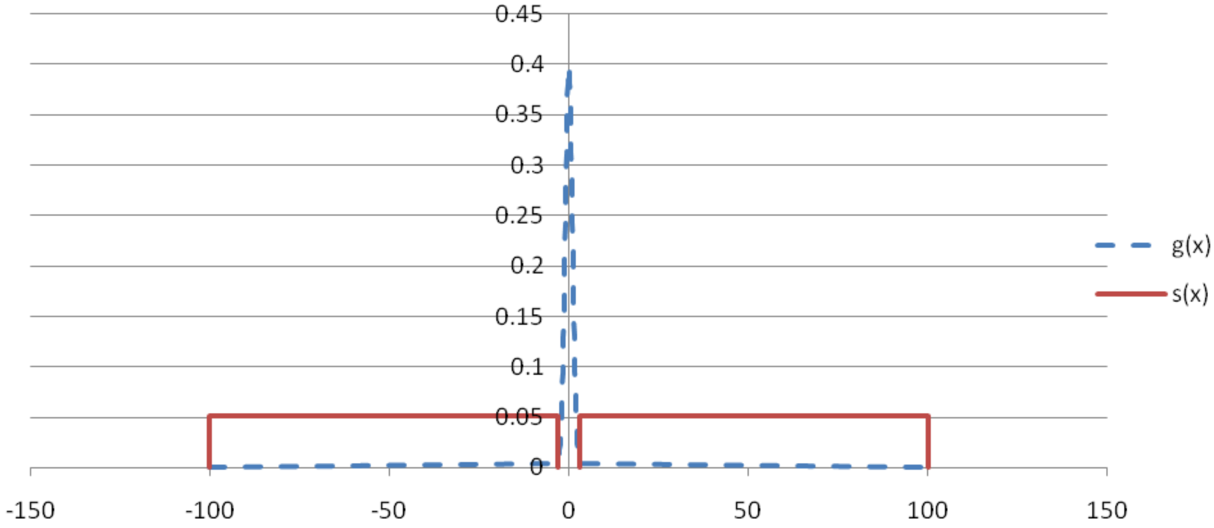

Figure 3. A Stress-testing Profile, s(x), Compared to an Operational Profile, g(x)

The methods outlined above should provide a systematic way to deal with the “known unknowns.” However, military environments are characterized by uncertainty and surprises. To hedge against the possibility of “unknown unknowns,” we recommend running additional tests on components to be reused in new environments with a “stress-testing profile” that purposely exaggerates the range of expected input values. This kind of stress testing is difficult to put on a scientific basis because we are trying to hedge against possibilities that we have no basis for predicting. The following heuristics are proposed as strategies to try:

1. Use a uniform distribution that extends from three to one hundred standard deviations in all directions from the measured mean of the distribution. This is illustrated in Figure 3. The curve g shown in blue represents the normal profile, which is the same as the curve g1 shown in Figure 1, and the curve s represents the stress-testing profile. The curve s has been scaled up by a factor of 10 to make it easier to see in the figure.
2. Use a uniform distribution that covers the entire valid range of input values. This will include completely unexpected input values.

Recalling that these strategies are intended to be used in the context of completely automated statistical testing, in which the marginal cost of running and analyzing additional test cases is very low, we recommend a mixed strategy that runs tests from all three of the proposed testing profiles, each with a number of samples derived from the risk-tolerance parameter k, specified by system stakeholders and the measured execution frequency parameters es according to the relation Ts = (kes)log2(kes), as explained in Berzins (2008). Ts represents the number of the test cases that are needed for testing services to the statistical confidence level implied by the specified risk-tolerance parameter.

Relevant Previous Work

Methods for detecting memory corrupting bugs via static and dynamic program analysis have been studied (Alzamil, 2006; 2008, November). Program slicing (Weiser, 1984, July) has been used in a wide variety of applications, including testing (Binkley, 1998; Gupta, Harrold & Soffa, 1992; Harman & Danicic, 1995; Hierons, Harman & Danicic, 1999; Hierons, Harman, Fox, Ouarbya & Daoudi, 2002), debugging (Agrawal, DeMillo & Spafford, 1993; Lyle & Weiser, 1987), program understanding (De Lucia, Fasolino & Munro, 1996; Harman, Hierons, Danicic, Howroyd & Fox, 2001), reverse engineering (Canfora, Cimitile & Munro, 1994), software maintenance (Gallagher, 1991, August; Cimitile, De Lucia & Munro, 1996; 1994), change merging (Horwitz, Prins & Reps, 1989; Berzins & Dampier, 1996), and software metrics (Lakhotia, 1993; Bieman & Ott, 1994). More detailed surveys of previous work on slicing can be found in Binkley and Harmon (2004).

The problem of state transfers for modules upgraded at run-time is addressed by Vandewoude and Berbers (2005). A method for assessing the impact of timing constraints on proposed system upgrades is described in Qiao, Wang, Luqi, and Berzins (2006, March).

Conclusion

Program slicing and invariance testing are methods that can be used to identify cases in which it is safe not to retest an unchanged component. These methods need to be augmented with other means for establishing the absence of other possible failure modes such as the possibility of memory-corrupting bugs and timing faults. This paper identifies ways to solve these issues.

When components are reused in environments with substantially different load characteristics than previous deployment environments, it is important to test the components under the new modes of operation. This paper presents systematic and efficient ways to accomplish that.

Further work is needed to explore ways to address other possible failure models, including possible interference due to shared system resources, and to address the longer-term goal of eventually eliminating the need for repeating integration testing after every system change. Specifically, more work is needed on methods for certifying the reliability of architectures independently from the components that they contain and for certifying the conformance of an implementation to a given architecture in order to attain the long-term goals outlined in the introduction.

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Mathematical Modeling for Optimal System Testing under Fixed-cost Constraint

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Abstract

Testing of complex systems is a fundamentally difficult task, whether locating faults (diagnostic testing) or implementing upgrades (regression testing). Branch paths through the system increase as a function of the number of components and interconnections, leading to exponential growth in the number of test cases for exhaustive examination. In practice, the typical cost for testing in schedule or in budget means that only a small fraction of these paths are investigated. Given some fixed cost, then, which tests should we execute to guarantee the greatest information returned for the effort? In this work, we develop an approach to system testing using an abstract model flexible enough to be applied to both diagnostic and regression testing, grounded in a mathematical model suitable for rigorous analysis and Monte Carlo simulation. Early results indicate that in many cases of interest, a good, though not optimal, solution to the fixed-constraint problem (how many tests for budget *x*?) can be approached as a simple best-next strategy (which test returns the highest information per unit cost?). The goal of this modeling work is to construct a decision-support tool for the Navy Program Executive Office Integrated Warfare Systems (PEO IWS) offering quantitative information about cost versus diagnostic certainty in system testing.

Keywords: diagnostic testing, regression testing, automated testing, Monte Carlo simulation, sequential Bayesian inference, knapsack problem

1. Introduction

Many of us commute to work every day in what has become a relatively complex system: an automobile. When this system fails us, we are forced to allocate resources (i.e., time and money) to diagnostic testing and repair of one or more components within the system. The budget for this testing and repair is generally constrained by our prudence and our pocketbooks; we hope that the service technician employs a testing strategy that develops the best answer (e.g., replace the alternator) for the least cost.

There are several possible stopping criteria for this testing. In particular, a logical choice would be to stop testing when the cost of replacement of all suspect parts is less than the cost of conducting one more test. This presupposes, however, that our system under test is in a failed state. Suppose we replace a known defective part or perform upgrade maintenance on a component: how much testing must we accomplish to convince ourselves that the system will operate correctly under all conditions?

In this paper we present a language of description and a mathematical model to describe a system under testing, with the goal of evaluating strategies in terms of the information returned by a set of tests. In this framework, then, testing is the mechanism by which we trade some fixed cost (e.g., time, money) for information about the state of subcomponents in our system. In general, we seek the maximum information available for the minimum cost. In the present study, we consider the following question: Given a fixed budget, what is the maximum information discoverable from a particular test suite?

Mathematical models of component and system reliability have roots in the work of von Neumann (1952) and Moore and Shannon (1956a; 1956b), as well as the seminal text by Barlow and Proschan (1965). The focus of these early works is generally on assessing the overall system reliability, particularly with regard to the economics of preventative vice reactive maintenance (e.g., see, Bovaird, 1961). In the present work, the focus is on efficiently identifying either a defective-by-design or failed component in a complex system.

This fault diagnosis is sometimes referred to as the test-sequencing problem, and has also been well studied (e.g., see, Sobel & Groll, 1966; Garey, 1972; Fishman, 1990; Barford, Kanevsky & Kamas, 2004). In general, these investigators start with a system in a known failed state with the goal of finding the most cost-effective sequence of diagnostics to locate the failed component (or components) under a given set of assumptions.

In contrast to fault diagnosis, the general case of regression testing appears to have received less attention in the open literature, with more specific cases examined in the realm of software engineering (e.g., Leung & White, 1991; White & Leung, 1992; Weyuker, 1998; Tsai, 2001; Rothermel, Untch & Harrold, 2001; Mao & Lu, 2005). These studies typically start with a fully functioning system undergoing component modifications or upgrades, with the task of establishing that component modifications have not introduced new defects into the system.

In the present study, we treat testing as a unified activity, with risk and cost as the common tension regulating the degree of testing required. From a fault-diagnosis perspective, we want to arrive at a replacement or maintenance decision quickly while ensuring the system is restored to perfect functionality. From a regression testing perspective, particularly with the open architectures employed within the Integrated Warfare System, following an engineering change or upgrade to a component, we want to conduct enough testing to verify that the system remains in perfect function. The element of risk is that costs incurred for perfect knowledge may approach infinity, *or may not be achievable with a given test suite*. From a practical perspective, then, we accept with some level of confidence (e.g., 99% certainty, 95% certainty) that our diagnosis or prognosis is correct.

The rest of this paper is organized as follows. Section 2 presents the model formulation and fundamental definitions. Section 3 details the mathematical model derived from this framework. Section 4 outlines numerical experiments examining testing strategies in terms of this model and presents simulation results. Section 5 discusses conclusions and avenues for future work.

2. Definitions and Model Formulation

The growing use of commercial off-the-shelf technologies in current weapons systems (Caruso, 1995; Dalcher, 2000), coupled with the complexity of end-to-end systems (Athans, 1987; Brazet, 1993), suggests that we may never have enough information to fully specify our system as a white box, with all software, hardware and communication interfaces perfectly characterized. Thus, we construct our model with broad parameters that can be constrained as narrowly as available information permits.

We characterize the model system **S** as a collection of modules and a suite of tests used to interrogate these modules. We examine the system through this test suite to identify defective modules or to determine that no defective modules exist. We assume that tests return ambiguous information about the state of modules within the system; that is, no single test is likely to return perfect knowledge about a particular module.

Thus, in general, we expect that some sequence of tests must be applied to arrive at a correct diagnosis, where the term *correct* may require careful definition in terms of acceptable risk or required level of confidence. Stochastic simulation of the model system provides a framework in which different testing strategies may be applied and measured for further insight. Using this Monte Carlo approach, we may also test the bounds of our initial assumptions with additional simulation.

2.1 System and module objects

Within the system **S**, each module M_i represents the smallest diagnostic or replaceable unit, which does not necessarily correspond to a single physical component in the modeled system. We consider, for example, a motherboard comprised of a central processing unit (CPU), physical random access memory (RAM), a graphics adapter, and keyboard interface, each of which may cause the motherboard to fail. This might be modeled as a single module labeled *Motherboard* if the standard corrective maintenance action is to replace the motherboard. With more granular diagnostics and maintenance practices, however, we might model these components as *MB_CPU, MB_RAM, MB_Graphics, and MB_Keyboard* because each was testable and replaceable.

Fundamental to this aspect of the model is a source of failure rate data for the system components. These failure rates become the a priori data in the larger probability model and do not necessarily need to be precise to add value to the iterative simulation results. The relative rates among the modeled components (e.g., the *Server* module fails about five times as often as the *Router* module) should be close to the observed data in the physical system to provide the most realistic convergence in testing to a correct diagnosis.

2.2 Test objects

Tests are modeled as system of objects which, when executed, provide an ambiguous assessment of one or more modules within **S**. This ambiguity stems from two essential elements that map the tractable model to physical reality.

The first ambiguous aspect is that any given test likely exercises only a portion of the functionality within a module. Each M_i is modeled as a unit circle A_i (Figure 1). Defects, when present, are assumed uniformly distributed on this circle. We assume that while multiple modules may be defective, only one defect exists per module. A defect in M_i is modeled as a random point on A_i or equivalently a random point on the interval [0, 1]. Although the module is the unit of replacement, we parameterize the sub-module details by treating them as a continuous space covered, in part, by a given test.

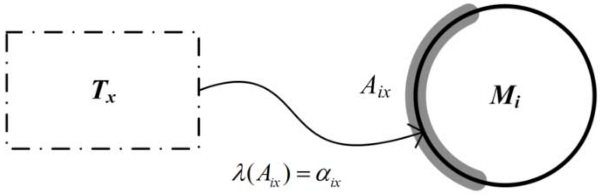

Figure 3. The Simple Coverage of Test T_x on Module M_i, Indicated by the Gray Arc A_{ix}. (The scalar measure of this coverage $\lambda(A_{ix}) = \alpha_{ix}$ represents the fraction of M_i exercised by T_x.)

We model the coverage of test T_x on module M_i as the arc A_{ix} (Figure 1). When T_x is executed, or applied to the model system, the arc A_{ix} on M_i is inspected for a defect. Given the assumption that defects appear uniformly on this unit circle, the probability that a defect in M_i will be detected by T_x is the measure of this arc $\lambda(A_{ix}) = \alpha_{ix}$. The scalar probability of detection by a test is precisely this user-specified functionality exercised by the test. This element of our language of description permits some ambiguity in characterizing the physical system without loss of rigor in modeling these tests and modules. In practice, given a sufficient number of real-world cases from the physical system, this estimate for A_{ix} could be refined through analysis of simulation results.

The second ambiguous aspect is that any given test likely covers multiple modules, such that any test result must be interpreted as applying to *all* modules covered by that test (Figure 2). For example, a positive result (FAIL) from a diagnostic test that covers the modules *Carburetor, Distributor Cap,* and *Spark Plug Wiring* indicates that at least one of these modules contains a defect (has failed), though additional testing would be required to identify which module is the culprit. Because we expect that a given test exercises multiple modules in the system, we speak more generally of the coverage of T_x on **S** (Figure 2).

Within the model, an executed test assumes one of two values: PASS or FAIL. A PASS result for a given test T_x indicates that no region covered by this test contains a defect. A FAIL result indicates that at least one of the modules covered by T_x contains a defect or is BAD in the model definition. While a FAIL result should reduce the set of modules that may need to be replaced, a perfect result—replacing only failed modules—will typically require some sequence of tests. Indeed, for a particular configuration of tests and modules, this perfect result may not be achievable. Analysis of simulation results should help identify those cases in which further testing will yield no new information.

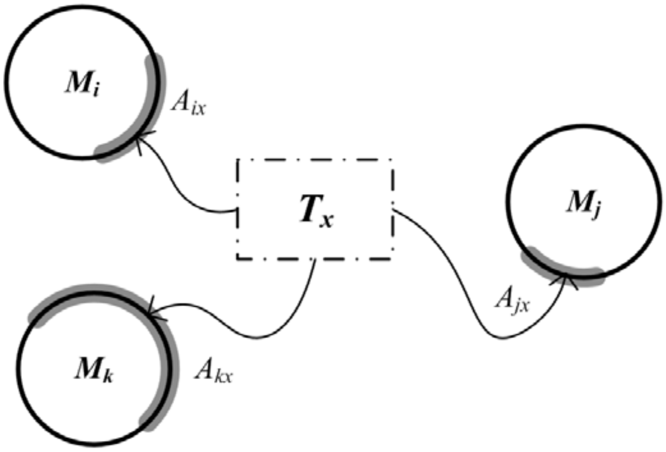

Figure 4. Notional Depiction of the Coverage of T_x on S, with Multiple Modules Exercised by This Test (A FAIL result from T_x indicates that at least one of the subset {M_i, M_j, M_k} has failed.)

The use of vector arcs to model the coverage relationship between tests and modules enables precision when specifying the coverage by multiple tests on a single replaceable unit (Figure 3). Although several tests in the system suite may exercise a given module, it is likely in the physical system that these tests overlap significantly. This language of description, then, permits a user specification of the physical system in broad terms (e.g., the *Remote Control* test and *Obstacle Detection* test both exercise about 70% of the *Garage Door Motor* module, with about 20% overlap between the two tests). Even if these data are estimated from the physical system, existing case data and simulation results could be used to provide better specification of these joint coverages.

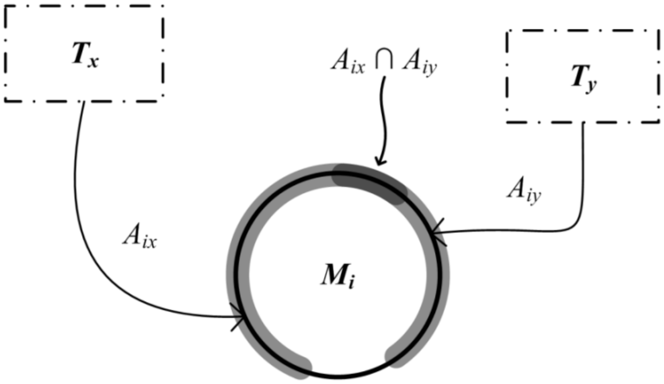

Figure 5. Overlapping Coverage between Tests T_x and T_y Are Characterized with the Arcs A_{ix} and A_{iy} (The joint coverage is computable as the intersection of these arcs.)

2.3 Summary

This conceptual model captures the essential elements of a system with respect to testing, suitable for both diagnostic and regression work. The physical system is specified in terms of modules, tests, and coverages, with model elements constructed in such a way that imperfect information can still be used as an initial state.

Although the model requires that the physical system be decomposable into discrete units of replacement, this does not limit the usefulness of this approach. Within the system, we expect different levels of maintenance (e.g., depot maintenance, field-level maintenance) and different levels of diagnostic techniques, all of which could be treated as different layers within this framework. We next formalize these model elements in mathematical language to construct a suitable computer simulation to investigate these testing strategies.

3. Mathematical Analysis

Our goal in this study of system testing is to maximize certainty for a given cost. In developing a probability framework to model this process, we first form simple objective measures to characterize knowledge of the system state. We next examine a simple, step-wise strategy to predict a test sequence that will maximize or minimize these measures. We then compare this strategy to a two-test approach.

The motivation for examining a two-test (or *k*-test) strategy under fixed cost is that this problem very much resembles the classic knapsack problem (Corman, Leiserson & Rivest, 2002). Choosing at each step the single test that offers the largest increase in information (that is, inserting the largest item into the knapsack first) does not guarantee that we will, for a fixed cost, achieve the greatest information gain (maximize the content of our knapsack). It would be computationally advantageous, though, if we could demonstrate that for many cases of interest, a simple best-next strategy can approach a *k*-step strategy in information return (Cover & Thomas, 1991).

3.1 Module definitions

Within our system **S**, we define B_i and G_i as the events that module M_i is bad or is good, with corresponding probabilities:

$$\begin{aligned} \mathrm{P}(B_i) &= b_i \\ \mathrm{P}(G_i) &= 1 - b_i \end{aligned} \tag{3.1}$$

Each b_i represents information we have about the state of module M_i, and the collection $\{b_i\}$ gives us some insight into the health of **S**. Prior to any testing, we expect each b_i is initialized based on an a priori failure rate for M_i.

The probability b_i is an intuitive measure of information, and we see that as b_i tends to 0 (good) or 1 (bad), our knowledge about M_i becomes more certain. A classic, quantitative measure of this knowledge is the information entropy (Shannon, 1948):

$$h_i = -b_i \log_2 b_i - (1 - b_i)\log_2(1 - b_i) \tag{3.2}$$

We see that as b_i tends to 0 or 1, h_i is minimized (Figure 4). By applying tests from our diagnostic suite, we should become more certain about the state of a module (good or bad) and so act to nudge b_i to the edges of the interval [0, 1]. We can measure this improvement in certainty as a reduction in the individual module entropy h_i, aggregated over the system:

$$H = \sum_{i=1}^{n} -b_i \log_2 b_i - (1 - b_i)\log_2(1 - b_i) \tag{3.3}$$

Entropy is computationally attractive as a continuous and differentiable function over the interval of interest (Figure 4), though h_i may be less intuitive when deciding which modules to replace. A measure similar to entropy, though not differentiable at maximum entropy, is:

$$q_i = \max(b_i, 1 - b_i) \tag{3.4}$$

We can think of q_i as a quality gauge of this replacement (or maintenance) decision with respect to a particular module. If, for example, a particular module has a $b_i = 0.70$, we may replace it knowing that this informed guess should be correct 70% of the time. This also means that in 30% of these cases, we will unnecessarily replace or perform more granular debugging on this module. Our number of correct diagnoses across the system will increase as each b_i is adjusted, by testing, away from b_i=0.5 towards either 0 or 1 (Figure 4). Although this is not a rigorous result, it can be shown that minimizing system entropy is approximately equivalent to maximizing the number of correct diagnoses.

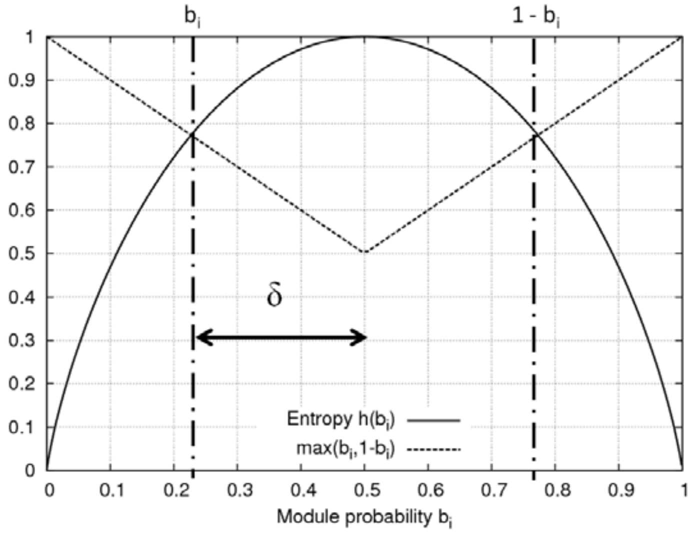

Figure 6. Module Entropy $h(b_i)$ and $q_i = \max(b_i, 1-b_i)$, with Notional Module Probability b_i Indicated (The scalar δ represents the displacement of b_i from maximum entropy ($b_i = 0.5$). Note that by symmetry, $h(b_i) = h(1 - b_i)$, with distance 2δ between these states.)

Consistent with previous studies (e.g., Birnbaum, Esary & Saunders, 1961; Butterworth, 1972; Ben-Dov, 1981), we characterize our knowledge of **S** as a vector of these module probabilities, $\{b_i\}$, where each component probability b_i is on the interval [0, 1]. The true state of **S** is a bit vector with each component exactly 0 (good) or 1 (bad); in practice, we are unlikely to achieve this “perfect” knowledge, but computation of h_i or q_i permits some insight into this true state.

Earlier studies typically examined scenarios in which **S** will function only if all modules are working correctly (serial system), some modules are working correctly (k-of-n system), or if at least one module is working correctly (parallel system). In the present study, we make no assumptions about whether **S** is in a known down state and instead focus on characterizing the health of the system—similar to literature in optimal maintenance strategies (e.g., Boivard, 1961; or Barlow & Proschan, 1965). The focus in the present work is on the nature of the test suite available to the diagnostician or maintainer, and the most effective use of that suite to better characterize **S.** We next present the mathematical model for tests and testing.

3.2 Test definitions

Similar to our model of modules, we define P_x and F_x as the events that test T_x passes or fails, respectively. We expect either result (pass or fail) to return ambiguous information because a test likely exercises or covers only some fraction of the functionality of a module (Figure 1), and because the test likely exercises several modules simultaneously (Figure 2). Thus, a passing result for T_x indicates only that no defect was detected, while a failing result narrows the pool of suspect modules to those exercised by T_x.

After execution of a test, we update the prior probability b_i to the new probability b_i' based on the test outcome:

$$b_i' = \begin{cases} \mathrm{P}(B_i \mid P_x) & \text{if } T_x \text{ passes} \\ \mathrm{P}(B_i \mid F_x) & \text{if } T_x \text{ fails} \end{cases} \tag{3.5}$$

Using Bayes' rule, we can compute these probabilities as:

$$\mathrm{P}(B_i \mid P_x) = \frac{\mathrm{P}(P_x \mid B_i)\mathrm{P}(B_i)}{\mathrm{P}(P_x)} = \left(\frac{\mathrm{P}(P_x \mid B_i)}{\mathrm{P}(P_x)}\right) b_i \tag{3.6}$$

$$\mathrm{P}(B_i \mid F_x) = \frac{\mathrm{P}(F_x \mid B_i)\mathrm{P}(B_i)}{\mathrm{P}(F_x)} = \left(\frac{\mathrm{P}(F_x \mid B_i)}{\mathrm{P}(F_x)}\right) b_i \tag{3.7}$$

These results suggest that tests can be seen as operators that transform b_i into b_i'. We note that the module probability is unchanged if test T_x has no coverage on M_i. In this case, the conditional probabilities P($P_x|B_i$) and P($F_x|B_i$) degenerate to the unconditional probabilities P(P_x) and P(F_x), and so we have $b_i' = b_i$.

Because the execution of test T_x necessarily incurs some cost in budget or schedule, we are motivated to compute a forecast value, q_{ix}, from a weighted sum of the unconditional probabilities on P_x and F_x (Equation 3.8). Given the prior state of the system as the set of module probabilities $\{b_i\}$, this method can then be used to assess the expected change *across the system* for a particular test T_x.

$$\begin{aligned} q_{ix} &= \max\begin{pmatrix} \mathrm{P}(B_i \mid P_x) \\ \mathrm{P}(G_i \mid P_x) \end{pmatrix} \mathrm{P}(P_x) + \max\begin{pmatrix} \mathrm{P}(B_i \mid F_x) \\ \mathrm{P}(\mathrm{G}_i \mid F_x) \end{pmatrix} \mathrm{P}(F_x) \\ &= \max\begin{pmatrix} \mathrm{P}(P_x \mid B_i)\mathrm{P}(B_i) \\ \mathrm{P}(P_x \mid G_i)\mathrm{P}(G_i) \end{pmatrix} + \max\begin{pmatrix} \mathrm{P}(F_x \mid B_i)\mathrm{P}(B_i) \\ \mathrm{P}(F_x \mid G_i)\mathrm{P}(G_i) \end{pmatrix} \end{aligned} \tag{3.8}$$

Using the expected value of b_i after test T_x (Equation 3.8), we can form a composite measure over our system of n modules with the sum Q(T_x):

$$Q(T_x) = \sum_{i=1}^{n} q_{ix} \tag{3.9}$$

We expect that if Q(T_x) > Q(T_y), then test T_x will return more information than test T_y (Figure 4). This value, however, is a forecast; the actual information returned for a particular test execution may vary widely by scenario.

We note also that because Q depends upon our current knowledge of the system as the set of probabilities $\{b_i\}$, and because this set is constantly updated by testing, the choice of a particular test T_x may yield widely varying Q(T_x) depending upon **when** T_x is executed in the test sequence.

To calculate q_{ix} we need the conditional probability $\mathrm{P}(P_x|B_i)$, which we compute by first considering the unconditional probability $\mathrm{P}(P_x)$. We note that a test T_x will pass if every module covered is either good (Equation 3.1) or bad but undetected. A test T_x will fail to find a defect with probability $(1 - \alpha_{ix})$, or the complement to the fractional coverage of T_x on M_i (Figure 1). Considering all n modules in the system, then, we have:

$$\begin{aligned}\mathrm{P}(P_x) &= \prod_{i=1}^{n}\left(\underbrace{(1-b_i)}_{GOOD} + \underbrace{(1-\alpha_{ix})b_i}_{BAD, NOT\,DETECTED}\right) \\ &= \prod_{i=1}^{n}\left[1-\alpha_{ix}b_i\right]\end{aligned} \tag{3.10}$$

Given that module M_i is bad ($b_i = 1$), we then have:

$$\mathrm{P}(P_x \mid B_i) = (1-\alpha_{ix})\prod_{j\neq i}^{n}\left[1-\alpha_{jx}b_j\right] \tag{3.11}$$

Similarly, we note that $\mathrm{P}(F_x) = 1 - \mathrm{P}(P_x)$, and we can then see that:

$$\mathrm{P}(F_x \mid B_i) = 1-(1-\alpha_{ix})\prod_{j\neq i}^{n}\left[1-\alpha_{jx}b_j\right] \tag{3.12}$$

We see that if T_x has no coverage on M_i ($\alpha_{ix} = 0$), Equations 3.11 and 3.12 reduce to the unconditional probabilities on T_x. Similarly, if T_x has perfect coverage ($\alpha_{ix} = 1$), Equations 3.11 and 3.12 reduce to 0 (T_x cannot pass if M_i is bad) and 1 (T_x must fail if M_i is bad).

Using Equation 3.10 and its complement, the conditional probabilities given that M_i is good are:

$$\mathrm{P}(P_x \mid G_i) = \prod_{j\neq i}^{n}\left[1-\alpha_{jx}b_j\right] \tag{3.13}$$

$$\mathrm{P}(F_x \mid G_i) = 1-\prod_{j\neq i}^{n}\left[1-\alpha_{jx}b_j\right] \tag{3.14}$$

A quick check of the boundaries shows that if M_i is good and there are no other coverages on M_i (all $\alpha_{jx} = 0$), Equation 3.13 reduces to 1 (T_x must pass), and Equation 3.14 reduces to 0 (T_x cannot fail). Indeed, this set of equations (3.11-3.14) addresses computationally the ambiguity associated with test results, coverages and modules (Figure 1 and Figure 2).

3.3 Test strategies

The objective function $Q(T_x)$ (Equation 3.9) is necessarily a one-step method if we choose that T_x which maximizes Q. If we have only the budget or schedule to execute one more test, maximizing Equation 3.9 will yield the optimal result. In practice, though, we expect that we may have the resources to execute some number of tests; and, similar to the classic knapsack problem (Corman, Leiserson & Rivest, 2002), we are not guaranteed that this simple, one-step strategy will generally yield the largest information gain for a given cost.

As a simple example of this knapsack problem, consider three tests {T_1, T_2, T_3} with a forecast information return of {$Q(T_1) = 3$, $Q(T_2) = 4$, $Q(T_3) = 6$} for associated cost {3, 4, 5}; the units of information and cost are not important to our point and can be thought of as unit cost per bit. Given a fixed cost constraint of 7, the single best-next test choice is T_3, with a cost-per-bit 5/6 and a net return of 5. The choice of T_3, though, means that we cannot execute another test within the cost constraint of 7. This strategy, then, is clearly not optimal for the fixed constraint because the choice of T_1 and T_2, each individually more expensive than T_3, yields a net information return of 7.

To guarantee an optimal solution, then, we are obligated to compute 2^k possible outcomes for a suite of k tests for all n modules in **S**. To mitigate this computational burden, we examine the real differences between an optimal solution and a good solution for our scenarios of interest.

For additional insight, we consider a two-step strategy and its associated objective function with four components (Equation 3.15), computed over all modules (Equation 3.16):

$$\begin{aligned} q_{ixy} &= \max\begin{pmatrix} \mathrm{P}(P_xP_y \mid B_i)\mathrm{P}(B_i) \\ \mathrm{P}(P_xP_y \mid G_i)\mathrm{P}(G_i) \end{pmatrix} + \max\begin{pmatrix} \mathrm{P}(F_xP_y \mid B_i)\mathrm{P}(B_i) \\ \mathrm{P}(F_xP_y \mid G_i)\mathrm{P}(G_i) \end{pmatrix} \\ &+ \max\begin{pmatrix} \mathrm{P}(P_xF_y \mid B_i)\mathrm{P}(B_i) \\ \mathrm{P}(P_xF_y \mid G_i)\mathrm{P}(G_i) \end{pmatrix} + \max\begin{pmatrix} \mathrm{P}(F_xF_y \mid B_i)\mathrm{P}(B_i) \\ \mathrm{P}(F_xF_y \mid G_i)\mathrm{P}(G_i) \end{pmatrix} \end{aligned} \tag{3.15}$$

$$Q(T_xT_y) = \sum_{i=1}^{n} q_{ixy} \tag{3.16}$$

We note that in these pair-wise calculations (or in k-wise calculations), we must consider the possible intersection of coverages between T_x and T_y (Figure 3). That is, we expect two tests with significant overlap in module coverage should not yield a higher q_{ixy} than two paired tests with similar fractional coverages but no overlap or intersection between the two tests. Although the analytic work for these conditional probabilities follows Equation 3.11—3.14, we next turn to simulation to exercise this strategy for comparison to the single-step, best-next strategy.

3.4 Summary

We have presented the mathematical details supporting the abstract model presented in Section 2. We characterize our knowledge of the system health as a collection of probabilities {b_i}, where b_i indicates the probability that component M_i is bad (b_i=1) or good (b_i=0). Using a sequential Bayes' approach, prior probabilities in {b_i} are updated following test execution. As more tests are applied, each T_x should act to minimize entropy H (Equation 3.3) or increase our certainty about the state of each module as either good or bad.

The paper focuses on strategies to choose a test, or sequence of tests, to guarantee the best (or at least a very good) return on the budget or schedule allocated to testing. In the present work, our constraint is a given, fixed cost and our goal is to find the greatest information gain possible in the test suite within this cost. Although an optimal solution may often be computationally untenable, we next examine simulation results to better estimate the distance between “optimal” and “good.”

4. Modeling Approach and Simulation Results

In support of this research, a desktop simulation was developed to implement the analysis presented in Section 3 and to further examine the choices among test strategies. In addition to the best-next and two-step strategies, a random-strategy case was coded to select a test sequence randomly, and a pathological worst-case strategy was created to minimize rather than maximize the information return per test. The random and worst-case configurations were developed to provide some contrast to the “best” strategies.

4.1 Model description

The simulation code implements object models of Tests and Modules, collected under a System object. Configuration parameters are set in an XML text file (Figure 5). Each XML file represents a *simulation,* which is comprised of one or more *configurations* or simulation cases. Each configuration or case is then executed for some number of trials.

Within each configuration, the number of modules and tests are explicitly set, while the module a priori failure rates and test-module coverages are established randomly within minimum and maximum parameters (Figure 5). These random coverages are reconfigurable between trials to permit a Monte Carlo investigation of the initial data. While these randomized scenarios provide some insight into systems testing, sufficient flexibility exists in the computer code and the XML configuration parameters to encompass more realistic systems.

Because of the iterative nature of the model, the algorithm should be relatively insensitive to the initial conditions in the model with respect to module a priori failure rates. That is, the state vector $\{b_i\}$ is constantly adjusted through the application of tests, and we expect this convergence to dominate the final or quasi-steady state of knowledge regarding our system.

```xml
<?xml version="1.0"?>
<simulation>
<!-- ========================= -->
<!-- SAMPLE CONFIGURATION FILE -->
<!-- ========================= -->
<configuration>
<!-- ==================== -->
<!-- EXECUTION PARAMETERS -->
<!-- ==================== -->
<CaseName>best</CaseName>
<Strategy>best</Strategy>
<RandomSeed>-1</RandomSeed>
<NumberOfTrials>10</NumberOfTrials>
<DecisionThreshold>0.90</DecisionThreshold>
<DefectsPerTrial>1</DefectsPerTrial>
<LogFileName>simulation.log</LogFileName>
<ReconfigureTestsPerTrial>yes</ReconfigureTests
PerTrial>
<!-- ================= -->
<!-- MODULE PARAMETERS -->
<!-- ================= -->
<NumberOfModules>10</NumberOfModules>
<FailureRate>
  <Minimum>0.5</Minimum>
  <Maximum>0.5</Maximum>
</FailureRate>
<CostPerModule>
  <Minimum>1.0</Minimum>
  <Maximum>1.0</Maximum>
</CostPerModule>
<SumCostOfAllModules>100.0</SumCostOfAllModules
>
<TestsPerModule>
  <Minimum>1</Minimum>
  <Maximum>5</Maximum>
</TestsPerModule>
<!-- =============== -->
<!-- TEST PARAMETERS -->
<!-- =============== -->
<NumberOfTests>35</NumberOfTests>
<CostPerTest>
  <Minimum>1.00</Minimum>
  <Maximum>1.00</Maximum>
</CostPerTest>
<SumCostOfAllTests>100.0</SumCostOfAllTests>
<ModulesPerTest>
  <Minimum>1</Minimum>
  <Maximum>3</Maximum>
</ModulesPerTest>
<CoveragePerModule>
  <Minimum>0.20</Minimum>
  <Maximum>1.00</Maximum>
</CoveragePerModule>
</configuration>
<!-- ==================== -->
<!-- END OF CONFIGURATION -->
<!-- ==================== -->
</simulation>
```

Figure 7. Sample Configuration XML File

4.2 Model processing

Prior to the start of a configuration run (set of trials), a failure deck is created based on the relative failure rates of modules within the system. Similar to a deck of playing cards, modules appear in the failure deck based on their standing relative to the minimum failure rate in the system; thus, if the minimum failure rate across the system is 0.2, a module with a failure rate of 0.6 will appear three times within the failure deck. The same deck is employed across all trials in a configuration run to simulate the relative appearance of failures in a physical system. No a prior assumption was made in the mathematical analysis (Section 3) about the number of, and the simulation code reflects this versatility.

Prior to the start of a trial, a test deck with one entry for each test is created (copied) from the system configuration. Strategies (best-next, best-next-two, random, and worst) consume this list as the “next” choice is executed; thus, as a test is executed it is removed from the deck, insuring that no test will be executed more than once per trial. This also reduces the search space for the next test. A new test deck must be generated with each trial.

A single trial is processed in the following manner:

1. All module b_i are initialized from failure rate data.

2. All module coverages are established; these are either duplicated from the previous trial or randomized subject to the same configuration parameters.

3. Some p number of modules (where $0 \le p \le n$) are selected from the failure deck and a defect is planted in each module. It is possible (and interesting) to run the simulation with no defects planted.

4. A test is chosen based on a simple strategy (e.g., best, random, or worst)

5. This test is applied to the system object

6. All affected b_i are updated based on the outcome of (5)

7. If there is still a test in the test deck, return to (4)

Although we are interested in improving test strategies under fixed-cost constraint, in these trials we simply execute until the set of tests is exhausted. The motivation for this approach is that by allowing the simulation to process all tests available, we also gain insight into the effectiveness of the given test suite; this line of investigation will be pursued in future studies.

4.3 Simulation results

Using a 2 GHz Intel processor, a simulation of 300 trials using the best-next, best-next-two, random and worst strategies required about 17 minutes (for all four) using a randomized configuration of 40 modules and 100 tests, with one defect planted. The zero-defect simulations required about the same execution. In all of these cases, the initial probability distribution was to set each module to b_i=0.5 (maximum entropy).

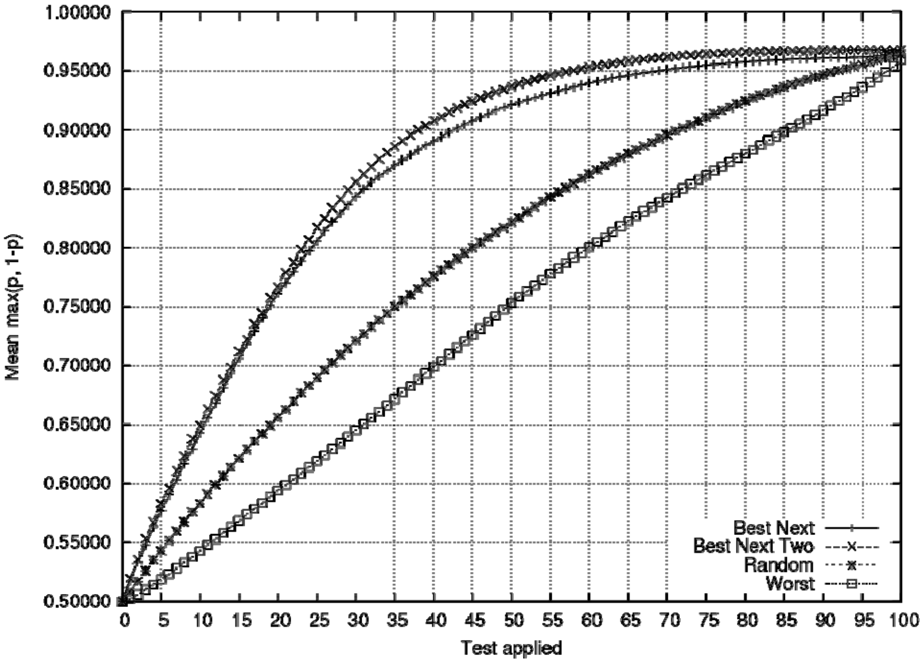

Figure 8. Comparison of Mean q_i among Simulations of a 40-module, 100-test System with One Defect Planted (using the one-step (best-next), two-step (best-next-two), random and worst cases)

Comparisons between the one-step and two-step approach (Figure 6) show little difference in the first 25 or so tests in terms of the mean maximum probability q_i—suggesting that the one-step approach would yield an acceptable return on a fixed budget or schedule for testing *for the randomized system configurations tested.* More realistic scenarios may show more significant divergence between one-step and two-step (and by extension, *k*-step) methods.

Similar comparisons in terms of information entropy (Figure 7) show more displacement between the one-step and two-step methods, though both methods are clearly superior to the random and “worst” case methods. In a similar simulation configuration but with no defect (Figure 8), the information entropy shows similar descent. At the tail end of the testing process, though, the steady-state *H* is lower in the no-defect case (Figure 8) than in the one-defect (Figure 7) case.

Although the best-next-two strategy appears somewhat better than the best-next strategy for the fixed-cost constraint, the CPU time required for this two-step simulation expanded roughly by a factor of four on a per-trial basis, which is consistent with Equation 3.8 and Equation 3.15.

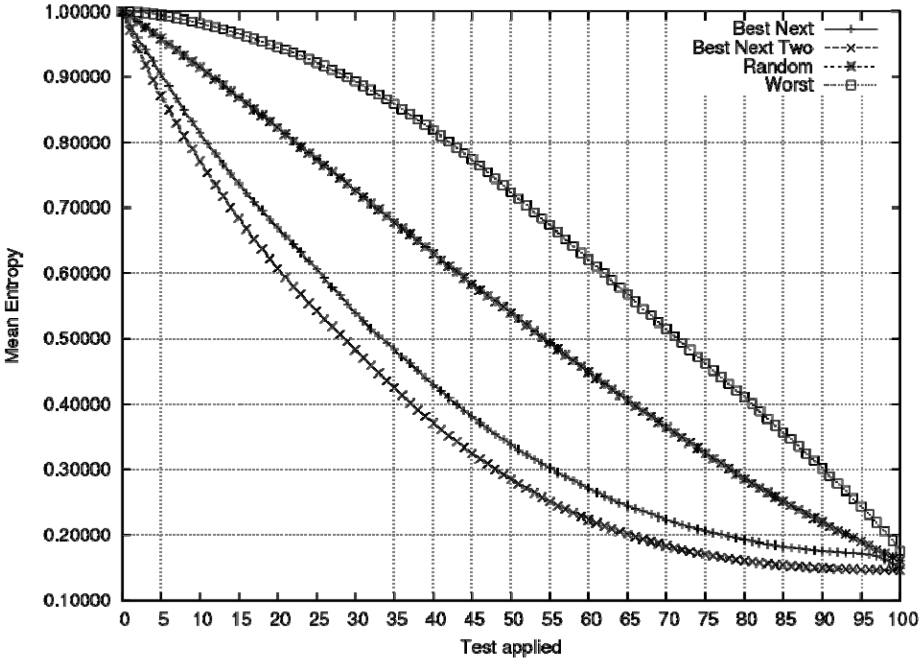

Figure 7. Comparison of Mean Entropy *H* among Simulations of a 40-module, 100-test System with One Defect Planted (using the one-step (best-next), two-step (best-next -two), random and worst cases)

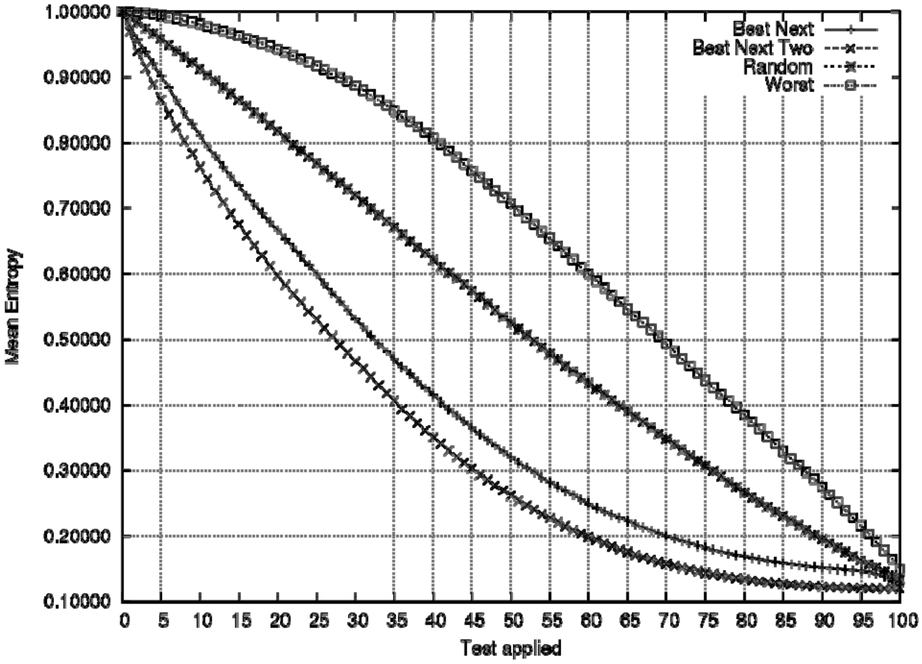

Figure 8. Comparison of Mean Entropy *H* among the NO DEFECT Simulations of a 40-module, 100-test System (showing only slightly lower entropy values for all cases, though slope of descent is similar in all cases)

5. Conclusions and Future Work

In this study, we have developed a simple, effective framework to examine the testing of complex systems. The idealized numerical experiments demonstrate that a simple best-next approach is computationally efficient if not optimal, though the convergence to a correct diagnosis appears to be very close to a two-step approach. Further investigation with more exhaustive *k*-step testing strategies should confirm that for many cases of interest the simple best-next approach yields acceptable results for a fixed-cost constraint.

A novel aspect of this approach is the focus on tests as distinct objects providing information about modules. Much of the previous work in this area has focused on knowledge of the initial distribution of failure rates, requiring almost perfect knowledge of these a priori data in order to be effective (Butterworth, 1972; Ben-Dov, 1981). In terms of software testing, previous studies have relied on some knowledge of the internal structure of components or reusable objects, or near-perfect knowledge of the module interconnections (Rothermel, Untch & Harrold, 2001; Mao & Lu, 2005). Here, we assume only that our system has some test suite; these tests may be derived from requirements documents, from formal system acceptance plans, or from daily systems operations. Application of this model requires only that we be able to characterize these tests in terms of approximate coverages on units of replacement.

Although a variable cost per test is accounted for in the simulation code, the runs presented in this paper assumed a constant cost per test. In effect, we assume a unit cost per test, such that the number of tests becomes the associated cost. Further simulation work with more realistic configurations of modules, tests and coverages should yield more insight into operational diagnostic and regression problems.

The treatment of tests as distinct objects readily enables use of this approach for simulation even when no bug or defect is known to be present. This testing scenario, which commonly follows a major system upgrade or engineering change to a system, is often referred to as regression testing. This zero-defect case may also be useful to evaluate the quality of a test suite with respect to all states of a system. In the zero-defect cases run in this study, the mean entropy (Figure 8) and maximum probability (not shown) do not go to 0 and 1, respectively, as we would expect if all states were reachable from the test suite. This line of research would be particularly well-suited for the classic regression or test-retest problems.

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Panel 8 - Contemporary Acquisition Issues and the Way Ahead

Wednesday, May 13, 2009

3:30 p.m. – 5:00 p.m.

Panel 8 - Contemporary Acquisition Issues and the Way Ahead

Chair: Laura Dwinnell, Systemic Analysis Team Lead, Systems and Software Engineering, Assessments and Support, Office of the Under Secretary of Defense (Acquisition, Technology & Logistics)

Panelists:

Peter Nolte, Systems and Software Engineering, Assessments and Support, Office of the Under Secretary of Defense (Acquisition, Technology & Logistics)

Hal Wilson, Northrop Grumman Corporation

Extract from: ***National Defense Industrial Association Systems Engineering Division Systemic Root Cause Analysis Task Group Report***

Extract from: National Defense Industrial Association—Systems Engineering Division: Systemic Root Cause Analysis Task Group Report

Background

Since 2004, the Office of the Under Secretary of Defense for Acquisition, Technology and Logistics (USD (AT&L)), Systems and Software Engineering/Assessments and Support (SSE/AS) Directorate has been conducting Program Support Reviews (PSRs) for major defense programs to help identify and resolve program issues and risks and, ultimately, to improve the probability of program success. Through analysis of the PSR data, SSE/AS has identified systemic issues seen across Major Defense Acquisition Programs (MDAPs) and Major Automated Information Systems (MAIS) that impede acquisition success.

Objective

The National Defense Industrial Association (NDIA) Systemic Root Cause Analysis (SRCA) Task Group was formed to analyze the data and attempt to extract the lowest level root causes of program failures. The Group used information generated from SSE/AS's analysis to derive a joint government-industry set of recommendations to address the systemic issues and improve the execution discipline of acquisition programs. Although the analysis focused on Acquisition Category I (ACAT I) programs, the results are scalable and can be applied to most acquisition programs.

Results

The Task Group developed recommendations and actions in three areas:

- Acquisition Strategy and Planning
- Decision Gate Review
- Enhanced Staff Capability

Acquisition Strategy and Planning (ASP) pertains to the early program planning that is critical to posture a program for success. The ASP recommendations and actions promote the following end-states:

- Program planning is executable with a high degree of confidence.
- Requests for Proposal and supporting documentation clearly define the government's expectations in terms of requirements, planning, process, risks, and assumptions; they direct offerors to integrate their approach accordingly.
- Independent schedule estimates are performed to support cost-estimating source selection and milestone decisions.

Decision Gate Review (DGR) pertains to the Department of Defense (DoD) implementing objective criteria to assess technical maturity at key decision points. The criteria should include independent reviews of program technical maturity and include enforceable criteria specific to the decision gate. The DGR recommendations and actions promote the following end-states:

- Technical maturity assessed through systems engineering technical reviews; high-confidence estimates achieved for both cost and schedule.
- Government program office staffing verified by the Milestone Decision Authority (MDA).
- Trigger conditions defined for the conducting of in-process reviews.

Enhanced Staff Capability (ESC) pertains to having an adequate number of people with the appropriate skill mix and the required experience to properly staff, manage, and execute a program. The ESC recommendations and actions promote the following end-states:

- The number, skills and experience of DoD acquisition personnel are adequate to properly staff acquisition programs.

Recommendations

The Task Group effort formally concluded with publication of this report (released via NDIA early Spring 2009). The Task Group offers the recommendations contained in this report to DoD and defense industry acquisition leadership, suggesting the following to them:

- Consider and validate the Task Group-developed actions.
- Assign action owners and develop Plans of Action and Milestones to implement selected recommendations.
- Monitor progress of actions to closure.

Summary

The systemic root cause analysis concluded that the most significant causes were directly related to poor or inadequate activities early in acquisition strategizing and planning efforts and in conducting management gate reviews during the early stages of execution. The analysis also concluded that there was a significant root cause related to staff size, training and experience.

The task group recognizes there is a strong relationship between disciplined systems engineering and good management decision-making in the critical, early stages of an acquisition cycle. The creation of a successful acquisition strategy, plan, and staffing profile are heavily reliant on judgment and program management analysis that are often significantly enhanced by the application of good systems engineering practices.

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Panel 9 - Acquisition Challenges in the United Kingdom

Wednesday, May 13, 2009 **3:30 p.m. – 5:00 p.m.**	Panel 9 - Acquisition Challenges in the United Kingdom **Chair: David Moore**, Director, Centre for Defence Acquisition, Cranfield University **Panelists:** **Stuart Young**, Centre for Defence Acquisition, Cranfield University **Pete Ito**, Centre for Defence Acquisition, Cranfield University ***Innovative UK Approaches to Acquisition Management*** **David Moore, Stuart Young** and **Pete Ito**, Centre for Defence Acquisition, Cranfield University

Chair: David Moore worked in purchasing, logistics and supply chain management within public sector and commercial organisations before entering academia. He has designed, developed and delivered a range of professional courses, Undergraduate and Masters' programmes for organisations and universities. He has undertaken extensive education, training, speaking and consultancy assignments in the UK, USA, Europe, Middle East and Far East. Particular interests include outsourcing, using contractors for service provision, developing professionalism and humanitarian logistics. He has written a number of books, book chapters, and conference and journal papers. Moore completed his service in the Royal Logistic Corps as a Lt Colonel in 1999.

Panelists:

Stuart Young retired from the Royal Navy as an engineer officer in 2008, having served in a variety of postings at sea and in the UK Ministry of Defence. These included three years based in the British Embassy in Washington as a technical liaison officer, and as programme manager for a major multi-national technology development programme. In his final appointment, he was responsible for the development of acquisition management skills for military and civilian personnel across the MoD. Joining Cranfield University in 2008, he is Deputy Director of the Centre for Defence Acquisition, with a particular interest in the relationship between the MoD and Industry and the development of acquisition strategies for major defence programmes.

Pete Ito earned a Bachelor's degree in Political Science from the University of California at Berkeley, and a Juris Doctor (law) degree and a Master's degree in International Affairs from George Washington University in Washington, DC. He worked for 25 years as a Foreign Service Officer for the US State Department, serving in South Korea, Denmark, Germany, The Netherlands and Washington, DC. His primary focus was political affairs, particularly defence and security policy. He joined Cranfield University in September 2007, working as a researcher in the areas of strategic management and change management, before moving to his current position.

Acquisition Challenges in the United Kingdom

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Abstract

The panel discussion will address four critical defence acquisition issues and programmes which illustrate the innovative approaches the United Kingdom is undertaking in this area. All four cases will echo the challenges facing the US and other countries and provide valuable "lessons learned" in a number of key areas. The first topic is the UK decision to acquire C-17 transports, which provides a good example of the benefits of capability management. The second topic is the UK implementation of a defence industrial strategy which demonstrates a concerted effort to identify those national defence capabilities that must be maintained, and those more efficiently addressed by foreign acquisition and/or cooperation. The third topic is the UK assessment of European defence cooperation, including the difficulties with such efforts and the impact of the controversial "re-evaluation" of the contract for the next generation of aerial tankers. The final topic is the UK experience with the Joint Strike Fighter program, in which the UK is the largest non-US participant, and which holds major implications on future military cooperation with the US Ultimately, the UK experiences show the benefits of more research on international efforts to identify best practices in acquisition management.

> “You never want a serious crisis to go to waste. Things that we had postponed for too long, that were long-term, are now immediate and must be dealt with. This crisis provides the opportunity for us to do things that you could not do before.”
>
> White House Chief of Staff Rahm Emanuel (Capital Journal, 2008).

Introduction

While the military procurement challenges facing the United States are enormous, it is important to bear in mind that the United Kingdom and other US friends and Allies are also confronting the task of pursuing critical acquisition programs at a time of exceptionally tight defence budgets. Although in monetary terms, the task for Washington is of greater magnitude, the decisions that are facing London and other capitals are of equal significance on a national basis. However, it is clear that the impact of Department of Defense (DoD) decisions will reverberate in defence ministries around the world, while the converse is not necessarily the case.

It remains beneficial for Allies to compare notes on valuable "lessons learned" from their individual acquisition experiences. There have been recommendations for change from domestic think-tanks and policy experts as well as from within the military. With resources dwindling, it arguably would be best to draw upon initiatives based on practice (and not just theory), and the best data to analyse would be the practice of other defence forces. If “business as usual” is no longer affordable, then it is useful to assess the practices of other defence forces to see what has worked elsewhere, provided more efficient management, and increased value for money.

There are innovative initiatives which have been undertaken by the UK in the area of defence acquisition in recent years, some of which warrant attention and consideration by other defence forces. UK participation in some of the most current key defence equipment programs provides lessons and insights that may be valuable to other states, particularly regarding the future of multinational defence programs.

Four critical areas and examples of UK defence acquisition are highlighted in this paper. First, the area of efficient capability management is examined, as demonstrated by the UK decision to acquire Boeing C-17s. Second, the example of UK defence industrial strategy is reviewed, indicating how it has moved the focus from a haphazard attempt to preserve as many jobs as possible to a serious assessment of which domestic military capabilities are essential for the nation. Third, the UK assessment of the general area of European defence cooperation practice is analysed, including commentary on the negative impact of the controversial "re-evaluation" under Congressional pressure of the US Air Force decision awarding Northrup Grumman/EADS the contract to meet future US aerial tanker requirements. Finally, the example of the UK experience with the Joint Strike Fighter program, particularly in the area of technology transfer, is assessed with a focus on implications on future multinational military cooperation led by the US.

In his outline of the eight steps needed for successfully transforming an organisation, John Kotter (1995) stresses that the first step is establishing a sense of urgency. In the UK Ministry of Defence (MOD), and probably in most defence establishments, that requirement has presumably been met. What is now important is determining what type of change is required. Assessing the experience of other defence establishments is useful in making better informed decisions, and the UK has taken innovative approaches to address acquisition challenges that warrant consideration and analysis.

Examining UK policy with an eye to possible use in the US is not a new exercise. In a recent report to Congress, the Government Accountability Office (GAO) (2008, December) review on the DoD use of performance-based logistics included an extensive examination of the UK MOD's experience with performance-based contracting. Similarly, John Schank

(2006) testified to the Senate Armed Services Committee about the RAND evaluation of the trends in the UK Naval Shipbuilding Industrial base, recommendations to the UK, and the lessons for the US industrial base.

There is no question that the UK still faces room for improvement in the area of defence acquisition, as has been emphasised by commentators like Bill Kincaid (2008). The MOD Major Projects Report from the UK National Audit Office (NAO) (2008a, p. 5) indicates that for the 20 largest MOD projects (with a combined estimated cost of £28 billion[1]), the estimated total cost of the projects increased during the 12-month reporting period by £205 million, and there was an additional total slippage in the programs of 96 months. The projected total increase in costs for these 20 programs compared with the budgeted cost indicates an increase of 12%, or some £3 billion and an aggregate delay for the programs of 483 months, 36% over the anticipated timetable at the time the project was approved (NAO, 2008a, p. 5).

However, the UK MOD has made a conscious effort to pursue innovative management processes and increase flexibility. There is also a willingness to seek out outside assessments and new approaches. It is notable that the MOD has frequently commissioned RAND to provide an outside perspective on projects ranging from the Type 45 destroyer (Birkler, Schank, Arena, Smith & Lee, 2002) to the UK nuclear submarine industrial base (RAND, 2005).

In a time of scarce resources, it is arguably important for defence establishments to seek out such different perspectives and compare national policies, practices and accomplishments. The common theme which runs through the four UK examples that follow is the value of pursuing innovative and flexible approaches to defence acquisition, which can arise from analysing the best practices of other defence forces. The UK has worked hard to try and pursue such an approach and be an exemplar of innovation. Its efforts, as well as those of other defence establishments, warrant greater research to address the challenges of defence acquisition.

Air Transport

All the indications to date are that the UK decision in 2000 to obtain Boeing C-17 transports was a very sound decision, not only because it was cost-effective, but it also met the critical requirements of the UK military. The House of Commons Defence Committee (2007, July 5) assessment was that:

> The leasing of four C-17 large transport aircraft, which are to be purchased when the lease ends, has greatly increased the MOD's strategic airlift capability and performed extremely well. We welcome the fact that these four aircraft will be purchased once the lease ends and that the MOD is to purchase a fifth C-17 aircraft. (paragraph 62)

In its response to the Committee report, the MOD (2007, October 12) echoed the view that the C-17 "has proved a great success on operations" (paragraph 12) and noted its announcement that it would purchase a sixth C-17 as part of its effort to enhance operational effectiveness. The acquisition of the C-17s (along with the earlier acquisition of

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[1] On April 3, 2009, 1 UK pound sterling equalled 1.46 US dollars.

25 C-130Js) has more than met MOD requirements, despite their having intensified with operations in Afghanistan and Iraq. While the C-17s originally were intended to provide strategic lift capability, their operational use in those two countries has been essential to UK forces.

The benefits of the C-17 decision have been amplified by the fact that the European A400M transport, launched in 1982, has still to commence flight testing. The House of Commons Defence Committee (2009) noted that once the MOD has a better fix on the extent of the delays in the A400M, it must decide whether "abandonment would be preferable, and to take timely decisions either to procure or lease other airlift assets so that a capability gap in air transport does not develop" (p. 3). Secretary of State for Defence Hutton stated in March 2009 that the government would make a decision with regard to continuing with the A400M in the beginning of July, adding that the UK "will not be content with a gap in capability" (Hollinger & Pfeifer, 2009).

To provide some background: In 1994, the UK announced that it would replace its aging C-130K Hercules fleet. Those 50 transports had been in the Royal Air Force (RAF) inventory since the 1960s. The MOD decided on a two-part replacement program (NAO, 2008b, p. 8). The first stage was replacement of 25 C-130Ks with 25 C-130Js from Lockheed Martin, which are an updated version of the Hercules. The second stage would be participation in the A400M program which would replace the other C-130Ks. Approval for participation in the A400M was achieved in 1997.

The C-130Js came into the UK inventory in 1998 and were fully operational by 2001. As the A400M timescales became increasingly questionable, the MOD recognised that it would need to find an alternate solution to meet immediate requirements. There was concern in the UK that the purchase of the C-17s would destabilise the A400M project, which provided opportunities for British industry, particularly in the areas of wings and engines. After extensive evaluation, Secretary of State for Defence Hoon announced on 16 May 2000 the decision to lease four C-17s.

It is important to note that the C-17s have handled a wide variety of missions that would have required a diverse and much larger fleet of transports. The C-17 has been a solid contribution to the RAF fleet and has clearly met UK capability requirements. With further delays to A400M accrued and with extensive C-17 operating experience, the UK has now decided that an outright purchase of the leased aircraft is now a more cost-effective option and has expanded the fleet to reflect the operational demands.

The C-17 decision and implementation are noteworthy for a number of reasons, particularly in view of the timeframe in which the decisions were taken. At the time transport options were being considered, Smart Procurement was still relatively new. To acquire these new capabilities, Smart Procurement had been introduced with the mantra of "cheaper, faster and better." Smart Procurement adopted a more streamlined approach to acquiring equipment capability by reducing the number of approval decision points (to Initial Gate and Main Gate) aligned to the new CADMID (Concept, Assessment, Development, Manufacture, In-Service and Disposal) procurement cycle. Smart Procurement was subsequently renamed Smart Acquisition, reflecting the wider scope of activities needed to deliver effective defence equipment capability. Guidance on an incremental approach to acquiring systems was also introduced with the process being managed by Integrated Project Teams (IPTs), comprising MOD, military and industry representatives.

At this time, the IPTs were also in the early stages of viewing decisions through the optic of best commercial practice. The MOD's Defence Procurement Agency had maintained its traditional focus on requirements, rather than capabilities, and was in the early phases of moving to a concentration on the latter. Despite that fact, the transport decision centred on capability requirements, resulting in acquisition of an air transport capability greater than sought which ultimately remained within budget. It is critical to note that although a strategic airlift capability was originally required, the C-17 also had a tactical capability that has subsequently been utilised and is reflected in the UK's follow-on purchase on a further aircraft.

The UK is working assiduously to implement Through Life Capabilities Management (TLCM). One key structural component is a change in process. TLCM takes a programme approach to delivering capability, with a single Capability Manager (the Programme Manager) having responsibility for all Strategic Mobility capability through life, including C130J/K, C-17 and A400M, focusing not on specific projects or equipment, but on the capabilities that need to be delivered. The Capability Manager, supported by a wide team across all the Defence Lines of Development (Infrastructure, Personnel, Equipment, Organisation, Doctrine, Training, Logistics and Information), is now in a better position to judge the trade-offs required to provide effective capability to the front line. This step change has been supported by a huge effort to embed a change of culture in the MOD, which takes an integrated view of acquiring capability, breaking down the traditional single-service stove-pipes.

While European defence cooperation is addressed later, it is useful to briefly review UK views regarding the A400M. France and Germany have decided to stay with the A400M as they believe it is imperative to establish a European airlift capability. However, in view of continued program difficulties and delays, it is arguable that the A400M may carry too high a price for London to pay just to establish the UK's European credentials. It is also important to note that BAE Systems has divested itself of its stake in Airbus, leaving no significant UK industrial investment (though there are UK participating firms) in the A400M project.

Europe has moved forward with efforts to promote defence cooperation, including the A400M. The organisation for Joint Armament Cooperation (OCCAR) was created in 1998 to facilitate and manage European cooperative armament programs. It is noteworthy that NATO (2009) and OCCAR signed an agreement on security of information on 5 February 2009 which protects classified NATO data given to OCCAR to meet NATO requirements and conformity with NATO standardisation agreements. This is critical as NATO participates in three projects managed by OCCAR: the COBRA Target Locating Radar, the TIGER helicopter, and the A400M.

But while the OCCAR Business Plan (2008, p. 5) indicates a staff of over 200 and a budget of some four billion Euros, its efforts to tighten performance targets have not had a major impact on the programs it manages. To return to the A400M, the transport requirement was announced in 1997 by eight European nations, the decision of the Airbus A400M was made in 2000, the decision on the engine was made in 2003, OCCAR (2008, p. 11) lists the total program cost as 20.3 billion Euros—and the plane has yet to have its inaugural flight. The UK has reduced its original pledge to purchase 45 A400Ms down to 25, and there remains speculation it may be considering reducing the number even further.

The UK showed great flexibility and innovation in addressing its air transport requirements. The key "lesson learned" from the C-17 experience is that the UK made a decision focussed on capabilities. The US, UK, Canada, Australia and New Zealand have adopted a capabilities-driven acquisition process. Whatever the shortfalls in implementation, it is worthwhile for defence establishments to seriously consider and analyse the benefits of a capabilities-driven approach. The UK's air transport decision is a good example of the results when the focus is not on equipment, but on capabilities.

Defence Industrial Strategy

The political imperative to protect domestic jobs and industries is always present and intensifies during hard times. When coupled with the legitimate concern about retaining key indigenous defence capabilities, protectionism in the defence industrial area is a powerful force. The fact that this political, economic and security priority is often at odds with the acquisition of the best military capabilities at the best price is an eternal problem. As all military forces seek to grapple with these difficult decisions, it is worth considering the approach taken by the UK in generating an innovative and extensive *Defence Industrial Strategy* (*DIS*) (MOD, 2005), released as a follow-on to the wider *Defence Industrial Policy* published in 2002.

The *DIS* concisely notes that the strategy carefully considers:

> which industrial capabilities we need to retain in the UK to ensure that we can continue to operate our equipment in the way we choose to maintain appropriate sovereignty and thereby protect our national security. The Strategy sets these out, and explains clearly for the first time which industrial capabilities we require to be sustained onshore, noting that—as now—there are many that we can continue to seek to satisfy through open international competition. (Foreword)

The *DIS* makes a concerted effort to outline in a more transparent manner how defence procurement decisions are made. It also seeks to assist UK industry in its future planning by seeking to be more open on future UK defence acquisition plans. Perhaps most important, the *DIS* puts an emphasis on the need for a change in the relationship between government and industry as well as a change in behaviour between the two. As a structural mechanism for actually monitoring progress of implementation of the *DIS*, the National Defence Industries Council is tasked to follow the extent of progress, and the *DIS* is reviewed in every defence spending review period.

The *DIS* is comprised of three sections. Section A, the "Strategic Overview," is extensive, and provides a thorough analysis of the key overriding factors in UK defence policy and acquisition. Section B is a "Review by Industrial Sector and Cross-cutting Capabilities." The extensive assessment of 12 separate sectors and categories is the heart of the document, and provides an impressive detailed analysis. Section C concludes with discussion on "Implementing the Defence Industrial Strategy."

Perhaps the most critical aspect of the *DIS* is simply the effort undertaken by the MOD to seriously analyse and put forth in a coherent structure what is a critical domestic defence industrial capability. The 145-page document is an essential first step in generating a clear national policy on this critical issue. It assesses the various parameters and aspects of UK national defence requirements, determines areas where cooperation with non-UK firms carries an acceptable risk and benefit, and candidly recognises those areas where the UK cannot maintain a domestic industrial capability at an acceptable cost. The focus on such a detailed analysis in the *DIS* is borne out by the fact that Section B is roughly half the document.

Certainly the *DIS* and resulting UK policy seek to protect the defence industry, which the MOD has judged to be critical from threats to its viability. But there is no “buy British” backdrop to the *DIS*. To take a larger overview of UK defence acquisition policy, there is a UK willingness to enter into multinational arrangements when the need is clear. In 2006, the European Defence Agency (EDA) reported that a total of 6.66 billion Euros was spent on projects or programs involving two national defence structures, one of which is an EDA participating state. The UK was far and away the largest practitioner, with 2.58 billion Euros of such collaborative projects, well beyond the 1.63 billion Euros conducted by France (EDA, 2006a, p. 22). Of the specific subset of European collaborative procurement that year, the total spent by EDA states was 6.07 billion Euros, of which the UK comprised 2.26 billion Euros (p. 23). Just over 30% of the UK’s total equipment procurement was conducted in a collaborative program with another EU member state (p. 24).

There are key lessons from the *DIS* exercise and experience which are worth noting. One critical point is the fact that this issue received serious attention from senior MOD political and uniformed military leadership and led to the Defence Acquisition Change Programme which, in turn, introduced Through Life Capability Management and the merging of the previously separate Procurement and Support functions. A top-down process was critical to instituting a change in culture and attitudes among the MOD personnel working on acquisition. That may have been even more critical than the changes in processes and structures that were implemented.

A clear, high-level political imprimatur was essential to generating a cooperative attitude from industry, a key outcome worth serious consideration. The UK does much more outsourcing of service contracts than other European states. In 2006, the UK comprised some 10 billion Euros out of a total reported outsourcing of 14.1 billion Euros (EDA, 2006a, p. 21). The UK also has pursued partnering initiatives, a good example of which is the establishment of the Complex Weapons initiative (House of Commons Defence Committee, 2009, p. Ev102), which was part of the *DIS*. The MOD announced in 2008 that six study contracts would be undertaken by Team Complex Weapons, an industry grouping led by MBDA (UK), Thales UK, Roxel and QinetiQ, with the MOD as a partner.

The focus of the Complex Weapons initiative is on missiles and guided weapons. The MOD pledged long-term support for key programmes and technology, with industry pooling resources and streamlining personnel. The common stated goal was to move from bespoke weapons development to flexible, modular weapons design. The six assessment-phase contracts totalling £74 million were an effort to keep skills in these critical areas within the UK, and secure operational sovereignty. The effort is in its early days, and commentators (Hewson, 2008), note that a long-term source of steady funding is critical for success. But such efforts to establish a cooperative, rather than adversarial, relationship will be even more essential for defence and industry as funding becomes ever more difficult to obtain.

To cite some other examples: a Private Finance Initiative is being considered to provide the RAF with refuelling tankers for normal operations, with surplus air-transport capacity available for lease for civilian use whilst retaining a surge capacity for major operations. Similarly, the RAF is considering putting its extra capacity for pilot training to use to train pilots for commercial airlines.

The MOD has also put the goals and guidelines of the *DIS* into practice on larger acquisition programmes. The block construction of the Type 45 destroyer, the first of which was recently unveiled to great public support, is the most high-profile example. The Type 45 will provide the Royal Navy's primary anti-air warfare capability for over 30 years. And while the announced delays in the two planned Future Aircraft Carriers (CVF) tarnishes the programme, the cooperative effort with France is an indication of an effective international programme, and the work of the Carrier Alliance is a concrete example of a mutually beneficial relationship with industry.

Once again, what is perhaps most noteworthy about the *DIS* is the fact that the UK made the concerted effort to organise its priorities and extensively assess requirements, costs and opportunities regarding defence industrial capabilities. Where the decision has been made on systems that need to be produced domestically, there is an effort to establish a long-term relationship with the suppliers to ensure that capability is maintained. One example is the MOD completion of a “Foundation Contract” with BAE Systems in 2007. Such arrangements admittedly change, if not eliminate, the requirement for competition, and can effectively lock in the status quo. However, the UK decision is the result of a policy calculation of what needs to be preserved, rather than an instinctive reaction that because it is domestic, a firm must be maintained.

The UK MOD has been equally rigorous in analysing the down-side of allowing defence capabilities to be located off-shore. In a report provided by RAND (Arena et al., 2005) for the MOD on the UK's naval shipbuilding industrial base, the authors addressed the consequences of foreign procurement of naval vessels. Emphasising that its focus was on UK shipbuilding capacity, the authors noted that there were several disadvantages. In addition to the domestic economic benefit of having ships built in UK shipyards, a foreign purchase would generate a concern that the UK would not be able to acquire the latest technologies such as advanced sensors. The UK also would run the risk that it would not acquire ships that would meet its requirements or leave it open to political pressure to delay or even cancel the sale (p. 157-158).

It is noteworthy that in a subsequent study for the MOD, the RAND researchers concluded that the UK would "need to preserve and sustain several key technical skills in the maritime domain" in order to "preserve its ability to design, build, and support complex warships and submarines" (Pung, et al., 2008, p. xv). The authors focussed in particular on the need for "detailed designers and professional engineers involved in various stages of surface ship and submarine acquisition and support" (p. xv). Such considerations have clearly been taken into account in structuring and concluding various naval programmes, such as the Type 45 and the CVF.

Certainly more needs to be done. In submissions to the House of Commons Defence Committee (2009), the Defence Industries Council noted that many steps have been taken toward embedding the principles of the *DIS* into business practice. But the "overall progress has been much slower than industry would have wished" (p. 67). The Committee highlighted the concern expressed from industry that there is still insufficient transparency about MOD plans. In particular, it noted that an updated version of the *DIS* should have been published in December 2007 and has yet to be presented. The Committee criticised the failure to publish the updated document, adding that it considers that "its continuing absence increases the risk that the UK Defence Industrial Base will not be able to meet the future requirements of our Armed Forces" (p. 76).

Unfortunately, since Lord Drayson, who as Minister (Defence Equipment and Support) was the main driving force behind the *DIS*, resigned in early 2008, the momentum behind the *DIS* has decreased. Political and economic uncertainty has increased the pressure for a Strategic Defence Review in the UK, and it appears unlikely that the next edition of the *DIS* will be published in the near future. There is also concern about whether it is possible to generate a follow-on *DIS* programme that is affordable. As noted above, industry now perceive a lack of commitment by the MOD to a sustainable industrial strategy and this impression has been reinforced by an ongoing lack of transparency in the MOD's planning activities, despite promises to the contrary.

The UK approach in the area of a defence industrial strategy is innovative and extensive. Like any other country, the UK is concerned about the possibility of being held hostage to foreign sources of key military equipment. It is also cognisant of the political pressure to protect "British jobs for British workers." However, to summarise the "lesson learned" in this example, the value of the *DIS* is that it provides a more stable framework in which to conduct the policy discussion and reach the programmatic decision. Defence establishments that do not undertake such a study are more vulnerable to wide-ranging, ad hoc debates which focus on the latest set of unemployment figures, rather than strategic military considerations.

European Defence Cooperation

Political factors and job preservation are particularly relevant with regard to consideration of European defence cooperation, the third area in which UK experience and policy provide a number of noteworthy points about the utilisation of flexible, innovative approaches. First, as indicated by UK acquisition decisions and endorsed in the *DIS*, the UK is interested in pursuing worthwhile multinational projects. This is driven by the focus on capabilities. It is accentuated by the prospects with regard to overall defence spending and the need to focus on continuing operations, resulting in an even bleaker picture on available acquisition funding.

However, the second point is that there are limits to UK support for European initiatives. The A400M delays and the difficulties which plagued the Typhoon/Eurofighter have diminished UK enthusiasm for such efforts. Certainly the UK will be open to hearing the case for European projects, and if they are well thought-out and in line with the *DIS*, will be willing to pursue such projects. The agreement with France on the CVF is an indication that the UK continues to be ready to conclude arrangements if the programmes meet policy goals and the numbers add up. On the other hand, the UK Type 45 destroyer programme resulted from a decision to withdraw from a European programme when work-share arrangements and misalignment of requirements did not satisfy the UK. Indeed, the Type 45 programme arose because the UK was not satisfied with two European attempts to establish a joint destroyer programme: the NFR-90 and the Horizon CNGF.

It is clear the UK will be closely monitoring the track record on European military programmes and will want to see if such efforts will become more efficient at delivering capabilities, rather than just parcelling out jobs and funding. It would appear that European states and trans-European organisations are taking steps in the right direction. The question is whether they are large enough steps. Many European actions continue to be merely restatements of lofty goals, without concrete action. This is exemplified by the November 10, 2008, declaration of intent among 12 European countries to establish a European Air Transport Fleet. This project, taken within the EDA, recognises the importance of a

European airlift capability, but does nothing to move the generation of concrete capabilities forward. Citing another example, there are constructive initiatives undertaken by the EDA and individual states to promote European defence cooperation. The "Guide to the EDA's new European Defence Equipment Market" notes that the EDA's "Electronic Bulletin Board" provides an opportunity for European firms to bid for defence contracts in virtually all other EU member states, and is a small step toward generating a Europe-wide defence equipment market (EDA, p. 3).

The question remains whether increased opportunities to bid will actually generate greater willingness for national governments to give contracts to firms from other nations. The EDA generated an Intergovernmental Regime in Defence Procurement, which operates within Article 296 of the EC Treaty and is aimed at enhancing international competition for public procurement. Similarly, the associated Code of Conduct is also aimed at promoting more equal treatment of suppliers, promoting transparency. However, the EDA itself makes clear that all these steps can only offer an improved approach for changing the way Europeans handle defence acquisition, and “It now falls to national governments and industry to take full advantage of it" (p. 8).

As a result, it would appear that the public and political sentiment in the UK would be to acquire the last generation of US equipment, rather than the next generation of European capabilities. For example, if the clock could be rolled-back, there arguably would be general support for acquisition of destroyers with the Aegis system rather than initiating the Type 45 destroyer project. There are other reasons for preferring acquisition from the US: national security policy, the desire to be on the cutting edge of military technology, history, etc. The numbers are clearly in favour of military cooperation with the US. The US spends twice as much on defence as Europe combined, outspends Europe six to one in defence R&D, and, most critically, targets 35% of its defence spending on investment compared to 20% in Europe. (EDA, 2006b, para 67). For all of these reasons, there is arguably a strong sentiment that cooperative efforts centred on the US may be the optimal way to achieve future military capabilities, especially at the high end of the scale. While each European state will make its own preferences known in its policy decisions, it would seem from the UK perspective that many, if not most, European countries would agree on the need to work with the US.

However, only one state can prevent the US from assuming that essential role in military development and acquisition programs: the US. That is arguably the generally accepted UK view. And from a UK vantage point, it may well be the general European perception. While the JSF, which has a particular significance for the UK, will be addressed later, it is important at this point to address the ramifications of the action by the US Congress in 2008 to overturn the DoD decision to award the aerial tanker contract to the Northrup-Grumman/EADS proposal for the KC-30 tanker. Simply put, this decision has damaged the European desire to work with the US in the area of defence acquisition.

To provide a short history: EADS had made no secret of its desire to enter the US market, and the DoD requirement to find a new aerial tanker to replace the KC-45 provided a unique opportunity which EADS ardently pursued. Boeing was the only obvious source for the new tanker, and there were no viable competitors. Indeed, Congress itself recognised and made clear its views on the importance of ensuring there was a competition. EADS then made extra efforts to acquire the political support it would need. It partnered with Northrup-Grumman on the tanker proposal, emphasised the KC-30 would be an American tanker, and proposed to maximise US domestic content by having the Airbus A330 airframe produced in the US.

The Air Force decision of February 29, 2008, to award the contract to the Northrup-Grumman/EADS consortium could well have marked a critical juncture in the promotion of multinational defence acquisition. From the UK perspective, the stereotypes of the way the US and Europe view each other with regard to defence acquisition carries a great deal of truth. The US believes it has the best military technology and Europe is pursuing protectionist policies which focus on jobs and money rather than military capabilities. In an "objective" competition, Europe would buy US equipment and get more value for money. For Europeans, there is a policy concern about becoming reliant on US military equipment and a political focus on European jobs. European defence industry believes it has the technology and capability to contribute to a modern military program. But as the prognosis for European defence spending is bleak, it wants an opportunity to enter the US market, since that is where the money can be found. In this respect, BAE System's approach has been to re-invent itself as a global company with wholly owned US subsidiaries who are able to market themselves in the USA as US companies under the BAE Systems, Inc., banner.

The decision in favour of Northrup-Grumman/EADS was quickly met with a protest by Boeing, loudly supported by members of Congress, and was subsequently sustained by the Government Accountability Office [GAO] (2008b) in its June 18, 2008, decision. The GAO cited seven reasons for sustaining the Boeing protest, all of which focussed on shortcomings in the Air Force selection process, and recommended the competition be conducted again.

It might be fair to state that the GAO decision has not been widely read by Europeans and that they only know that the GAO is an arm of the Congress. More important, the perception is that procedural flaws only became material when a "foreign" consortium won the competition. Such a perception can have an impact on defence industrial cooperation. First, it casts doubt on the US willingness to engage in an "objective" competition assessing cost and capabilities. Second, it validates the views of some that even if European firms partner with US defence contractors, they will still not be able to enter the US market. Third, the Congressional impetus for the re-opening the decision provides validation for those who argue that the US also will act to preserve its sovereign military capabilities as well as American jobs, so there is no reason for Europe to bow to US criticism on this count.

Finally, the re-opening of the decision damages the goal of promoting competition, emphasised by Congress itself. There was no competitor to Boeing for the next generation of tankers, and it was Congress which pressed for a competition. A situation with no competing US firms may become increasingly common in the future, and in a situation in which there are few bidders, they have power due to the threat to not participate in the bidding process (Franck, Lewis & Udis, 2008, September 30, p. 36). In view of the outcome of the tanker decision, European firms will be reluctant to pursue the time and expense of trying to provide a competitive bid which it will not be allowed to win.

The history of the aerial tanker decision has damaged the European perception of the opportunities to cooperate with US firms and enter the US market. It has also strengthened the case for European defence cooperation, particularly in areas where programs cannot be funded by individual defence budgets. As stated previously, the UK believes that there are many reasons to support cooperative military programs centred on the US as the optimal path for increasingly expensive investments in defence programs. Discussion of UK support for such efforts leads to the program which currently has the greatest impact on views of US-led development projects: the JSF program.

Joint Strike Fighter

The fourth and final example which is valuable to analyse is the JSF, the largest multinational development program in history and a prime example of the UK commitment to pursuing innovative approaches to defence acquisition. It is a high-profile project which has numerous aspects, each of which could justify an entire discussion. There is, however, one key aspect which needs to be highlighted, particularly in a US forum: the impact of US technology transfer rules on future multinational military development programs.

This is not simply the litany of long-standing complaints about US technology transfer rules and the International Trafficking in Arms Regulations (ITAR). The high-profile US-UK dispute over JSF source codes, which needed to be resolved at the level of President and Prime Minister, is merely the most notable case of the difficulties faced by US partners in such endeavours. Simply put, the application of US technology transfer rules as exemplified in the JSF damages the prospects for multinational military development programs centred on the US If that is the perception from arguably the closest US ally, one which is committed to cooperative programs with the US whenever possible, that is an indication of the seriousness of the threat posed by US regulations and practice to the future of US-led programs.

It is important to begin with a short history of the program to indicate why the JSF is such a significant commitment (if not a gamble) by the UK. In the 1990s, the US Navy, Marine Corps and Air Force were working on a next-generation strike aircraft. In 1996, the JSF project was announced by the US At about the same time, the British Royal Navy was also looking at new Future Carrier Borne Aircraft capability for its CVF programme. The US and UK combined efforts in this area. The requirements of the US services drove the program, but the UK focus was on an attack aircraft with advanced Short Takeoff and Vertical Landing (STOVL) capabilities so that it could operate from forward battlefields as well as from aircraft carriers. The UK preference for the JSF was confirmed in a 2001 MOU with the US In 2002, the UK selected the STOVL variant to meet its future requirements, with a positive review of the JSF program and the STOVL design completed in 2005 (NAO, 2008b, p. 45).

It was important that as an indication of US support for this endeavour, the Office of the Secretary of Defence sent down instructions that the JSF program should emphasise international participation, and there was a consensus that the UK would participate in the program (Franck, Lewis & Udis, 2008, January 29). The US and UK engaged in extensive, detailed exchanges on the nature of the program and the UK role, compiled in the US-UK Engineering and Manufacturing Development Framework MOU. Comprised of agreements, letters and other supporting material, it provides the details of the US-UK relationship on JSF.

While decisions on specific numbers of fighters to be purchased were not required at the outset, the Royal Navy and Air Force were looking at the purchase of some 150 STOVL fighters to replace the Harriers. The UK participation began at the outset of the program, and the UK is the only "Level 1" partner contributing some $2 billion to the system design and development phase (Bolkcom, 2009). That designation means that the UK has significant access to most aspects of the program as well as the ability to influence requirements and design solutions. And the UK will not have to pay the non-recurring R&D cost recoupment charge that normally accompanies the purchase of US military equipment and will receive a share of the levies on sales to third parties.

However, the UK commitment to the JSF is not primarily based on programmatic considerations such as cost savings, but on a key national security determination. The UK made a policy decision on the need to retain an aircraft carrier capability, and the requirement for carrier-based fighters derived from that critical decision. The recent announcement by the Defence Minister of a postponement of the aircraft carrier production schedule by another two years due to constraints on the defence budget is obviously critical for that specific programme. The delays mean that the two carriers now have projected in-service dates of 2015/16 and 2016/17. However, that decision on the carriers is separate from the discussions on the JSF fighters that will operate on those carriers.

There is no doubt that the UK has made a significant wager in tying itself to the JSF program, for if there are major problems with the fighter, the UK will need to generate a "Plan B" to avoid having its aircraft carriers merely serving as floating platforms. If the STOVL version of the JSF does not emerge, the UK would be faced with the challenge of re-designing ships so that, for example, they would have new catapults. As of April 2007, the UK plan had been to bring in a total of 138 JSF fighters, with the bulk of the acquisition to begin starting in calendar year 2012 (Joint Strike Fighter Program Office, 2007). The MOD is already in the process of working through modelling and simulation to optimise the safety and operability of the new aircraft carriers and the JSF when the fighters arrive (Scott, 2009).

The delays and cost increases associated with the Eurofighter program were a factor in the UK consideration of participation in the JSF. In the aftermath of the Eurofighter experience, the fact that the JSF was structured so that the most competitive firms would win contracts was appealing to the UK, and in line with the goal of pursuing more efficient acquisition programs. And the fact that the US was providing the overwhelming amount of funding for a program with cutting-edge military technology was significant to all the participating states, including the UK.

Adding to the list of factors pressing the UK to participate in JSF, the Defence Industrial Strategy places great emphasis on the need for the UK to remain interoperable with Allies, particularly the US It is also noteworthy that British industrial participation amplifies the UK focus on the JSF project. BAE Systems is the largest non-American participant in the JSF and has hoped for around £14 billion in development and production contracts (McGhie & Gee, 2006). Such a high level of BAE participation is to be expected, as it does the majority of its business in the US and is one of the largest suppliers to DoD. It is also noteworthy that BAE participation in the JSF was viewed in the UK as a seal of approval on the British ability to participate in cutting-edge military projects. Trade and Industry Secretary Patricia Hewitt said that BAE participation “proves that British companies can compete with the best in the world for the big contracts” (”Jet contract,” 2001). And there are potentially significant economic benefits. A Congressional Research Service (2009, p. 17) study notes that the DoD conducted a 2003 assessment which determined that partner nations could potentially earn between $5 and $40 of revenue for every $1 invested in JSF program contracts.

As the technology transfer issue came to dominate the discussions on the JSF, it is also important to note the backdrop for US-UK military cooperation. Franck, Lewis & Udis (2008, January 29) note that it is estimated that 99.8% of licenses for UK-US transactions are approved, which accounts for some 8,500 items with a value of $14 billion, indicating that the routine operation of bilateral defence cooperation and technology transfer proceeds without friction. Moreover, the extent of UK-US defence industrial interconnection has increased substantially. Aside from BAE, UK firms have acquired 50 aerospace and defence firms in the US since 2001, which constitutes some three-quarters of all foreign investment in the US defence sector (p. 20-21). Major American defence contractors are established in the UK or have acquired operations or set up a presence in the UK.

With this backdrop of increasing cooperation, the specific problems that arose regarding access to JSF source codes generated doubts in the UK regarding US-led military cooperative efforts that could have been avoided. Initially, commentary on the JSF was full of praise as a model for future multinational defence cooperation. That turned to criticism of the JSF as an example of why such efforts may not pass an all-encompassing cost-benefit analysis.

It is a key operational requirements as well as a matter of sovereignty for the UK to be able to have the information needed to integrate, upgrade, operate and sustain the JSF as required. As a practical matter, the UK cannot buy into a system which requires a US maintenance team to take care of any problems that may arise or to arrange for required modifications. The House of Commons Defence Committee (2005) reported that:

> It is vital that the UK gets all the information and access to technology it requires from the U.S. to have 'Sovereign Capability'—the ability to maintain the Joint Strike Fighter aircraft and undertake future upgrades independently. The UK must receive adequate assurances that it will get all the information and access to technology it requires before the programme is too far advanced. If these assurances are not given, it is questionable whether the UK should continue its involvement in the programme. (p. 3)

The Committee (2005, p. 29) emphasised that the UK could not accept a situation in which it could not operate the JSF independently of the US and pressed the Defence Minister to act to ensure the UK would have operational independence. It noted its expectation that the MOD would set a deadline by which the assurances on sovereign capability would be obtained from the US In December 2006, as the source code issue was heating up, the Committee warned that an assurance from the US was needed by the end of the year that it would provide the UK with all the requested technical information. In the absence of such an agreement by the end of 2006, the committee called on the government to develop a “plan B” to obtain alternative aircraft (”MPs warn,” 2006).

From the UK perspective, the history of the political discussions to resolve the source code issue is not the best advertisement for multinational programs. Indeed, the fact that such issues never seemed to be fully resolved added to the frustration with US policy and practice. The technology transfer dispute had already been addressed in 2004, when Secretary of State for Defence Hoon wrote to Secretary of Defense Rumsfeld on the issue and referred to the fact that the US had signed an outline agreement on defence technology cooperation in 2002 (O'Connell, 2004). It is noteworthy that PM Blair believed he had reached an agreement with President Bush in May 2006, but, however, the dispute lingered on unresolved until the end of the year (Baldwin, 2006). Indeed, in the Defence

Authorization Act for Fiscal Year 2007, Congress, aware of UK concerns over this issue, advised the Secretary of Defence to share technology consistent with the national security interests of the US and UK (Bolkcom, 2009, p. 18).

The importance of technology transfer in cooperative arrangements with the US was already set out in the *DIS*, where the significance of the US defence market and US defence spending was acknowledged. The DIS observation on the technology transfer point warrants a full recitation:

> To meet our own sovereign needs, it is important that we continue to have the autonomous capability to operate, support and where necessary adapt the equipment that we procure. Appropriate technology transfer is therefore of crucial importance. This is so for any cooperative project, but in practice difficulties have arisen particularly with the U.S., whose technology disclosure policy we have found less adapted to the needs of cooperative procurement than those of our partners in Europe. To reiterate, this is not about gaining competitive advantage for UK industry; it is about being confident that the equipment we buy meets the capability requirements against which it is procured and can be modified effectively to meet emerging requirements through life. We fully recognise the need to ensure that intellectual property is protected, and that appropriate measures are put in place to ensure this; security is a key issue for us, just as it is for the USA. But a certain degree of technology transfer is required if we are to be able to fully cooperate with the USA (or any other partner) on our equipment programmes. What we are striving towards is an agreed framework which facilitates this whilst ensuring that our mutual security needs are met. (MOD, 2005, December, p. 45)

Difficulties with US practice arise even when it is not the most sensitive technology. One Lockheed-Martin employee noted that the restrictions on technology transfer have been “far more cumbersome and impenetrable than originally envisioned” and that it is necessary to ask for Washington’s approval of “even unclassified information exchanges” (Metz, 2005, p. KN3-7). Such requirements make it difficult for partners to participate, and generates a large administrative burden on the team members, who face the requirement that “all information is releasable under penalty of jail terms—not a conducive atmosphere for co-engineering a product” (p. KN3-7).

It is worth noting that the report of the Inspector General (IG) of the Department of Defense (2008) on security controls regarding JSF classified technology assessed seven applications from Northrup Grumman and BAE systems for detailed review. In addition, the IG's office evaluated security reports on BAE Systems facilities. While the assessment from the IG's office was a frank statement that JSF advanced technology "may have been compromised by unauthorized access at facilities and in computers at BAE Systems" (p. ii), the specific criticism was that DoD did not always use sufficient controls to evaluate potential unauthorised access to such technology (p. i). Indeed, the specific recommendation with regard to BAE Systems is that the Defence Security Service (DSS) could have bolstered its efforts by collecting, analysing and retaining security audit reports completed by BAE Systems, a point on which the Director of DSS concurred. The other recommendations involved the actions of DSS.

Now that the source code issue has been resolved, the JSF is once again a low-profile project. The House of Commons Defence Committee (2009) simply noted that the MOD has assessed that the JSF program is "progressing well" and the Committee would monitor the progress of the program (p. 47). Secretary of State for Defence Hutton announced in March 2009 that the UK would purchase three F-35B operational test aircraft, indicating the UK commitment to the Operational Test and Evaluation phase of the JSF (JSF, 2009).

Unfortunately, that does not erase the contentious history. If the JSF is an example of the future of multinational military cooperative programs, the source code dispute has clouded the picture. In late 2006, with the issue of source codes at its most contentious, an unnamed UK MOD official was quoted as stating, “If we can’t trust the Americans to provide this, then you would have to ask what else we should be doing with them in defence terms” (Baldwin, 2006).

It is unfortunate that the US-UK Defence Trade Cooperation Treaty, signed in 2007, is still on hold. In September 2008, the Senate Foreign Relations Committee deferred a decision on ratification of the defence trade treaties with the UK and Australia until 2009 due to "too many unresolved questions" about both treaties (Wagstaff-Smith, 2009). The goal of the treaty, to cut red tape in the bilateral exchange of defence goods services and information, would have been a productive step forward.

On the other hand, such complaints about US policy are long-standing, and it is not clear how heavily they will weigh on the decisions of other nations to work with the US on military projects. As Franck, Lewis and Udis (2008, January 29) point out, “very few national military establishments can generate sufficient orders to sustain a weapons source of efficient size in any category” (p. 17). And with the rapid growth of military technology (and the concomitant growth of costs) the essential nature of the US in any development program will clearly increase.

However, the US should consider whether it can afford to be indifferent to the willingness of other nations to participate in, and carry some of the costs of, such defence programs. Spreading the burden of large development costs would presumably be appealing to the DoD. Increasing costs also have ramifications with regard to the production phase of future programs. It is an open question whether DoD contracts alone would be sufficient to sustain US military contractors.

The Congressional Research Service has noted that while the US aviation industry is positioned to compete in the growing global market for civil aircraft, "the extent to which such economic conditions may preserve an adequate US defence industrial base for the development and production of combat aircraft is debatable, however, given the significant differences between civilian and military aircraft requirements and technologies" (Bolkcom, 2009, p. 17). Even US firms and the DoD may need to focus more on overseas sales to sustain programs. And if the US wishes to generate significant sales to other nations, then it is important that such equipment address the fundamental issues of operational requirements and sovereignty which have been critical to the UK in the JSF.

If the JSF experience is an indication of wider structural problems, it suggests that multinational military development programs may be too difficult to be politically or economically feasible. Technology transfer issues may generate too much friction. Difficult decisions on the awarding of contracts may be too hard to overcome. Increased costs may not be sufficient to counter-balance political and programmatic challenges. The extent of the obstacles to multinational projects should be more thoroughly researched and analysed.

If these problems are indeed too difficult to overcome to allow for efficient multinational development programs, then perhaps the better option might be for multinational acquisition programs. In such arrangements, there would be fewer states participating in development and more states signing up for purchase of the equipment. This could reduce the impact of some of the more contentious issues while increasing interoperability. However, there would still be significant difficulties, especially political problems, and technology transfer problems would only be reduced, but not eliminated. Once again, it would be important to more thoroughly research and analyse the potential benefits of greater multinational acquisition programs. If the structure of such arrangements allows for more efficiency in development and production, and addresses the concerns of individual military establishments, it might be a more cost-effective option.

Conclusion

To return to a central theme of this paper, it appears to the UK that scarcer resources and increasingly expensive military projects make it imperative to look closely at innovative approaches to defence acquisition. While new theories should be welcomed and encouraged, it is far less speculative to study the concrete "lessons learned" from the practice of other defence establishments. The goal of examining these four critical areas of UK defence acquisition was not to indicate that the UK has a formula or solution. Instead, it was to highlight new approaches to new challenges and the results of some innovative practices.

The C-17 decision indicates the benefits that can be obtained by focussing on capabilities. The UK Defence Industrial Strategy shows the value of a serious assessment of which domestic military capabilities are essential. The UK view of European defence cooperation theory and practice provides a sobering assessment of its shortcomings. And the UK experience with the JSF indicates the extent of the difficulties generated by US technology transfer and export control policies to promoting military development programs led by the US.

The expectation is that commentators will have other views on these UK examples. From the UK perspective, that is the point: close scrutiny and analysis of practice in other nations is an important exercise for any defence force, particularly in these financially challenging times. It would be valuable to intensify research on the comparative policies and practices of various defence establishments. And it would be instructive to bear in mind the approach taken by the defence industry: increasingly ignoring national boundaries, and working to ensure that they can operate and transfer expertise across boundaries.

At a time when defence budgets are under pressure and the use of the word "crisis" may not be an overstatement, it is important for military establishments to reassess how they are conducting defence acquisition and to consider new and innovative ways of doing business. In short, there is no more appropriate time to intensively research and analyse the “lessons learned” from the wide range of national defence acquisition experiences.

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Panel 10 - Implementing Open Architecture in Weapons System Development

Wednesday, May 13, 2009

3:30 p.m. – 5:00 p.m.

Panel 10 - Implementing Open Architecture in Weapons System Development

Chair: William P. Bray, Director, Integrated Combat Systems, PEO Integrated Warfare Systems

Discussant: Victor Gavin, Executive Director, PEO Littoral and Mine Warfare

Application of Model-based Systems Engineering Methods to Development of Combat System Architectures

Mike Green, Naval Postgraduate School

Software Licenses, Open Source Components, and Open Architectures

Thomas Alspaugh, Hazeline Asuncion and **Walt Scacchi**, University of California, Irvine

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Chair: Mr. William P. Bray is currently the Director of Integrated Combat Systems for PEO IWS. In this position, Bray is responsible for systems engineering activities across the PEO, development and execution of the Surface Navy Open Architecture strategy, and the development of an integrated POM submittal for the PEO. As a collateral duty, the Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN RDA) designated Bray as the Deputy for the Joint PEO Single Integrated Air Picture (SIAP) in September 2006.

Bray was appointed to the Senior Executive Service (SES) in August 2006 and has 24 years of government service.

During the period of August 2006 through November 2008, Bray was the Major Program Manager (MPM) for Surface Navy Combat Systems. This included the program management and execution for the development, deployment, and in-service management of Combat Systems on the AEGIS Cruisers and Destroyers and the Ship Self Defense System (SSDS) that is on Carriers and Amphibious class ships. In this capacity, he managed a budget of approximately $650 million a year, and $4.1 billion across the FYDP and across all appropriations, and managed a headquarters organization composed of approximately 70 military and civilian personnel.

Prior to this selection, Bray was the Director for Naval Architectures and Integrated Combat Systems in the Office of the Deputy Assistant Secretary of the Navy for Integrated Warfare Systems (DASN IWS) within the Office of the ASN RDA from April 2004 until August 2006. He was responsible for the oversight and execution of a select portfolio which included Joint programs and initiatives such as SIAP, Naval Integrated Fire Control–Counter Air (NIFC-CA), Joint Battle Management Command and Control (JBMC2) and Integrated Air and Missile Defense (IAMD) Roadmaps and Navy Combat Systems.

In July 2003, Bray was the Mission Capability Manager in the Naval Sea Systems Command (SEA 06), Washington Navy Yard, DC, where he led efforts to assess the Sea Power 21 Pillars of Sea Shield, Sea Basing, Sea Strike, and FORCEnet for OPNAV.

In January 2001, Bray accepted a position in the Aegis Program Office, Washington Navy Yard, as the Air Defense Systems Engineer and, later, became the Deputy Combat Systems Engineer, responsible for the development of Combat Systems for the AEGIS Cruisers and Destroyers.

In 1998, Bray accepted a position with the STANDARD Missile Program Office (PMS 422), Arlington, VA, leading Program Office efforts in the areas of Performance Assessment, Test and Evaluation, and Reliability and In-service Engineering.

Prior to accepting the position in the STANDARD Missile Program Office, Bray began his professional career at the Naval Surface Warfare Center, Corona Division, CA in December 1984 as missile flight analyst for STANDARD Missile. For the next 14 years, Bray held a series of progressively more responsible positions at NSWC Corona—including STANDARD Missile Branch Manager, Command Chief Scientist, and the Battle Group Reconstruction Division Manager.

Bray graduated from The Pennsylvania State University in 1984 with a Bachelor of Science degree in Engineering. While at NSWC Corona, Bray earned a Master's of Science in Systems Management from the University of Southern California. In addition, he is *DAWIA* Level III certified in Program Management, Systems Planning, Research, Development, and Engineering, and Test and Evaluation. He has been a member of the Acquisition Professional Community since February 1998.

Discussant: Mr. Victor Gavin is currently Executive Director for the Program Executive Officer for Littoral and Mine Warfare, and was appointed to the Senior Executive Service on February 2007. PEO LMW executes the Navy's acquisition programs for Mine Warfare, Unmanned Maritime Vehicles, Explosive Ordnance Disposal, Antiterrorism Afloat, Naval Special Warfare, Maritime Surveillance Systems, and the Mission Modules for the Littoral Combat Ship.

Gavin's previous position was as Technical Director, PEO Submarines. He was responsible for all Submarine Combat Systems acquisition and PEO-directed Research and Development. This includes modernization of all in-service submarines (5 classes) and new construction (VIRGINIA Class) submarines under the Submarine Warfare Federated Tactical System (SWFTS) family of systems. In addition, Gavin coordinated the integrated budget development for all Team Submarine programs.

Gavin attended North Carolina Agricultural and Technology State University and graduated with a Bachelor of Science Degree in Electrical Engineering in 1985. He also obtained a Master of Science Degree in Systems Engineering from Virginia Polytechnic Institute in 1996.

Gavin's civilian service began in a cooperative education program between the Naval Underwater System Center and North Carolina A&T State University. After graduation, he returned to NUSC to serve as systems engineer for submarine combat systems. Here, he became a key participant in the development of the AN/BSY-1 Combat System, which was the primary combat system for second-flight fast-attack submarines.

From 1988 to 1996, Gavin served as the on-site government representative at Lockheed Martin in Manassas, VA. As the leader of this multidiscipline organization, he provided the technical oversight necessary to deliver the combat system to twenty-three submarines.

Gavin joined NAVSEA headquarters in 1996 as the Chief Engineer for the Submarine Acoustics Programs. He led the Navy's efforts to migrate sonar systems development from a Military Specification environment to a Commercial Off-the-shelf (COTS) environment as part of the Acoustic Rapid COTS Insertion Program (ARCI). In 2000, Gavin was selected as Assistant Program Manager for Submarine Acoustics, where he established the business processes for acquiring COTS-based systems.

In 2002, Gavin was assigned the Assistant Program Manager for Combat Systems development. He planned and managed the development of combat systems for every US submarine variant, as well as for Collins Class submarines of the Royal Australian Navy. He later became the first civilian Program Manager of the Combat System Program Office.

His awards include Navy Meritorious Civil Service Award, Navy Superior Civilian Service Award, and the Vice President Gore Hammer Award for Acquisition Streamlining.

Application of Model-based Systems Engineering Methods to Development of Combat System Architectures

Presenter:

John M. Green
Senior Lecturer
Department of Systems Engineering
Naval Postgraduate School

Authors:

Cohort Six
MSSE Program
NSWC
Port Hueneme, CA

Abstract

Navy acquisition activities frequently produce combat system architectures based on existing systems rather than on stakeholder requirements. This approach limits software component reuse, which, in turn, limits potential application to other platforms. The objective of this Capstone project was to develop a methodology for creating complex combat system architectures that emphasize the use of Software Product Lines (SPLs), requirements traceability, integrated supportability and Modeling and Simulation (M&S) early and throughout the approach. To address this objective, an integrated methodology that utilizes Model-based Systems Engineering (MBSE) to create open, supportable combat system architectures was developed. The methodology was evaluated by applying it to a naval surface combatant Anti-Air Warfare (AAW) mission area. Application of the methodology led to the following major findings: (1) Proven systems engineering practices, languages and tools can be integrated with the MBSE approach for developing complex architectures; (2) Creation of domain-centered SPLs facilitates planned reuse and allows for assessment to candidate architectures; (3) Requirements traceability can be achieved by using a combination of modeling languages and tools; (4) M&S application can extend beyond operational scenarios to address lifecycle cost, and (5) Engineers and logisticians can effectively use MBSE to integrate supportability into design. Overall, this project demonstrated the benefits of an MBSE approach tailored to developing affordable and supportable combat system architectures that meet mission requirements.

Overview

This paper is a description of the Master of Science in Systems Engineering Capstone project completed by the students of Cohort Six from Naval Surface Weapons Center, Port Hueneme, CA. They were assigned this problem because Navy acquisition activities frequently produce combat system architectures based on existing systems rather than on stakeholder requirements. This approach limits software component reuse, which, in turn, limits potential application to other platforms. The development of systems tends to be by platform rather than by application or warfare area. A second system development issue is that *Department of Defense Instruction* (*DoDI*) *5000.02* (2008) prescribes the early integration of supportability requirements; however, current methods or processes do not do so. Methodologies currently in use—such as the Acquisition, Technology, and Logistics framework—may identify supportability as a requirement but tend not to maintain it as a priority throughout the development process.

In response to these issues, an integrated methodology that utilizes MBSE and the Agile process was defined to create open and supportable system architectures. This methodology incorporates a common modeling language, utilizes domain analysis to support Software Product Line (SPL) reuse, maintains traceability of requirements and architecture functionality, and integrates supportability, sustainment and lifecycle cost considerations. Also described in this project is a system engineering process that outlines requirements generation analysis, functional analysis and allocation, architecture definition, and Verification and Validation (V&V).

The methodology was evaluated by applying it to an Anti-Air Warfare (AAW) mission thread—in particular, Anti-Ship Missile Defense (ASMD). The AAW implementation included the development of a systems architecture and design artifacts, including Department of Defense Architecture Framework (DoDAF) views. The project demonstrated the benefits of an MBSE approach tailored to developing architectures that support Open Architecture (OA), SPL, and integrating supportability early in the system development process. Technical conclusions resulting from the research, development and application of the methodology are summarized in the following paragraphs.

Problem Statement and Capstone Objective

Recognizing that current DoD processes for developing combat system architectures are heavily influenced by legacy processes and systems—which inhibit the incorporation of supportability requirements up-front in design—project leaders assigned the students to meet the DoD objective of acquiring and fielding interoperable, supportable system architectures that utilized the Open Architecture (OA) paradigm. They were further tasked to address the use of Software Product Lines (SPLs) and capture the results in a form that was compliant with the DoD Architecture Framework (DoDAF). They were specifically told to develop a MBSE approach. In addition, they were to integrate supportability issues, requirements traceability and identify a structure which supports combat system software reuse.

Project Organization

Figure 1 shows the various organizational structures the students adopted as they progressed through the project. At first there was a reluctance to change, but eventually they learned that they had to adapt the organization to the task. Once that lesson was learned, the students became proficient in developing their work products.

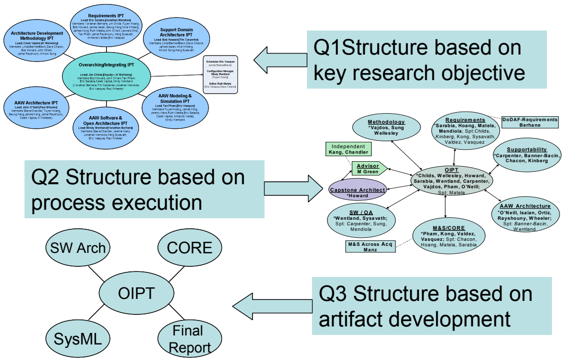


Figure 1. IPT Structure Evolving with Capstone Project Need

Two other lessons learned were that small teams were more efficient and that the project needs a chief architect.

Methodology Overview

The result of the literature searches into each element of the problem set is summarized in Figure 2.

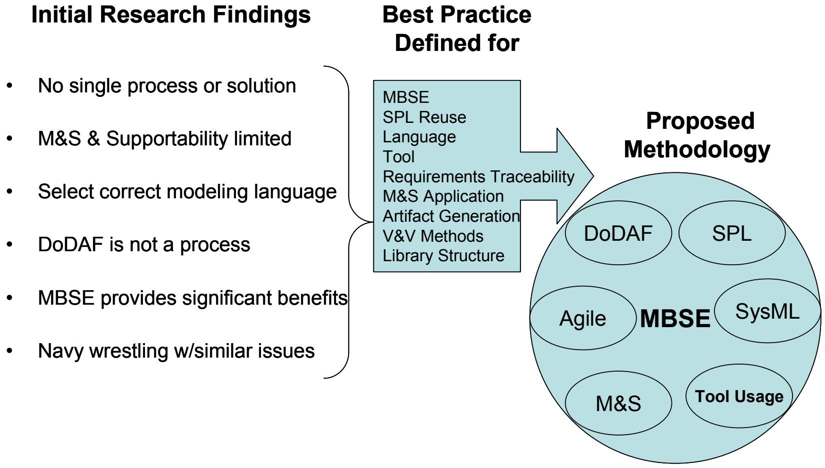


Figure 2. Overview of the Model Development

The initial research findings are significant in that the students came to understand that development of complex systems requires a through understanding of processes and tools available. Figure 3 illustrates how the students integrated the literature with practice.

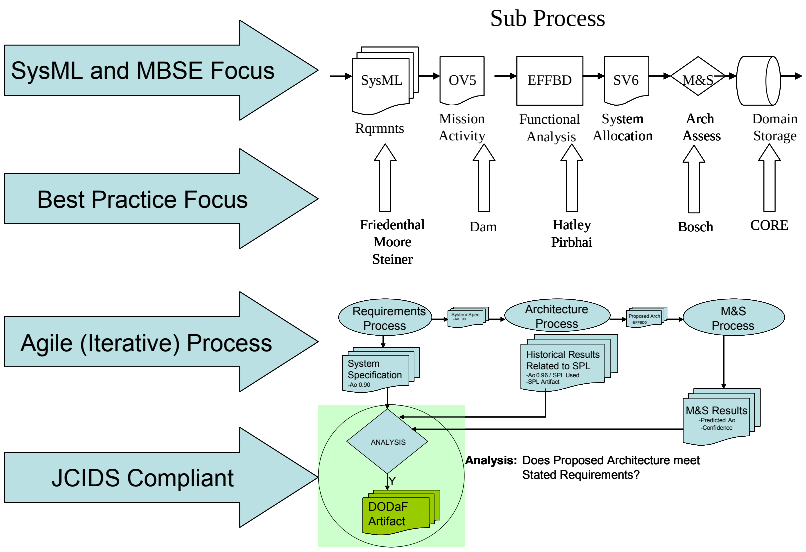


Figure 3. The Big Picture

Two of the takeaways from Figure 3 are these: 1) to deal with complex problems, one requires multiple frames of reference, and 2) integration of methods is needed to provide a more complete description of the potential solution. The following paragraphs provide more detail about the approach the students developed.

Methodology Top-tier Process

Figure 4 is the representation of how the students viewed the process of going from a specification to architecture.

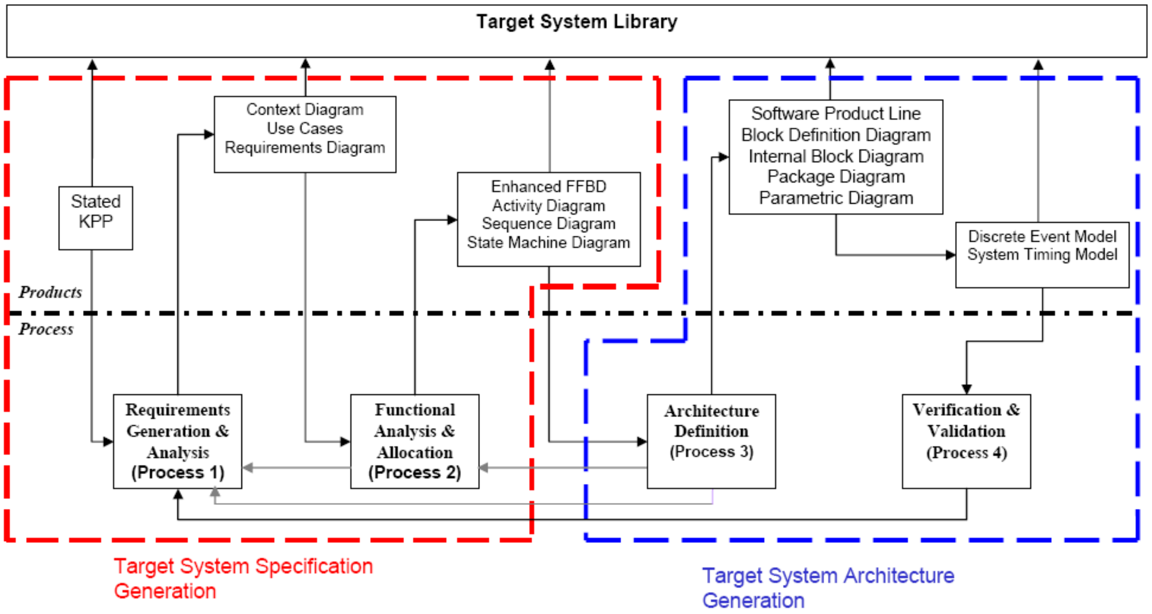


Figure 4. The Overall Methodology

They developed four main processes as shown in the figure above: (1) requirements generation and analysis, (2) functional analysis and allocation, (3) architecture definition, and (4) verification and validation. They verified these processes by developing an AAW Mission Architecture. The following paragraphs describe the four sub-processes.

(1) Requirements Generation and Analysis Process

Figure 5 provides the detail of the requirements generation and analysis step and how it interfaces with the other three steps in the methodology. Figure 6 shows the outcome of the requirements step.

Requirements lessons learned can be summed up as follows:

- It was necessary to expand the use of modeling because of the insights it provided in requirements decomposition and allocation. M&S can result in improved decomposition and allocation.
- It was important to understand the relationship between requirements artifacts for traceability at the tier level and across artifact boundaries.
- It was essential to keep the requirements tool set database current for both traceability and verification of allocation.
- Process execution improved over time; i.e., the teams became more effective with experience.
- The process resulted in valid artifacts that support Capstone objectives.
- The tools, skill sets, and processes are not in place to lead requirements development on large, complex systems.

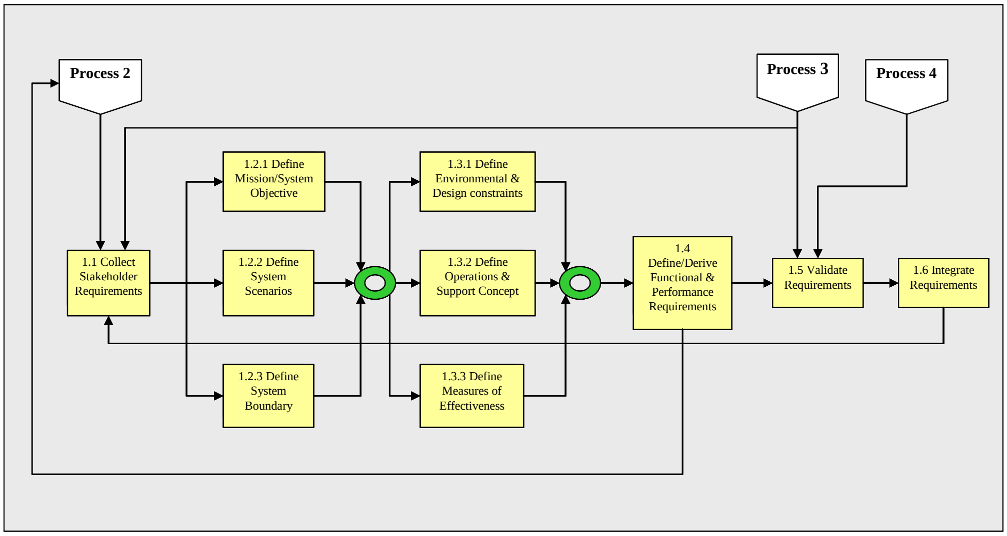


Figure 5. The Requirements Generation Process

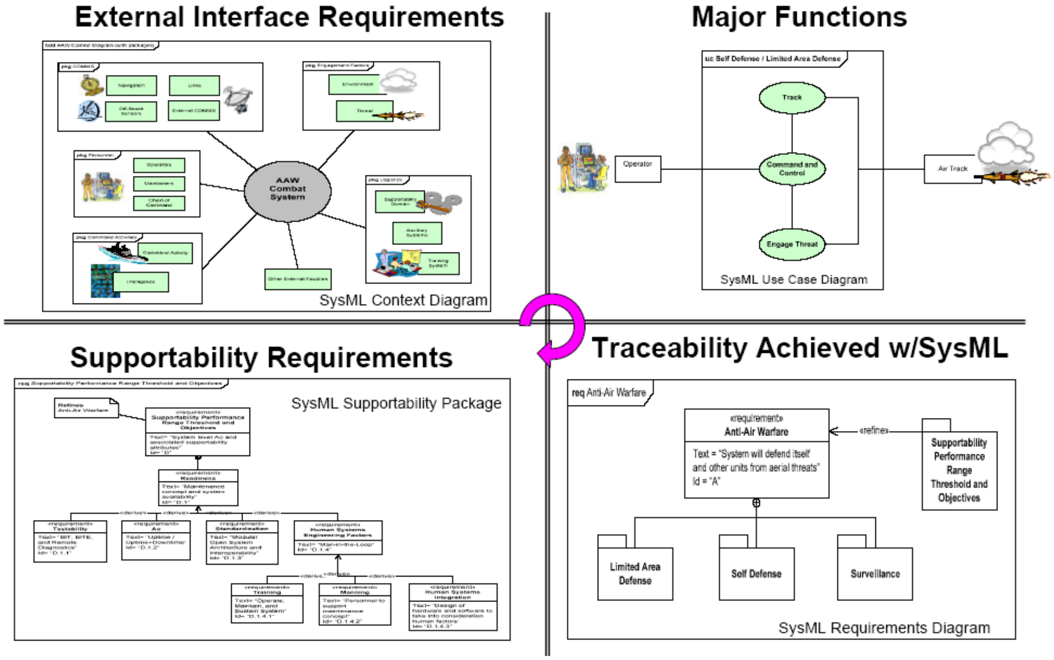


Figure 6. Requirements Results/Products

(2) Functional Analysis and Allocation Process

The approach to functional analysis was straightforward and is shown in Figure 7. Some of the key lessons learned were to plan tool usage. The process is iterative, and the data is developed in a drill-down manner. A second point was that to ensure that the result is correct, a subject-matter expert (SME) is important and should be readily available; otherwise, there is a tendency for engineers to map based on experience. The level of input is only as good as the SME's knowledge. It should be noted that technical, language, method, and tool SMEs are different and that a blend of talent is required.

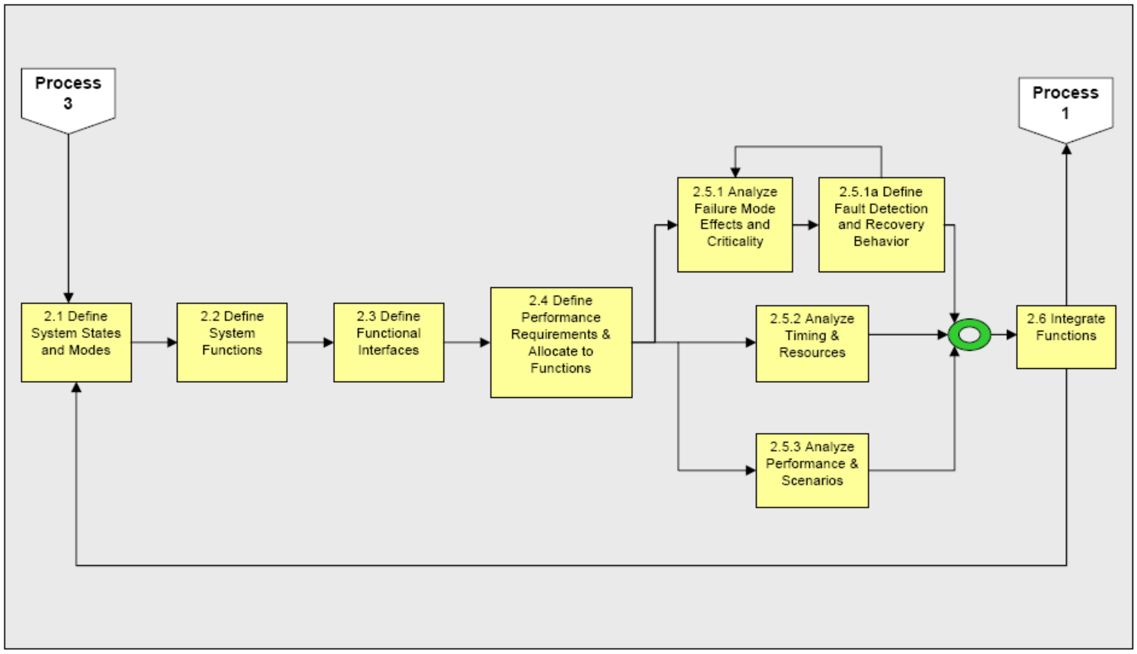
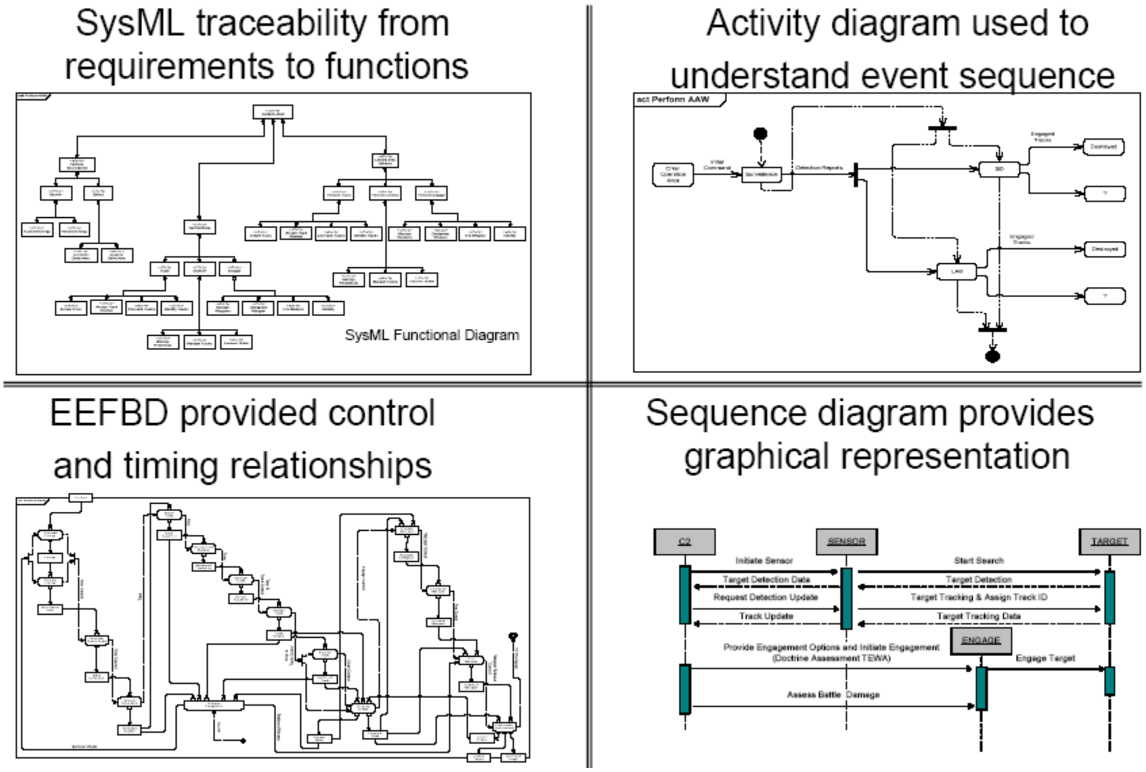


Figure 7. Functional Analysis Process Diagram

Figure 8 shows some of the key artifacts developed during this part of the process. The artifacts provided powerful depictions for communicating and for analysis in design and development.

In the execution of the process, the Hatley-Pirbhai method was integrated with the SysML language to provide a sound SE approach within the MBSE format. The outcome of this approach is a requirements model, as shown on the left side of Figure 9. The architecture process diagram illustrates how the students built the right side of the model.


SysML traceability from requirements to functions

Activity diagram used to understand event sequence

EEFBD provided control and timing relationships

Sequence diagram provides graphical representation

Figure 8. Functional Analysis Results/Products

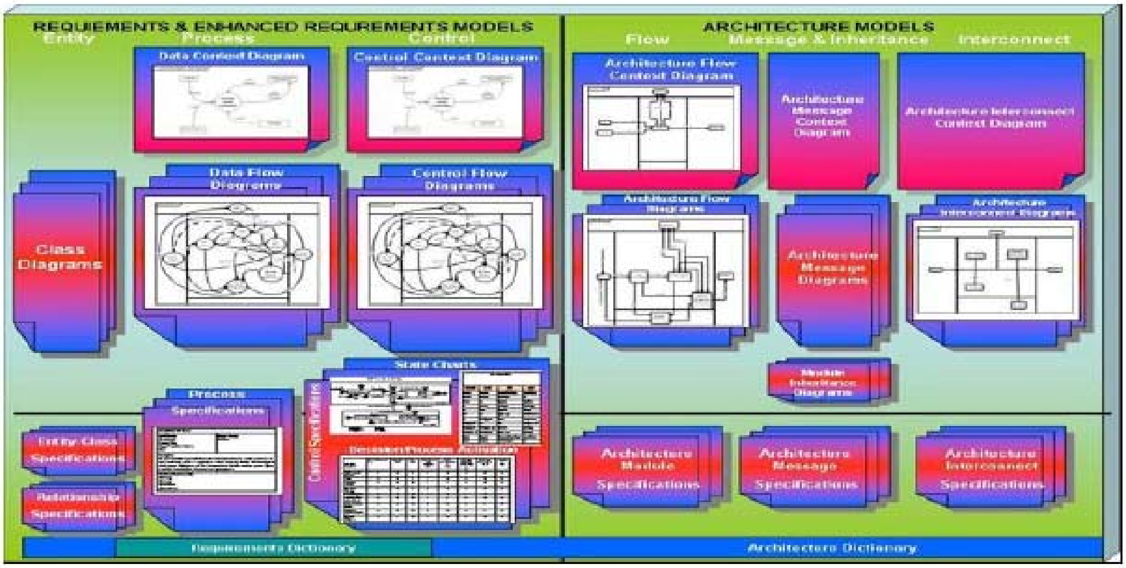


Figure 9. The Hatley-Pirbhai Models

(3) Architecture Definition Process

The development of the architecture followed the process shown in Figure 10. In developing the architecture from the previous step, the students encountered some interesting issues. First, there was a lack of core knowledge in the architecture development process. Use of the Hatley-Pirbhai paradigm provided an approach that overcame the inexperience issue. Figure 11 is the Hatley-Pirbhai architecture template. This template is reusable at every level of analysis and allows for a more formal approach than natural language descriptions.

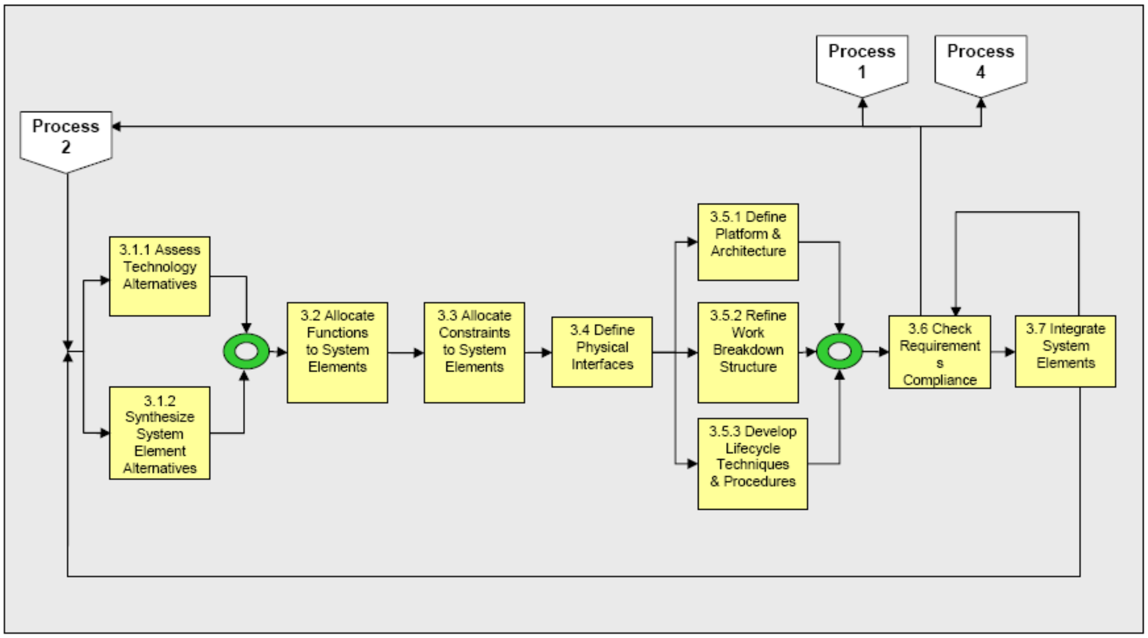


Figure 10. Architecture Process Diagram

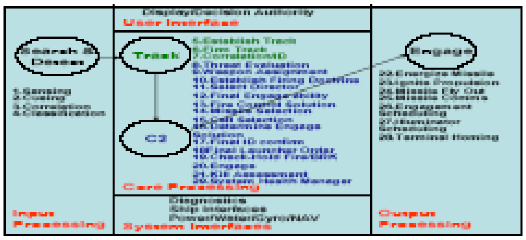


Figure 11. Hatley-Pirbhai Architecture Template

There was also an issue with software architecture quality attributes not being fully defined or measurable. The student solution was the use of an objective hierarchy to assess architecture, as shown in Figure 12. One of the subtle realizations by the students was the applicability of Six Sigma techniques to all the steps discussed so far.

The students initially had a problem with a lack of common task and function descriptions. This was caused by different teams working on different parts of the problem using different tools. This issue was resolved as the students reorganized and reduced the size of the team working on this area.

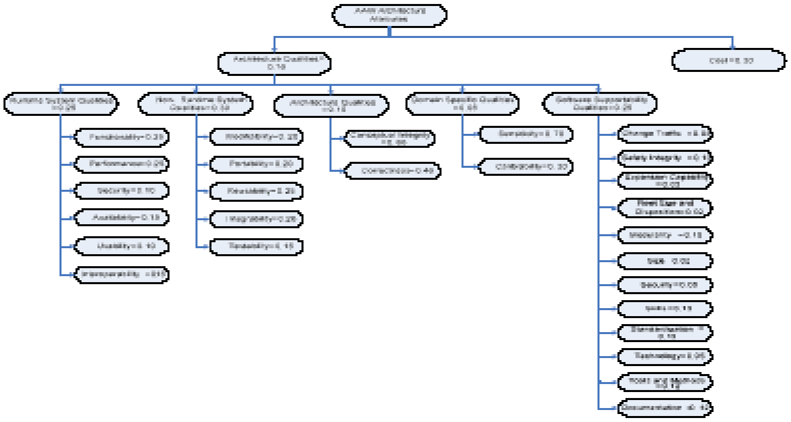


Figure 12. SW Architecture Objective Hierarchy

This reorganization helped with developing the software architecture shown on the left side of Figure 13. Figure 13 shows the relationship of the software architecture to the production plan (much simplified in this diagram) to the product line library on the right.

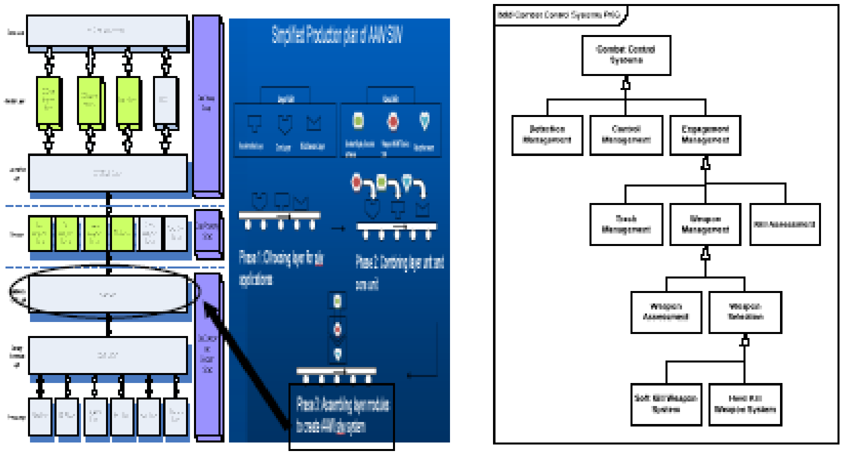


Figure 13. Project Software Architecture and SPL Library Framework

(4) Verification and Validation Process

As shown in Figure 14, modeling and simulation was used to identify both feasibility and configuration performance differences, as well as to verify requirements. The parallel analysis efforts for functional analysis and architecture development required adaptable models that could be updated as Systems Engineering artifacts were created. The students initially had problems with trying to put too much detail into the model rather than focusing on process execution. As they gained experience, they were able to use a block-oriented simulation language to develop model variations very quickly.

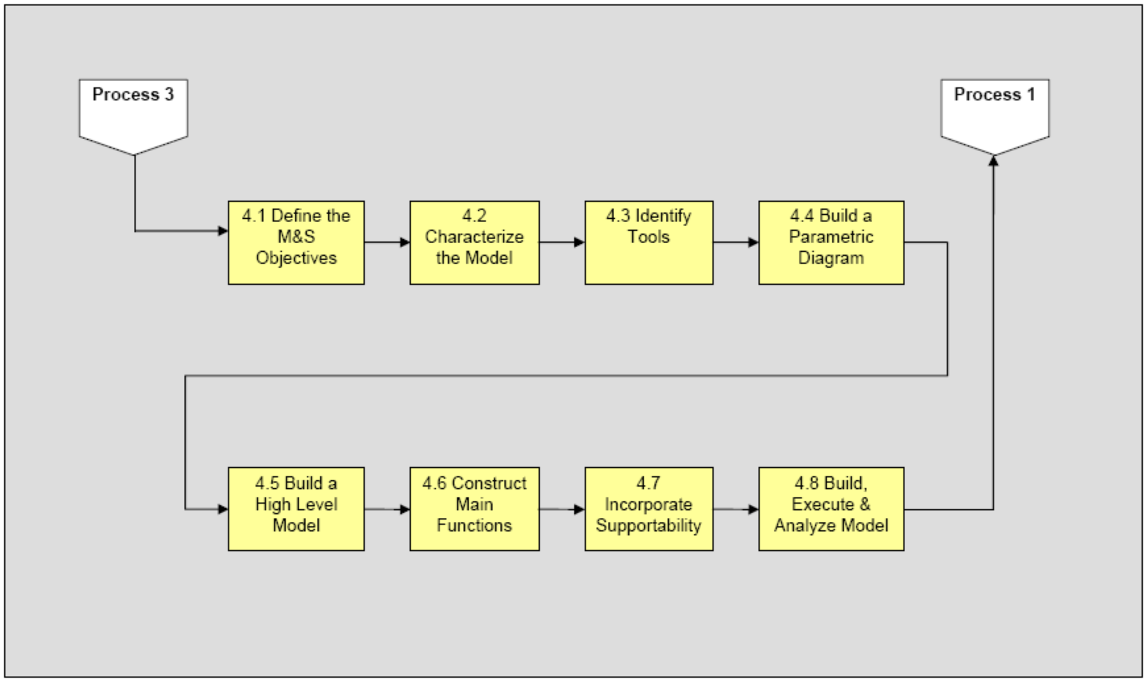


Figure 14. M&S Process Diagram

Overall, M&S provided valuable insight into architecture design, requirements decomposition, and related performance issues.

Capstone Conclusions and Recommendations

The students made the following recommendations. First, provide logisticians with the background to participate early in the acquisition cycle. In this study, logisticians demonstrated the required skills to work in systems concept and development. Second, establish domain-specific components and quality attributes. Identify a QA weighting system to balance sustainment and performance by domain. Third, develop SPL library criteria and characteristics. Define data tags required to assess SPL reusability. Fourth, continue the research effort to a V&V methodology. Execution of the methodology to develop S/W, H/W and Interface Components will result in additional findings/lessons learned. Finally, leverage the methodology to estimate lifecycle cost and RAM through M&S, and use artifacts to support early LCCE and RAM KPP reporting requirements.

Overall Project Summary

Proven systems engineering practices, languages and tools can be integrated with the MBSE approach for developing complex architectures. Through decomposition of the objectives and associated research, the students were able to identify many solutions and methodologies available to support a top-down or bottom-up approach. Based on tenets from multiple authors, the student teams developed a new end-to-end methodology for system design—to include key aspects in requirements generation, architecture development, and modeling and simulation.

Requirements traceability can be achieved by using a combination of modeling languages and tools. Traceability is critical on large, complex systems due to the sheer volume of technical data and the likelihood of human error when trying to conduct V&V manually using engineering artifacts. Students achieved requirements generation and traceability using the Systems Modeling Language (SysML) as the modeling language and CORE as the architecture tool. They reduced manual V&V errors, given that SysML contains methods based on the allocation relationship depicted in the artifacts for verifying traceability. They used sample test criteria and events to successfully verify that CORE could be used to assess demonstration of requirements.

M&S can provide significant value in conducting tradeoffs during design. However, the majority of M&S is focused on verifying operational parameters within scenarios vice optimizing system design. Students applied M&S using a top-down approach to verify system operational behavior and to validate initial operational requirements. They used the software tool Extend to perform the simulation of a raid scenario. Through multiple variations of models and simulations, it was found that there could be anomalies or elements that need adjustment in the architecture. The unexpected results from the raw data led to more extensive research of the initial inputs, which led to additional simulation runs. Defining objectives, processes and model development were all key milestones in building the Extend model.

Engineers and logisticians can effectively use MBSE to integrate supportability into system design. The Navy advocates the integration of supportability early in the concept development and design phases, but very little training or guidance is provided on how to effectively do this. Many logisticians are not equipped with the knowledge or experience to adequately support initial system concept and architecture development. Similarly, many design engineers lack the training and experience of considering supportability during concept exploration, design and development. On this project, engineers and logisticians collaborated to meet the expressed objective of integrating supportability into design as depicted in the resulting artifacts. Supportability was considered during requirements generation, functional analysis and architecture composition. The integration of supportability early in design provided the maintenance concept and planning phases with a solid foundation for conducting tradeoff decisions between operational enhancements and lifecycle sustainment considerations.

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Software Licenses, Open Source Components, and Open Architectures

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Abstract

A substantial number of enterprises and independent software vendors are adopting a strategy in which software-intensive systems are developed with an open architecture (OA) that may contain open source software (OSS) components or components with open APIs. The emerging challenge is to realize the benefits of openness when components are subject to different copyright or property licenses. In this paper, we identify key properties of OSS licenses, present a license analysis scheme to identify license conflicts arising from composed software elements, and apply it to provide guidance for software architectural design choices whose goal is to enable specific licensed component configurations. Our scheme has been implemented in an operational environment and demonstrates a practical, automated solution to the problem of determining overall rights and obligations for alternative OAs.

1. Introduction

It has been common for OSS projects to require developers to contribute their work under conditions that ensure the project can license its products under a specific OSS license. For example, the Apache Contributor License Agreement grants enough rights to the Apache Software Foundation for the foundation to license the resulting systems under the Apache License. This sort of license configuration, in which the rights to a system's components are homogenously granted and the system has a well-defined OSS license, was the norm and continues to this day.

However, we more and more commonly see a different license configuration in which the components of a system do not have the same license. The resulting system may not have any recognized OSS license at all—in fact, our research indicates this is the most likely outcome. Instead, if all goes well in its design, there will be enough rights available in the system so that it can be used and distributed—and perhaps modified by others and sublicensed, if the corresponding obligations are met. These obligations are likely to differ for components with different licenses; a BSD (Berkeley Software Distribution)-licensed component must preserve its copyright notices when made part of the system—for example, while the source code for a modified component covered by MPL (the Mozilla Public License) must be made public—and a component with a reciprocal license such as the Free Software Foundation's GPL (General Public License) might carry the obligation to distribute the source code of that component but also of other components that constitute "a whole which is a work based on" the GPL'd component. The obligations may conflict, as when a GPL'd component's reciprocal obligation to publish source code of other components is combined with a proprietary license's prohibition of publishing source code—in which case, there may be no rights available for the system as a whole (not even the right of use), because the obligations of the licenses that would permit use of its components cannot simultaneously be met.

The central problem we examine and explain in this paper is to identify principles of software architecture and software licenses that facilitate or inhibit success of the OA strategy when OSS and other software components with open APIs are employed. This is the knowledge we seek to develop and deliver. Without such knowledge, it is unlikely that an OA that is clean, robust, transparent, and extensible can be readily produced. On a broader scale, this paper seeks to explore and answer the following kinds of research questions:

- What license applies to an OA system composed of components with different licenses?
- How do alternative OSS licenses facilitate or inhibit the development of OA systems?
- How should software license constraints be specified to make it possible to automatically determine the overall set of rights and obligations associated with a configured software system architecture?

This paper may help establish a foundation for how to analyze and evaluate dependencies that might arise when seeking to develop software systems that embody an OA when different types of software components or software licenses are being considered for integration into an overall system configuration.

In the remainder of this paper, we examine software licensing constraints. This is followed by an analysis of how these constraints can interact in order to determine the overall license constraints applicable to the configured system architecture. Next, we describe an operational environment that demonstrates automatic determination of license constraints associated with a configured system architecture, and thus offers a solution to the problem we face. We close with a discussion of the conclusions that follow.

2. Background

There is little explicit guidance or reliance on systematic empirical studies for how best to develop, deploy, and sustain complex software systems when different OA and OSS objectives are at hand. Instead, we find narratives that provide ample motivation and belief in the promise and potential of OA and OSS without consideration of what challenges may lie ahead in realizing OA and OSS strategies. Ven (2008) is a recent exception.

We believe that a primary challenge to be addressed is how to determine whether a system, composed of subsystems and components each with specific OSS or proprietary licenses and integrated into the system's planned configuration, is or is not open, and what license constraints apply to the configured system as a whole. This challenge comprises not only evaluating an existing system at run-time but also at design-time and build-time for a proposed system to ensure that the result is "open" under the desired definition and that only the acceptable licenses apply; another important aspect of this challenge is understanding which licenses are acceptable in this context. Because there is a range of types and variants of licenses (OSI, 2008), each of which may affect a system in different ways, and because there are a number of different kinds of OSS-related components and ways of combining them that affect the licensing issue, an essential first step is to understand the kinds of software elements that constitute a software architecture, and what kinds of licenses may encumber these elements or their overall configuration.

OA seems to simply mean software system architectures incorporating OSS components and open application program interfaces (APIs). But not all software system architectures incorporating OSS components and open APIs will produce an OA, since the openness of an OA depends on: (a) how/why OSS and open APIs are located within the system architecture, (b) how OSS and open APIs are implemented, embedded, or interconnected, (c) whether the copyright (Intellectual Property) licenses assigned to different OSS components encumber all/part of a software system's architecture into which they are integrated, and (d) the fact that many alternative architectural configurations and APIs exist that may or may not produce an OA (Alspaugh & Antón, 2007; Scacchi & Alspaugh, 2008). Subsequently, we believe this can lead to situations in which new software development or acquisition requirements stipulate a software system with an OA and OSS, but the resulting software system may or may not embody an OA. This can occur when the architectural design of a system constrains system requirements—raising the question of what requirements can be satisfied by a given system architecture when requirements stipulate specific types or instances of OSS (e.g., Web browsers and content management servers) to be employed (Scacchi, 2002), or what architecture style (Bass, Clements & Kazman, 2003) is implied by a given set of system requirements.

Thus, given the goal of realizing an OA and OSS strategy together with the use of OSS components and open APIs, it is unclear how to best align acquisition, system requirements, software architectures, and OSS elements across different software license regimes to achieve this goal (Scacchi & Alspaugh, 2008).

3. Understanding Open Architectures

The statement that a system is intended to embody an open architecture using open software technologies like OSS and APIs does not clearly indicate what possible mix of software elements may be configured into such a system. To help explain this, we first identify what kinds of software elements are included in common software architectures, whether they are open or closed (Bass et al., 2003).

- *Software source code components*—(a) stand-alone programs, (b) libraries, frameworks, or middleware, (c) inter-application script code (e.g., C shell scripts), and (d) intra-application script code (e.g., to create Rich Internet Applications using domain-specific languages such as XUL for Firefox Web browser (Feldt, 2007) or "mashups" (Nelson & Churchill, 2006)).
- *Executable components*—These are programs for which the software is in binary form, and its source code may not be open for access, review, modification, and possible redistribution. Executable binaries can be viewed as "derived works" (Rosen, 2005).
- *Application program interfaces/APIs*—The availability of externally visible and accessible APIs to which independently developed components can be connected is the minimum condition required to form an "open system" (Meyers & Obendorf, 2001).
- *Software connectors*—In addition to APIs, these may be software either from libraries, frameworks, or application script code, whose intended purpose is to provide a standard or reusable way of associating programs, data repositories, or remote services through common interfaces. The High Level Architecture (HLA) is an example of a software connector scheme (Kuhl, Weatherly & Damann, 2000), as are CORBA, Microsoft's .NET, Enterprise Java Beans, and LGPL libraries.
- *Configured system or sub-system architectures*—These are software systems that can be built to conform to an explicit architectural design. They include software source code components, executable components, APIs, and connectors that are organized in a way that may conform to a known "architectural style" such as the Representational State Transfer (Fielding & Taylor, 2002) for Web-based client-server applications, or may represent an original or ad hoc architectural pattern (Bass et al., 2003). Each of the software elements—and the pattern in which they are arranged and interlinked—can all be specified, analyzed, and documented using an Architecture Description Language and ADL-based support tools (Bass et al., 2003; Medvidovic, Rosenblum & Taylor, 1999).

Figure 1 provides an overall view of an archetypal software architecture for a configured system that includes and identifies each of the software elements above, as well as including free/open source software (e.g., Gnome Evolution) and closed source software (WordPerfect) components. In simple terms, the configured system consists of software components (grey boxes in the figure) that include a Mozilla Web browser, Gnome Evolution e-mail client, and WordPerfect word processor, all running on a Linux operating system that can access file, print, and other remote-networked servers (e.g., an Apache Web server). These components are interrelated through a set of software connectors (ellipses in the figure) that connect the interfaces of software components (small white boxes attached to a component) and link them together. Modern-day enterprise systems or command-and-control systems will generally have more complex architectures and a more diverse mix of software components than shown in the figure here. As we examine next, even this simple architecture raises a number of OSS licensing issues that constrain the extent of openness that may be realized in a configured OA.

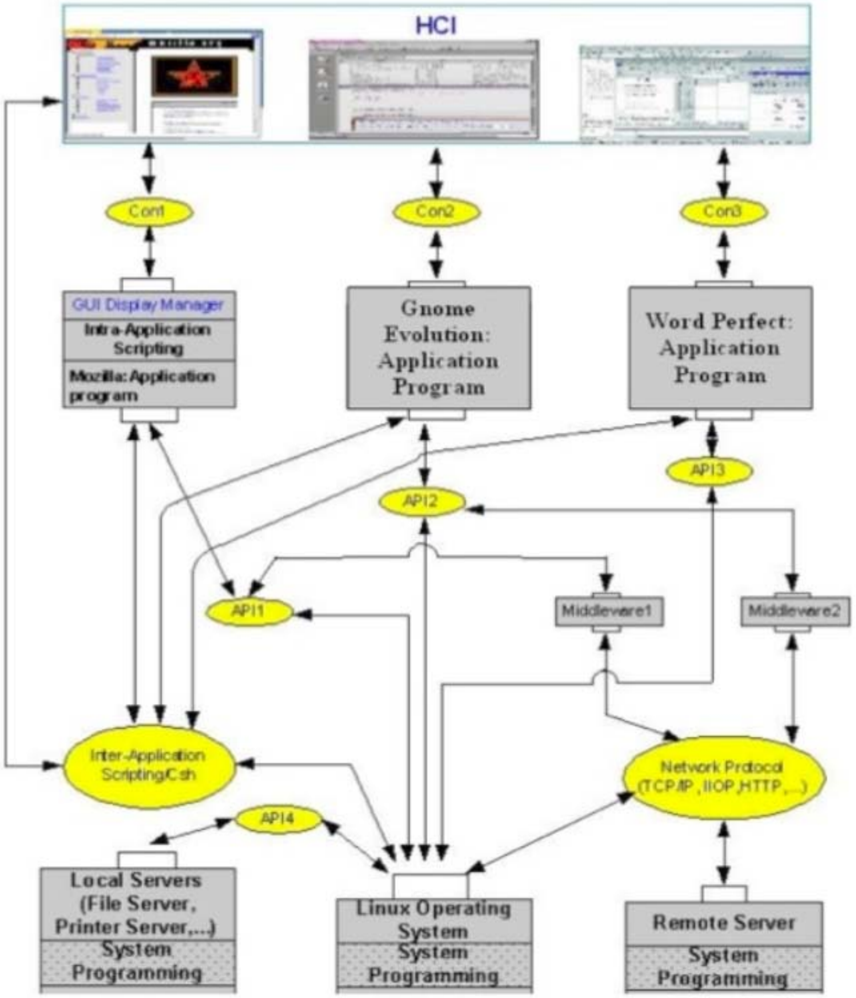


Figure 1. An Archetypal Software Architecture Depicting Components (grey boxes), Connectors (ellipses), Interfaces (small boxes on components), and Data/Control Links

4. Understanding Open Software Licenses

A particularly knotty challenge is the problem of licenses in OSS and OA. There are a number of different OSS licenses, and their number continues to grow. Each license stipulates different constraints attached to software components that bear it. External references are available which describe and explain many different licenses that are now in use with OSS (Fontana et al., 2008; OSI, 2008; Rosen, 2005; St. Laurent, 2004).

More and more software systems are designed, built, released, and distributed as OAs composed of components from different sources, some proprietary and others not. Systems include components that are statically bound or interconnected at build-time, while other components may only be dynamically linked for execution at run-time, and thus might not be included as part of a software release or distribution. Software components in such systems evolve not only by ongoing maintenance but also by architectural refactoring, alternative component interconnections, and component replacement (via maintenance patches, installation of new versions, or migration to new technologies). Software components in such systems may be subject to different software licenses, and later versions of a component may be subject to different licenses (e.g., from CDDL—Sun's Common Development and Distribution License—to GPL, or from GPLv2 to GPLv3).

Software systems with open architectures are subject to different software licenses than may be common with traditional, proprietary, closed source systems from a single vendor. Software architects/developers must increasingly attend to how they design, develop, and deploy software systems that may be subject to multiple and possibly conflicting software licenses. We see architects, developers, software acquisition managers, and others concerned with OAs as falling into three groups. The first group pays little or no heed to license conflicts and obligations; they simply focus on the other goals of the system. Those in the second group have assets and resources, and, in order to protect these, they may have an army of lawyers to advise them on license issues and other potential vulnerabilities; or they may constrain the design of their systems so that only a small number of software licenses (possibly just one) are involved—excluding components with other licenses independent of whether such components represent a more effective or more efficient solution. The third group falls between these two extremes; members of this group want to design, develop, and distribute the best systems possible, while they respect the constraints associated with different software component licenses. Their goal is a configured OA system that meets all its goals and for which all the license obligations for the needed copyrights are satisfied. It is this third group that needs the guidance the present work seeks to provide.

There has been an explosion in the number, type, and variants of software licenses, especially with open source software (OSI, 2008). Software components are now available subject to licenses such as the General Public License (GPL), Mozilla Public License (MPL), Apache Public License, (APL), Academic licenses (e.g., BSD, MIT), Creative Commons, Artistic, and others as well as Public Domain (either via explicit declaration or by expiration of prior copyright license). Furthermore, licenses such as these can evolve, resulting in new license versions over time. But no matter their diversity, software licenses represent a legally enforceable contract that is recognized by government agencies, corporate enterprises, individuals, and judicial courts, and, as a result, they cannot be taken trivially. As a consequence, software licenses constrain open architectures and thus architectural design decisions.

So how might we support the diverse needs of different software developers with respect to their need to design, develop, and deploy configured software systems with different, possibly conflicting licenses for the software components they employ? Is it possible to provide automated means for helping software developers determine what constraints will result at design-time, build-time, or run-time when their configured system architectures employ diverse licensed components? These are the kind of questions we address in this paper.

4.1. Software Licenses: Rights and Obligations

Copyright, the common basis for software licenses, gives the original author of a work certain exclusive rights, which for software include the right to use, copy, modify, merge, publish, distribute, sub-license, and sell copies. These rights may be licensed to others, including individuals or groups, and they may be licensed either exclusively so that no one else can exercise them or (more commonly) non-exclusively. After a period of years, the rights enter the public domain, but, until then, the only way for anyone other than the author to have access to the copyright is to license it.

Licenses may impose obligations that must be met in order for the licensee to realize the assigned rights. Commonly cited obligations include the obligation to buy a legal copy to use and not distribute copies (proprietary licenses), the obligation to preserve copyright and license notices (academic licenses), the obligation to publish at no cost source code that has been modified (MPL), or the reciprocal obligation to publish all source code included at build-time or statically linked (GPL).

Licenses may provide for the creation of derivative works (e.g., a transformation or adaptation of existing software) or collective works (e.g., a Linux distribution that combines software from many independent sources) from the original work by granting those rights, possibly with corresponding obligations.

In addition, the author of an original work can make it available under more than one license, enabling the work's distribution to different audiences with different needs. For example, one licensee might be happy to pay a license fee in order to be able to distribute the work as part of a proprietary product whose source code is not published, while another might need to license the work under MPL rather than GPL in order to have consistent licensing across a system. The result is the distribution of software under any one of several licenses, with the licensee choosing from two ("dual license") or three (Mozilla's "tri-license") licenses.

The basic relationship between software license rights and obligations can be summarized as follows: if you meet the specified obligations, then you get the specified rights. In other words, for the academic licenses, if you retain the copyright notice, list of license conditions, and disclaimer, then you have the right to use, modify, merge, sub-license, etc. For MPL, if you publish modified source code and sub-licensed derived works under MPL, then you get all the MPL rights. These same relationships apply for other types of licenses. However, one thing we have learned from our efforts to carefully analyze and lay out the obligations and rights pertaining to each license is that license details are difficult to comprehend and track—it is easy to get confused or make mistakes. Some of the OSS licenses were written by developers, and often these turn out to be incomplete and legally ambiguous; others, usually more recent, were written by lawyers and are more exact and complete but can be difficult for non-lawyers to grasp. The challenge is multiplied when dealing with configured system architectures that compose multiple components with heterogeneous licenses so that the need for legal interpretations begins to seem inevitable (Fontana et al., 2008; Rosen, 2005). Therefore, one of our goals is to make it possible to architect software systems of heterogeneously licensed components without necessarily consulting legal counsel. Similarly, such a goal is best realized with automated support that can help architects understand design choices across components with different licenses and that can provide support for testing build-time releases and run-time distributions to make sure they achieve the specified rights by satisfying the corresponding obligations.

4.2. Expressing Software Licenses

Historically, most software systems, including OSS systems, were entirely under a single software license. However, we now see more and more software systems being proposed, built, or distributed with components that are under various licenses. Such systems may no longer be covered by a single license, unless such a licensing constraint is stipulated at design-time and enforced at build-time and run-time. But when components with different licenses are to be included at build-time, their respective licenses might either be consistent or conflict. Further, if designed systems include components with conflicting licenses, then one or more of the conflicting components must be excluded in the build-time release or must be abstracted behind an open API or middleware, with users required to download and install to enable the intended operation. (This is common in Linux distributions subject to GPL, where, for example, users may choose to acquire and install proprietary run-time components, like proprietary media players.) As a result, a component license conflict need not be a show-stopper if identified at design time. However, developers have to be able to determine which components' licenses conflict and take appropriate steps at design-time, build-time, and run-time that are consistent with the different concerns and requirements that apply at each phase (Scacchi & Alspaugh, 2008).

In order to fulfill our goals, we need a scheme for expressing software licenses that is more formal and less ambiguous than natural language and that allows us to identify conflicts arising from the various rights and obligations pertaining to two or more components' licenses. We considered relatively complex structures—such as Hohfeld's eight fundamental jural relations (Hohfeld, 1913)—but, applying Occam's razor, selected a simpler structure. We start with a tuple <*actor, operation, action, object*> for expressing a right or obligation. The *actor* is the "licensee" for all the licenses we have examined. The *operation* is one of the following: "may," "must," or "must not," with "may" expressing a right and "must" and "must not" expressing obligations; following Hohfeld, the lack of a right (which would be "may not") correlates with a duty not to exercise the right ("must not"), and, whenever lack of a right seemed significant in a license, we expressed it as a negative obligation with "must not." The *action* is a verb or verb phrase describing what may, must, or must not be done, with the *object* completing the description. We specify an object separately from the action in order to minimize the set of actions. A license then may be expressed as a set of rights, with each right associated (in that license) with zero or more obligations that must be fulfilled in order to enjoy that right. Figure 2 displays the tuples and associations for two of the rights and their associated obligations for the academic BSD software license. Note that the first right is granted without corresponding obligations.

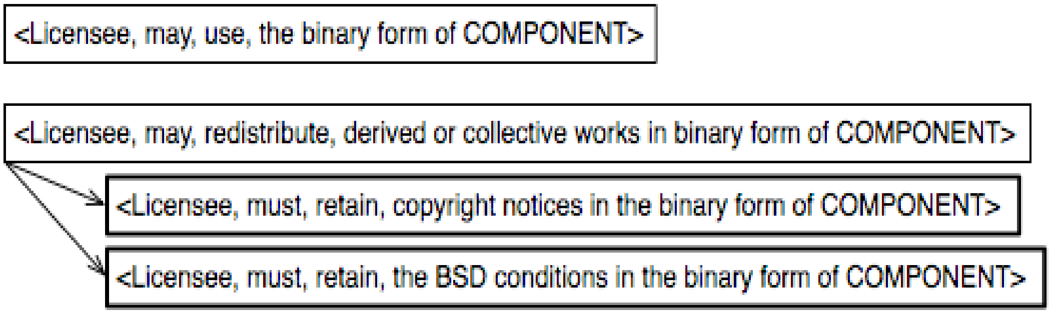


Figure 2. A Portion of the BSD License Tuples

We now turn to examine how OA software systems that include components with different licenses can be designed and analyzed while effectively tracking their rights and obligations.

When designing an OA software system, there are heuristics one can employ to enable architectural design choices that might otherwise be excluded due to license conflicts. First, it is possible to employ a "license firewall," which serves to limit the scope of reciprocal obligations. Rather than simply interconnecting conflicting components through static linking of components at build-time, such components can be logically connected via dynamic links, client-server protocols, license shims (e.g., via LGPL connectors), or run-time plug-ins. Second, the source code of statically linked OSS components must be made public. Third, it is necessary to include appropriate notices and publish required sources when academic licenses are employed. However, even using design heuristics such as these (and there are many), keeping track of license rights and obligations across components that are interconnected in complex OAs quickly becomes too cumbersome. Thus, automated support needs to be provided to help overcome and manage the multi-component, multi-license complexity.

5. Automating Analysis of Software License Rights and Obligations

We find that if we start from a formal specification of a software system's architecture, then we can associate software license attributes with the system's components, connectors, and sub-system architectures and calculate the copyright rights and obligations for the system. Accordingly, we employ an architectural description language specified in xADL (2005) to describe OAs that can be designed and analyzed with a software architecture design environment (Medvidovic et al., 1999) such as ArchStudio4 (2006). We have taken this environment and extended it with a Software Architecture License Traceability Analysis module (Asuncion, 2008). This allows for the specification of licenses as a list of attributes (license tuples) using a form-based user interface, similar to those already used and known for ArchStudio4 and xADL (ArchStudio, 2006; Medvidovic et al., 1999).

Figure 3 shows a screenshot of an ArchStudio4 session in which we have modeled the OA seen in Figure 1. OA software components, each of which has an associated license, are indicated by darker-shaded boxes. Light-shaded boxes indicate connectors. Architectural connectors may or may not have associated license information; those with licenses (such as architectural connectors that represent functional code) are treated as components during license traceability analysis. A directed line segment indicates a link. Links connect interfaces between the components and connectors. Furthermore, the Mozilla component, as shown here, contains a hypothetical subarchitecture for modeling the role of intra-application scripting—as might be useful in specifying license constraints for Rich Internet Applications. This subarchitecture is specified in the same manner as the overall system architecture and is visible in Figure 5. The automated environment allows for tracing and analysis of license attributes and conflicts.

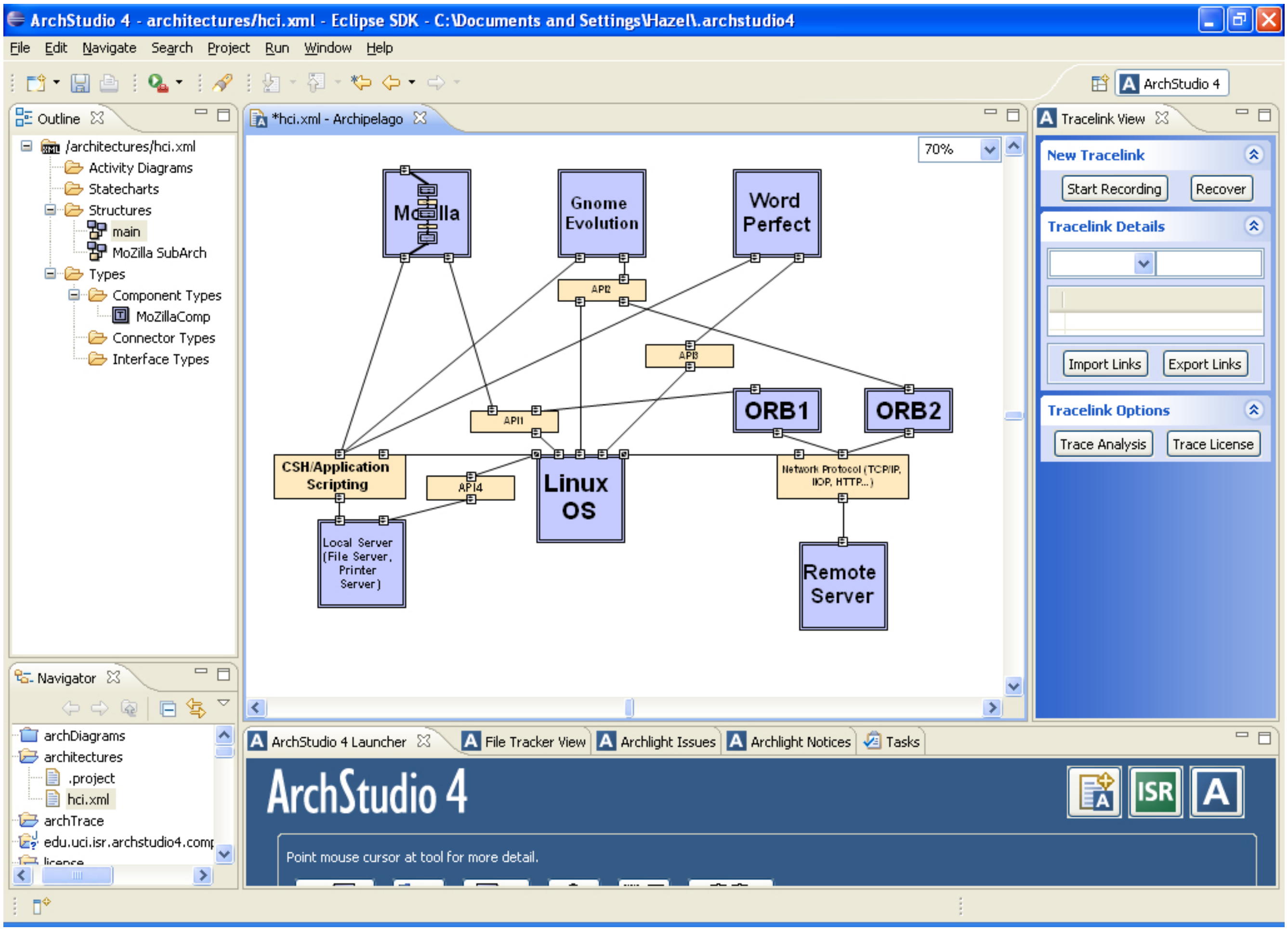
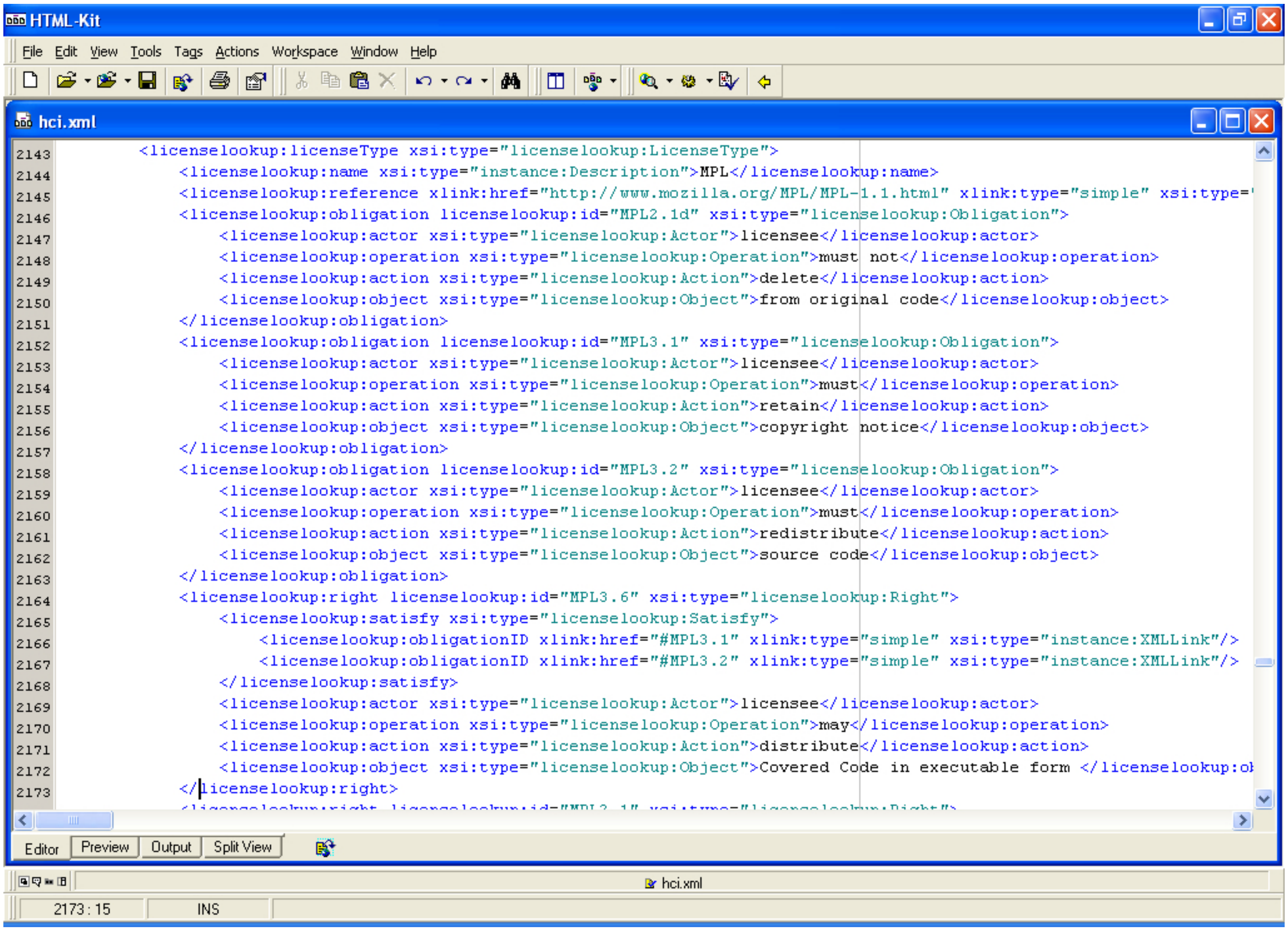


Figure 3. An ArchStudio 4 Model of the Open Software Architecture of Figure 1

Figure 4 shows a view of the internal XML representation of a software license. Analysis and calculations of rights, obligations, and conflicts for the OA are done in this form. This schematic representation is similar in spirit to that used for specifying and analyzing privacy and security regulations associated with certain software systems (Breaux & Anton, 2008).



```
        <licenselookup:licenseType xsi:type="licenselookup:LicenseType">
            <licenselookup:name xsi:type="instance:Description">MPL</licenselookup:name>
            <licenselookup:reference xlink:href="http://www.mozilla.org/MPL/MPL-1.1.html" xlink:type="simple" xsi:type="
            <licenselookup:obligation licenselookup:id="MPL2.1d" xsi:type="licenselookup:Obligation">
                <licenselookup:actor xsi:type="licenselookup:Actor">licensee</licenselookup:actor>
                <licenselookup:operation xsi:type="licenselookup:Operation">must not</licenselookup:operation>
                <licenselookup:action xsi:type="licenselookup:Action">delete</licenselookup:action>
                <licenselookup:object xsi:type="licenselookup:Object">from original code</licenselookup:object>
            </licenselookup:obligation>
            <licenselookup:obligation licenselookup:id="MPL3.1" xsi:type="licenselookup:Obligation">
                <licenselookup:actor xsi:type="licenselookup:Actor">licensee</licenselookup:actor>
                <licenselookup:operation xsi:type="licenselookup:Operation">must</licenselookup:operation>
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            </licenselookup:obligation>
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                <licenselookup:operation xsi:type="licenselookup:Operation">must</licenselookup:operation>
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                <licenselookup:object xsi:type="licenselookup:Object">source code</licenselookup:object>
            </licenselookup:obligation>
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                <licenselookup:satisfy xsi:type="licenselookup:Satisfy">
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                    <licenselookup:obligationID xlink:href="#MPL3.2" xlink:type="simple" xsi:type="instance:XMLLink"/>
                </licenselookup:satisfy>
                <licenselookup:actor xsi:type="licenselookup:Actor">licensee</licenselookup:actor>
                <licenselookup:operation xsi:type="licenselookup:Operation">may</licenselookup:operation>
                <licenselookup:action xsi:type="licenselookup:Action">distribute</licenselookup:action>
                <licenselookup:object xsi:type="licenselookup:Object">Covered Code in executable form </licenselookup:o
            </licenselookup:right>
```

Figure 4. A View of the Internal Schematic Representation of the Mozilla Public License

With this basis to build on, it is now possible to analyze the alignment of rights and obligations for the overall system:

- **Propagation of reciprocal obligations**

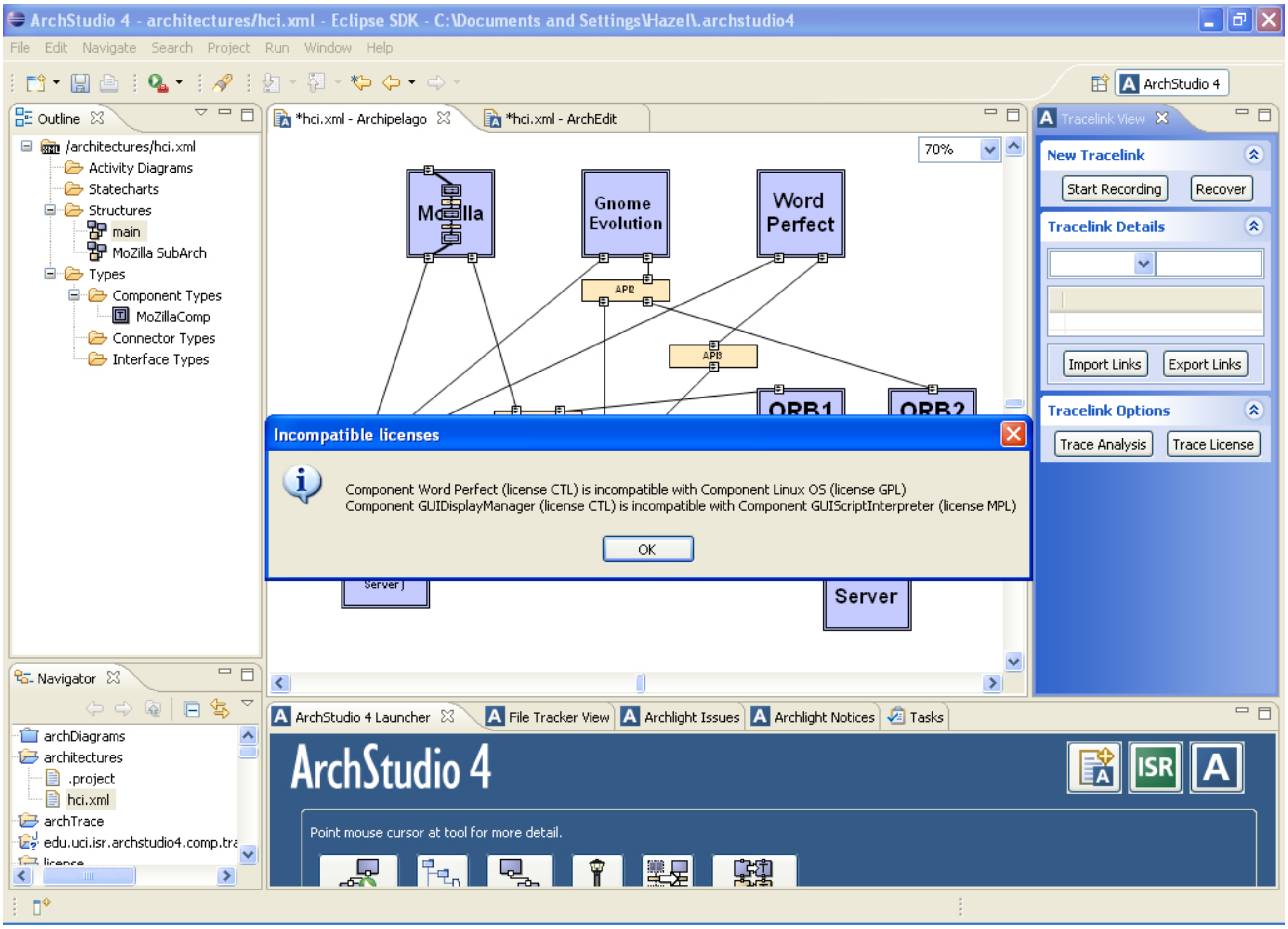
Reciprocal obligations are imposed by the license of a GPL'd component on any other component that is part of the same "work based on the Program" (i.e., on the first component), as defined in GPL. We follow the widely accepted interpretation that build-time static linkage propagate the reciprocal obligations, but the "license firewalls" do not. Analysis begins, therefore, by propagating these obligations along all connectors that are not license firewalls.

- **Obligation conflicts**

An obligation can conflict with another obligation contrary to it, or with the set of available rights, by requiring a copyright right that has not been granted. For instance, the Corel proprietary license for the WordPerfect component, CTL (Corel Transactional License), may be taken to entail that a licensee must not redistribute source code. However, an OSS license, GPL, may state that a licensee must redistribute source code. Thus, the conflict appears in the modality of the two otherwise identical obligations, “must not” in CTL and “must” in GPL. A conflict on the same point could also occur between GPL and a component whose license fails to grant the right to distribute its source code.

This phase of the analysis is affected by the overall set of rights that are required. If conflicts arise involving the union of all obligations in all components’ licenses, it may be possible to eliminate some conflicts by selecting a smaller set of rights—in which case, only the obligations for those rights need be considered.

Figure 5 shows a screenshot in which the License Traceability Analysis module has identified obligation conflicts between the licenses of two pairs of components (“WordPerfect” and “Linux OS,” and “GUIDisplayManager” and “GUIScriptInterpreter”).



Component Word Perfect (license CTL) is incompatible with Component Linux OS (license GPL)
Component GUIDisplayManager (license CTL) is incompatible with Component GUIScriptInterpreter (license MPL)

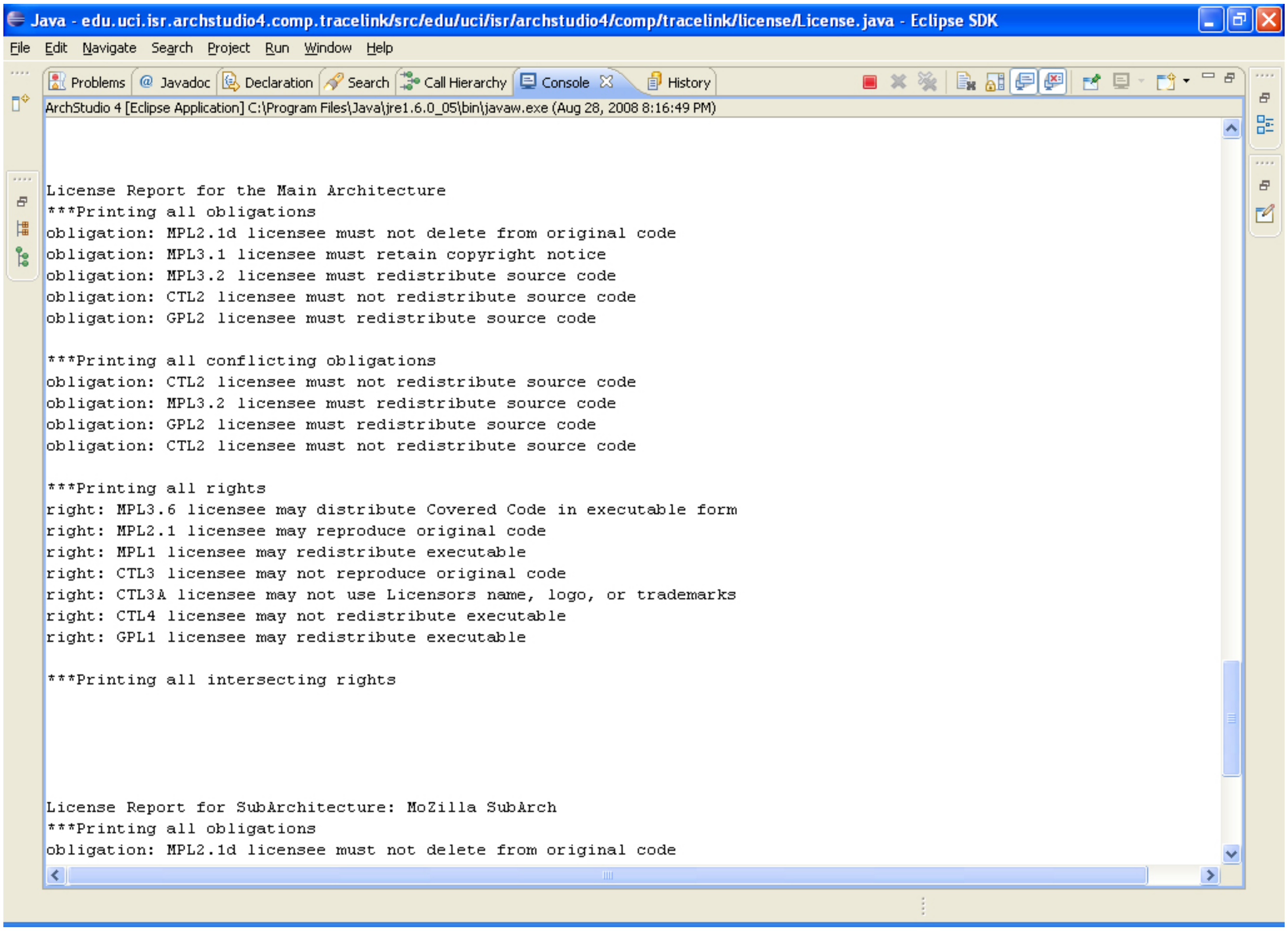
Figure 5. License Conflicts Identified between Two Pairs of Components

- **Rights and obligations calculations**

The rights available for the entire system (use, copy, modify, etc.) then are calculated as the intersection of the sets of rights available for each component of the system.

The obligations required for the whole system then are the union of the specific obligations for each component that are associated with those rights. Examples of specific obligations are “Licensee must retain copyright notices in the binary form of module.c” or “Licensee must publish the source code of component.java version 1.2.3.”

Figure 6 shows a report of the calculations for the hypothetical subarchitecture of the Mozilla component in our archetypal architecture—exhibiting an obligation conflict and the single copyright right (to run the system) that the prototype tool shows would be available for the subarchitecture as a whole if the conflict is resolved; a production tool would also list the rights (none) currently available.



```
ArchStudio 4 [Eclipse Application] C:\Program Files\Java\jre1.6.0_05\bin\javaw.exe (Aug 28, 2008 8:16:49 PM)



License Report for the Main Architecture
***Printing all obligations
obligation: MPL2.1d licensee must not delete from original code
obligation: MPL3.1 licensee must retain copyright notice
obligation: MPL3.2 licensee must redistribute source code
obligation: CTL2 licensee must not redistribute source code
obligation: GPL2 licensee must redistribute source code

***Printing all conflicting obligations
obligation: CTL2 licensee must not redistribute source code
obligation: MPL3.2 licensee must redistribute source code
obligation: GPL2 licensee must redistribute source code
obligation: CTL2 licensee must not redistribute source code

***Printing all rights
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Figure 6. A Report Identifying the Obligations, Conflicts, and Rights for the Architectural Model

If a conflict is found involving the obligations and rights of linked components, it is possible for the system architect to consider an alternative linking scheme—employing one or more connectors along the paths between the components that act as a license firewall, thereby mitigating or neutralizing the component-component license conflict. This means that the architecture and the environment together can determine what OA design best meets the problem at hand with available software components. Components with conflicting licenses do not need to be arbitrarily excluded but, instead, may expand the range of possible architectural alternatives if the architect seeks such flexibility and choice.

At build-time (and later at run-time), many of the obligations can be tested and verified, for example, that the binaries contain the appropriate notices for their licenses and that the source files are present in the correct version on the Web. These tests can be generated from the internal list of obligations and run automatically. If the system's interface were extended to add a control for it, the tests could be run by a deployed system.

The prototype License Traceability Analysis module provides a proof-of-concept for this approach. We encoded the core provisions of four licenses in XML for the tool—GPL, MPL, CTL, and AFL (Academic Free License)—to examine the effectiveness of the license tuple encoding and the calculations based upon it. While it is clear that we could use a more complex and expressive structure for encoding licenses, in encoding the license provisions to date, we found that the tuple representation was more expressive than needed; for example, the actor was always "licensee" and seemed likely to remain so, and we found use for only three operations or modalities. At this writing, the module shows proof of concept for calculating with reciprocal obligations by propagating them to adjacent, statically linked modules; the extension to all paths not blocked by license firewalls is straightforward and is independent of the scheme and calculations described here. Reciprocal obligations are identified in the tool by lookup in a table, and the meaning and scope of reciprocality is hard-coded; this is not ideal, but we considered it acceptable since the legal definition in terms of the reciprocal licenses will not change frequently. We also focused on the design-time analysis and calculation (rather than on build- or run-time), as it involves the widest range of issues—including representations, calculation of rights and obligations, and design guidance derived from them.

Based on our analytical approach, it appears that the questions of what license (if any) covers a specific configured system, and what rights are available for the overall system (and what obligations are needed for them) are difficult to answer without automated license-architecture analysis. This is especially true if the system or sub-system is already in operational run-time form (Kazman & Carrière, 1999). It might make distribution of a composite OA system somewhat problematic if people cannot understand what rights or obligations are associated with it. We offer the following considerations to help make this clear. For example, a Mozilla/Firefox Web browser covered by the MPL (or GPL or LGPL, in accordance with the Mozilla Tri-License) may download and run intra-application script code that is covered by a different license. If this script code is only invoked via dynamic run-time linkage, or via a client-server transaction protocol, then there is no propagation of license rights or obligations. However, if the script code is integrated into the source code of the Web browser as a persistent part of an application (e.g., as a plug-in), then it could be viewed as a configured sub-system that may need to be accessed for license transfer or conflict implications. A different kind of example can be anticipated with application programs (like Web browsers, e-mail clients, and word processors) that employ Rich Internet Applications or mashups entailing the use of content (e.g., textual character fonts or geographic maps) that is subject to copyright protection—if the content is embedded in and bundled with the scripted application sub-system. In such a case, the licenses involved may not be limited to OSS or proprietary software licenses.

In the end, it becomes clear that it is possible to automatically determine what rights or obligations are associated with a given system architecture at design-time and whether it contains any license conflicts that might prevent proper access or use at build-time or run-time, given an approach such as ours.

6. Discussion

Software system configurations in OAs are intended to be adapted to incorporate new innovative software technologies that are not yet available. These system configurations will evolve and be refactored over time at ever-increasing rates (Scacchi, 2007); components will be patched and upgraded (perhaps with new license constraints), and inter-component connections will be rewired or remediated with new connector types. As such, sustaining the openness of a configured software system will become part of ongoing system support, analysis, and validation. This, in turn, may require ADLs to include OSS licensing properties on components, connectors, and overall system configuration, as well as in appropriate analysis tools (Bass et al. 2003; Medvidovic et al., 1999).

Constructing these descriptions is an incremental addition to the development of the architectural design or alternative architectural designs. But it is still time-consuming and may present a somewhat daunting challenge for large, pre-existing systems that were not originally modeled in our environment.

Advances in the identification and extraction of configured software elements at build-time and their restructuring into architectural descriptions is becoming an evermore automatable endeavor (Choi & Scacchi, 1990; Kazman & Carrière, 1999; Jansen, Bosch & Avgeriou, 2008). Further advances in such efforts have the potential to automatically produce architectural descriptions that can either be manually or semi-automatically annotated with their license constraints, and thus enable automated construction and assessment of build-time software system architectures.

The list of recognized OSS licenses is long and ever-growing, and, as existing licenses are tested in the courts, we can expect their interpretations to be clarified and perhaps altered; the GPL definition of “work based on the Program,” for example, may eventually be clarified in this way, possibly refining the scope of reciprocal obligations. Our expressions of license rights and obligations are for the most part compared for identical actors, actions, and objects, then by looking for “must not” in one and either “must” or “may” in the other, so that new licenses may be added by keeping equivalent rights or obligations expressed equivalently. Reciprocal obligations, however, are handled specially by hard-coded algorithms to traverse the scope of that obligation so that addition of obligations with different scope, or the revision of the understanding of the scope of an existing obligation, requires development work. Possibly these issues will be clarified as we add more licenses to the tool and experiment with their application in OA contexts.

Lastly, our scheme for specifying software licenses offers the potential for the creation of shared repositories where these licenses can be accessed, studied, compared, modified, and redistributed.

7. Conclusion

The relationship between open architecture, open source software, and multiple software licenses is poorly understood. OSS is often viewed as primarily a source for low-cost/free software systems or software components. Thus, given the goal of realizing an OA strategy together with the use of OSS components and open APIs, it has been unclear how to best align software architecture, OSS, and software license regimes to achieve this goal. Subsequently, the central problem we examined in this paper was to identify principles of software architecture and software copyright licenses that facilitate or inhibit how best to ensure the success of an OA strategy when OSS and open APIs are required or otherwise employed. In turn, we presented an analysis scheme and operational environment that demonstrates that an automated solution to this problem exists.

We have developed and demonstrated an operational environment that can automatically determine the overall license rights, obligations, and constraints associated with a configured system architecture whose components may have different software licenses. Such an environment requires the annotation of the participating software elements with their corresponding licenses. These annotated software architectural descriptions can be prescriptively analyzed at design-time, as we have shown, or descriptively analyzed at build-time or run-time. Such a solution offers the potential for practical support in design-time, build-time, and run-time license conformance checking and the evermore complex problem of developing large software systems from configurations of software elements that can evolve over time.

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