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Valuation of capabilities and system architectural options to meet affordability requirement

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Valuation of Capabilities and System Architectural options to Meet Affordability Requirement

18 March 2014

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Table of Contents

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List of Figures

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List of Tables

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Executive Summary

This research addresses the problem of how to (1) value architectural options that deliver capabilities to the warfighter not inherently measured in dollar values and (2) conduct a trade study of architectural options, the option's cost, and the option's risk to support the affordability mandate for a more effective and efficient acquisition decision-making process. The research models acquisition as a sequential decision process with an options framework but with two significant distinctions: First, it identifies and values system architectural options available in the system design, and not options on the project, and second, it measures capabilities in terms of mission effectiveness compatible with how defense managers think. Architectural options provide flexibility to deal with technical and operational uncertainty. The research contributes to the performance of trade studies in acquisition through the definition of *architectural options* in terms consistent with defense acquisition (capabilities and not cash flows) and a theory for how program managers can value the capabilities those options provide. The research is intended to support the evolutionary acquisition of system capabilities. As RADM Rowden (2014), the director of Surface Warfare stated,

> We cannot afford to build ships that are retired because they have been outpaced by the threat; rather, they will need to be retired because they have reached the end of their service life. Defined interfaces and modular designs will treat capability as a commodity, enabling continuous modernization to stay one step ahead of the threat. These "designed-in" features will dramatically lower the complexity of modernizing ships, reducing the time spent in overhauls, increasing operational availability, and reducing total ownership cost.

Keywords: System architecture, capability-based analysis, real options, systems engineering.

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Valuation of Capabilities and System Architectural options to Meet Affordability Requirement

Introduction

The U.S. Department of Defense (DoD) acquires systems to deliver capabilities needed by the warfighter. Acquisition of a system starts with defining capability gaps and covers the system development life cycle from initial conceptualization to system production and delivery. Several challenges continue to plague the acquisition process of new systems; the adoption of a real options framework to evaluate architecture design might help address these challenges. In very complex systems for dynamic military environments, it is inevitable that user needs and operational requirements will change. While change is foreseeable, the exact nature of the change is not. The real options framework is intended to value and defend the inclusion of flexibility in system architectures to deal with uncertainty in technology and operational needs and ensure that the system delivers value to stakeholders over the span of its intended life cycle. Flexible system architectures hold out the possibility of systems that can evolve and adapt to changing operational and technical needs in order to achieve affordable programs over the long term. This research report describes a framework for applying real options to value flexibility in system architectures.

Acquisition Background

A capability is a system's enduring ability to generate a desired operational outcome or effect in the context of its environment. The U.S. DoD uses a capability-driven process to determine capabilities needed by the warfighter. The capability-based analysis (CBA) is governed by the Joint Capability Integration Development System (JCIDS). The intent of a capability-based acquisition model is to remain solution neutral to remove any bias toward a particular system or technology. CBA focuses on what the warfighter needs rather than how the needs can be delivered. Moreover, it emphasizes the combination of materiel or system solutions with non-materiel solutions achieved through what is called doctrine, organization, training, leadership and education, personnel, and facilities (DOT_LPF) changes. There are challenges with the CBA approach, among them the difficulty of envisioning abstract capabilities without also considering how those capabilities are delivered.

Under diminishing budgets yet a constant (or even a growing) threat environment, the DoD must be able to acquire and deliver capabilities more affordably. The Defense Acquisition System develops and fields systems to meet the requirements defined by JCIDS. In 2010, Dr. Carter, while serving as under secretary of defense for acquisition, technology, and logistics (USD[AT&L]), issued a memo for the Better Buying Power (BBP) initiative to improve the efficiency of the acquisition process. Part of the BBP initiative is to mandate affordability as a requirement when considering systems to acquire. Affordability is intended to ensure program success by balancing system performance, total ownership cost, and schedule while also considering the DoD's long-range investment plans. Two additional USD(AT&L) memos further addressed the incorporation of affordability considerations into the Defense Acquisition System. The affordability target is treated by the program manager as a key performance parameter that is used in pre–Milestone B decision-making and systems engineering trade-off analysis. New programs need to produce an affordability analysis pre–Milestone A, including an affordability element in the analysis of alternatives and a systems engineering trade-off analysis pre–Milestone B. The trade-off analysis should show how the program costs vary against the major design parameters as well as the projected schedule. The BPP initiative also calls on program managers to pay attention to spiral upgrades because it is apparent that systems will have to be upgraded in order to continue providing value during anticipated long operational lives.

Instituting the intent of the memo requires both a cultural shift in how the DoD views system architecture and programs as well as the tools, methods, and processes to support affordability analysis. The perspective of this research is that the acquisition system is a sociotechnical system, or an enterprise system consisting of people, processes, and data that are used to acquire systems that are the output of the acquisition process. Letting the sociotechnical perspective inform the research approach, this paper emphasizes that transforming how the DoD conducts acquisition to make it more efficient requires not just tools but also cultural change. I believe that the foremost needed change in perspective is for the DoD to start thinking about systems not as a point solution to a well-defined set of requirements but as a set of architectural options that will allow the system to adapt and change to shifting capability needs and threats over its lifetime. Koenig, Nalchajian, and Hootman (2009), from Naval Sea Systems Command, echoed this change in perspective when they remarked that conventional decision analysis methods are oriented to decision-making under certainty, which is inappropriate for the acquisition of ships that require the evaluation of large, risky expenditures for a long-lived investment. The defense acquisition process demonstrates and acknowledges that systems must change in the increasingly planned use of system spiral upgrades. However, the success of spiral upgrades is premised on the specification of a system architecture that will accommodate these changes. Designing such a system architecture is fraught with difficulty. To illustrate some of the challenges, consider the U.S. Army's lightweight counter mortar radar system (LCMR), which is part of a the Counter-Rocket, Artillery, and Mortar (C-RAM) system of systems. In the first spiral of the development and acquisition process, there was a trade-off decision to have a smaller hardware unit to save on weight and then make up for the smaller hardware's lower signal-to-noise ratio (SNR) performance with software that could provide a higher virtual SNR through a sampling algorithm. However, in the second spiral iteration to acquire additional capabilities for when the LCMR was integrated with the C-RAM, it was found that the trade-off decision to compensate for the lower hardware SNR with software in the first spiral led to an unacceptable time delay. As a result, a costly redesign of the LCMR software ensued to reduce the time delay. This very brief description of a complex acquisition program highlights the difficulty in making decisions because of the sequencing of decisions, the uncertainty involved, and the constantly evolving needs of our military. What was missing in this case was the perspective to define and value capabilities over the entire life of the system and feedback those valuations into a system architecture that can be affordably adapted to deliver those capabilities.

Acquisition Issues

This section reviews five of the main issues that architectural options can help address in DoD acquisition.

1. Complexity
   The DoD tends to acquire highly complex technological systems. The complexity is manifested as technology risk in the system and as long development times to iterate through design-test-build cycles. Technology risk arises because many systems are based on unproven technologies. Project development teams are uncertain about how the technology will perform and what issues might arise during both development and operation of the technology. This is epistemic uncertainty, which is resolved by gaining knowledge through modeling, analysis, simulation, and experimentation. The implication for this paper is that it is only under uncertainty—in this case, technical uncertainty due to complexity—that flexibility has value.

2. Development Lead-time
   The system acquisition process is a long process, with the average military project lasting almost 10 years (Charette, 2008). The high-level architectural decisions are among the first technical decisions made in the design process. The dilemma is that these early decisions are made under the greatest amount of uncertainty. The implication for the research is that architectural decisions, which are the earliest design decisions, have significant impact. If the architecture is designed with options to provide

flexibility, then it is possible to adapt the system design later as operational uncertainty and technical uncertainty are resolved.

3. Development Methods
   Systems are often designed and built to provide full capabilities in the first initial delivery of the system. This is one aspect of the development process contributing to very long development times for some programs. Acquisition is shifting to an evolutionary acquisition strategy that fields the initial system with operationally acceptable capabilities and then adds new capabilities in subsequent increments. A benefit of the evolutionary approach is that the increments need not be done if the operational environment changes, budgets change, or technology changes. Another related approach to acquiring capabilities is via systems of systems, which are managerial independent systems that interoperate in such a way to provide unique and useful capabilities. A real options approach to systems engineering is best matched with one of the evolutionary types of design processes or a system-of-systems engineering approach. A traditional systems engineering process is not amenable to a real options approach because if all of the capabilities are delivered at once in a single system without consideration of future upgrades, then there is no role for options.

4. Opportunities As Well As Risks
   When dealing with risk, the systems engineering and project management concentrate on the downside risk and take steps to mitigate or avoid the risk or reduce the consequences of the risk in the system design. What is often ignored is the potential upside of an uncertain event that the system could take advantage of. A real options approach values the upside opportunities as well as the downside risks associated with architectural decisions.

5. Changing Technology
   In some cases, such as information technology (IT), it is important to design the system with the expectation that computing capabilities will grow exponentially and the computer portions of the system will be updated in a shorter cycle than other components.

Research Goal

This research is targeted to acquisition process efficiency and, more specifically, to enhancing Acquisition decision-makers' understanding of the relationship between system architecture, capabilities, and affordability. The research models acquisition as a sequential decision process with an options framework but with two significant distinctions: First, it identifies and values system architectural options available in the system design, and not options on the project, and second, it measures capabilities in terms of mission effectiveness compatible with how defense managers think. The research develops the theory, builds a computational tool, and demonstrates how to identify and value architectural options using a case study of a Navy system. The research contributes to the early trade studies in acquisition through the definition of *architectural options* in terms consistent with defense acquisition (capabilities and not cash flows) and a theory for how program managers can value the capabilities that those options provide. The research contributes to the design of systems that can be affordably developed to deliver value over their entire expected service life via a spiral acquisition process. The research also contributes to the incorporation of flexibility into system architectures through the concepts derived from real options.

Research Issues

The research addresses the following research issues:

1. how to define options in system architectures,
2. how to value military capabilities,
3. how architectural optionals interact with one another, and
4. how to link architectural options to the acquisition decision process for affordability analysis.

The following sections explain how the paper addresses these issues in our architectural options framework.

Research Approach

This research project is premised on the idea that delivering affordable capabilities starts with system architecture decisions that must be part of the trade-off decisions between performance, cost, and schedule. Affordability must consider the entire service life of the system. It is probable—in fact, most existing systems have illustrated—that the needs and subsequent system requirements will change over the life of the system. For example, the IT on a ship will become obsolete and require replacement in order to maintain value. The system architecture must be designed so that these, and other less obvious changes, can be accommodated in the future; otherwise, when the architecture is not designed for these changes, the upgrades become very costly.

The systems engineering process and the acquisition process are designed to deliver systems that meet stated requirements at a particular point in time. Many designs do not accommodate for changes in the system environment in terms of threats, changes in technology, or other external changes. To make good decisions justified by the available data, the program manager needs to do the following:

- Link architectural options and decisions to needed capabilities. Achieving more or less of a particular capability usually implies a change in the system architecture, which will then in turn affect other system capabilities, including desired future capabilities.
- Deal with the uncertainty in the underlying data, model predictions, and future needs, as well as the risk that emanates from those uncertainties.
- Value capabilities in terms of mission effectiveness and performance. Normally, the units of different capabilities will be incompatible and there will be more than a few that must be simultaneously traded off, limiting the efficacy of simple two-dimensional graphs. For example, in ship design, three design parameters—displacement, endurance, and speed—must be traded off simultaneously along with other architecturally significant design parameters.
- Account for how present decisions will affect future decisions. The systems engineering community knows that early decisions impact later system design as well as acquisition decisions. An essential characteristic of any decision support must leave flexibility—in this paper's approach, defined as *architectural options*—that will accommodate future decisions affordably.

It is under uncertainty that architectural options have value. If there were no uncertainty, there would be no risk and no need for architectural options. This research subtask investigates the nature of acquisition uncertainty, risk, and capability needs and then develops a framework to model and link them together in a causal network.

Real Options

The concept of real options is taken from the financial options on which they are based. Real options allow the holder of the option to exercise the option if conditions are favorable, but the holder is not obligated to exercise the option if conditions are unfavorable (Trigeorgis, 1995). Consequently, the value of options is that they allow for the upside potential while limiting the downside risk. Options only have value in the face of uncertainty and when that uncertainty is expected to be resolved before all of the investment decisions must be made. This situation is what is faced by advanced weapon system projects. During system development of advanced weapon systems, the uncertainty is due to technical and operational sources. Project success is only apparent after the project starts and progresses. A real options valuation considers the fact that decisions are made sequentially and that the decision-maker will use all available information at the time the decision is made.

Real options are based on the valuation of the underlying asset whose value is modeled as a stochastic process. In finance, the underlying asset is a tradeable stock and the stochastic process is an extension of the historic volatility and trend of the stock using Brownian motion. In finance, the Black-Scholes equation is used to value call and put options (Trigeorgis, 1995). For real options, selection of the underlying asset is less clear, identifying the volatility is more difficult, and there are several alternative approaches to model the stochastic process. Formulating architectural design in the context of real options allows valuation of architectural project options that in turn allows for both risk reduction and the possibility of exploiting upside potential if it should arise.

Real options give the right but not a symmetric obligation to evolve the system and enhance the opportunities for strategic growth by making future follow-on investments (e.g., case of reuse, exploring new markets, expanding the range of services while leaving the architecture intact). Since flexibility has a value under uncertainty, the value of these options lies in the enhanced flexibility to cope with uncertainty (i.e., the evolutionary changes). The importance of the real options concept cannot be overemphasized: It gives the architects/stakeholders an ability to reason about a crucial but previously intangible source of value and to factor the ability of an architecture to adapt into the tradeoff analysis and acquisition decision-making.

Real options are both a means to value investments as well as a means to define *flexibility* in system deployment (Trigeorgis, 2001). Koenig et al. (2009) discussed the high level of uncertainty, and hence risk, associated with conventional engineering economic analysis of projects that have long operational lives. They suggested that the DoD environment is actually rich with options, but until now, there has been no quantitative means to value them and incorporate them into the acquisition decision process. In fact, quite an extensive amount of research has been conducted on the proposed or actual use of real options with project planning and acquisition.

Real options are better at valuing investments in situations where the decision-maker has flexibility to make changes in the future and the environment is uncertain. Traditional approaches to valuing investments based on discounted cash flows are inadequate in dealing with both flexibility and uncertainty. To illustrate, consider a project to build a satellite. The investment in the satellite might be unattractive based on a pure net-present value analysis, but it may be that by launching the satellite, the organization has the opportunity to add additional valuable capabilities in the future. These possible future capabilities are not considered in the traditional value analysis, and it is these possible future capabilities, called options, that real options values. In uncertain environments when there is flexibility to make subsequent decisions, traditional valuation approaches undervalue flexibility in the system.

Architectural Options Framework

This section describes the method I used to identify system architectural options and to value those options. Figure 1 shows the overall concept that today's capability needs will evolve over time to future capability needs. Architectural options are needed to enable fulfillment of these future capability needs. Incorporating them into the architecture today requires understanding their value—hence, real options.

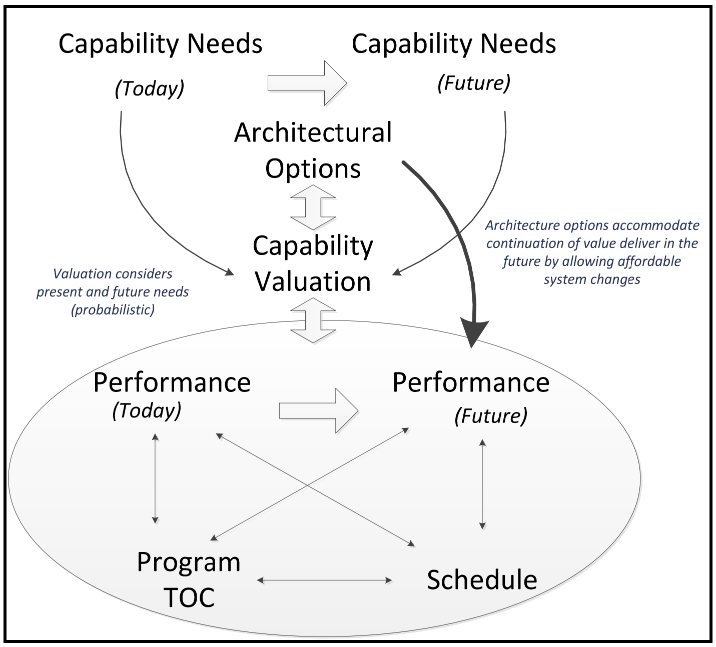

Figure 1. Architectural Options and Relationship to Capability Needs

System architecture is the representation of the structure of a system embodied by its elements, the logical and physical relationships between the elements, their relationships with the environment, and the principles or concept guiding the system's design and evolution over time. The types of elements and relationships in an architecture depend on the architectural view of operational, functional, or physical. A system architecture is divided into three main views—operational, functional, and physical architectures—with mappings showing how elements in one view are related to elements in the other views. Collectively, the three views provide a holistic model of how the system fulfills its mission. This paper considers all three architectural views in this research. The views are all included in Department of Defense Architectural Framework.

The development of a system architecture is driven by a design concept that gives form to ideas about how a system's functions and behaviors maximize stakeholder value. The architect must balance the many competing needs and objectives present in modern, complex system design projects. A design concept is a central part of an architecture because it describes how the system's form embodies working principles and how functions and behaviors are mapped to physical components. The concept guides future design decisions. Many acquisition professionals are familiar with operational concepts as described in the concept of operations (CONOPS) document. Likewise, design concepts underlie the functioning and physical structure of the system. Oftentimes, the architecture informally or inexplicitly defines the concept.

The architectural options approach involves the following steps:

1. identify sources of uncertainty,
2. define measures for the capabilities,
3. model uncertainty using scenarios,
4. partition the system architecture into modules,
5. define architectural options in the architecture,
6. value options, and
7. present the valuation to the decision-maker.

These steps are described in the following subsections.

Classification of Program Uncertainty, Risk, and Capability Needs

Uncertainty is the state of not knowing something exactly, and this is a pervasive state in the design of systems. Uncertainty in a system can arise in the operational environment, technology environment, and the acquisition process. Uncertainty can be classified as either epistemic uncertainty or aleatory uncertainty. Epistemic uncertainty is due to our incomplete knowledge of the system, threats, or operational environment and is especially prevalent in the early stages of the system design process. Through research and development, these uncertainties are systematically removed during the acquisition process. Aleatory uncertainty is due to the inherent variability of the system parameters, system input, or system environment. Aleatory uncertainty is the irreducible uncertainty; it cannot be removed and is quantified in a statistical manner.

The uncertainty most relevant to architectural options is operational uncertainty and technical uncertainty. Systems are acquired with very long expected operational lives. The USS *Gerald R. Ford* (CVN-78) aircraft carrier is being acquired with the intention of beginning its operational phase in 2016. The ship is designed to operate for 50 years—the planned disposal date is 2066. Given this long operational life, it is impossible to accurately forecast how naval warfare and the capability needs of the aircraft carrier will change during these years.

Systems are exposed to uncertainty in their technical environment in that the technology will change and technological opportunities will emerge over the system's operational life. Technology advances in both a predictable, evolutionary manner as well as in a disruptive manner. Technology evolution leads to obsolescence of technology and the need to periodically update the technology. The simplest obsolescence is when the technology can be replaced with a newer technology that has the same interface. Obsolescence that involves interface changes is more difficult to deal with, and the most difficult obsolescence to handle is if the functionality changes or there is a disruptive technology shift that leads to a new design concept incompatible with the system's architecture. A technology can become functionally obsolete because it is subsumed by another technology or a different design concept.

Systems are exposed to uncertainty in their operational environment. The operational environment is characterized by the missions that a system is designed for, the capabilities it needs to fulfill those missions, and the nature of the threats it will encounter.

To enable this strategy, the system architecture must be designed to support the incremental addition of capabilities. Sources of uncertainty are changes to the operational environment, to the funding availability, and to the technical environment. Changes to the operational environment flow down to the system and change system requirements.

Some uncertainty can be resolved, such as with technology evolution, which might be predicted to continue following Moore's Law in the near to mid-term future. In this case, the uncertainty is not in technology evolution but in the rate of growth and the implications of that growth.

Measuring Capabilities

A capability is defined as the ability to achieve a desired effect under specified standards and conditions through combinations of means and ways across DOTMLPF to perform a set of tasks to execute a specified course of action (JCIDS). The term *ways and means* refers to the non-materiel components and the materiel components of the capability, respectively. A capability is essentially a high-level operational requirement expressed in language that the stakeholder understands. A measure of effectiveness (MOE) is a measure that corresponds to the delivery of a capability in the system's expected environment. MOEs are defined from the stakeholder's perspective, specifically the acquirer. A good MOE is linked to the desired end state, has a strong relationship between cause and effect, and is observable and quantifiable. A MOE is defined without reference to the design solution and should in theory be a useful measure regardless of what technology, design, or process is used to meet the capability needs.

A measure of performance (MOP) is a measure of the performance of a system function. A MOP is defined from the technical viewpoint of designing a system that will fulfill the mission as characterized by the MOEs. Since a capability is fulfilled by one or more system functions, a MOP that measures the performance of a function will consequently map to a capability via the function.

Architectural Options

The first research issue, architectural options, is part of the system design process and requires awareness of the design team to think about options as well as creativity to design system architectures around those options. The need for architectural options in systems is to provide flexibility for the system in adapting to uncertainty in the operational and technical environment. As discussed in the Literature Review section, there is little work in identifying options in the architecture as opposed to the more common definition of options on the project.

The architectural options are all part of the same system and consequently will be interdependent—in essence, a system describes a portfolio of options. The interdependence must be included in the model since changes in any one option will affect others.

The system architectural options must be linked to the capabilities they provide and incorporated into the acquisition decision process. Linking options to capabilities entails understanding how the architectural options contribute to system performance and measuring them in a way that they can be included in the trade-off analysis conducted by the program manager and others for affordability analysis. Figure 2 shows the relationship between the sources of uncertainty, what actions could be taken to deal with the uncertainty, and how architectural options enable those actions. For example, future operations might require greater use of special operations forces, a source of operational uncertainty. A capability gap may be the Navy’s ability to deploy these forces. An action could be the development of a special operations module on the Littoral Combat Ship (LCS) — an “add component” action. The add component action is enabled by architectural options that include the infrastructure support, weight/space support, open interfaces, and ability to form modules.

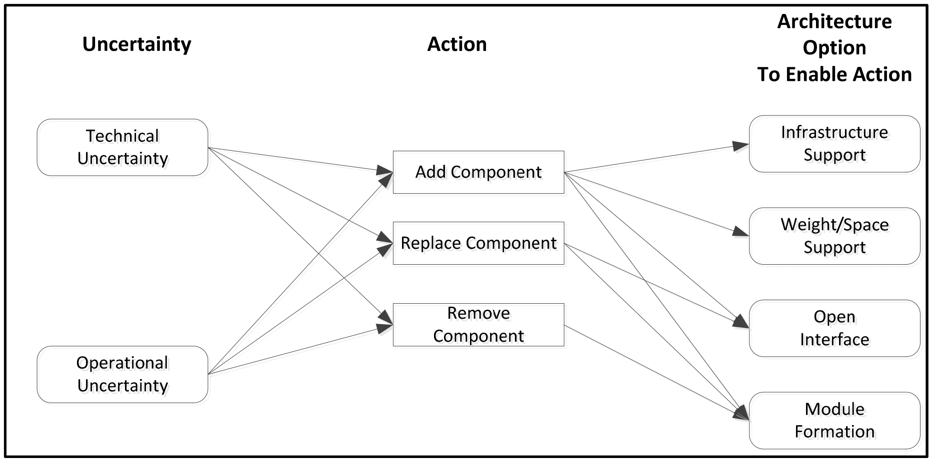

Figure 2. Relationship Between Uncertainty and Architecture Options

Clustering into Modules

Modularity and open architecture concepts are important enablers to a real options approach to system architecture. Architecture modularity is achieved by partitioning the system into self-contained subsystems that deliver complete functions independent of other subsystems. The interfaces between subsystems should use open standards and be transparent to the greatest extent possible. Another important consideration is the expected technical operational use of the subsystem. Computer and IT subsystems tend to become obsolete much faster than most hardware-oriented subsystems. Separating these subsystems into self-contained subsystems or designing them for easy updating of software increases the modularity of the system.

Mission modules apply the modularity concept to the operational architecture because they provide flexibility to respond to different missions. The best example of mission modularity is the LCS, which has mission modules planned for antisubmarine warfare, surface warfare, and mine warfare.

A module has high internal cohesion and low coupling with other elements in the system. Ulrich and Eppinger (2011) defined three types of modularity: slot modular, bus modular, and sectional modular. Slot-modular components are defined with unique interfaces. Bus-modular components are defined with a common interface. Sectional-modular components can be attached to other modules by means of a standard interface.

Interdependence

A module has low coupling with other modules and high internal cohesion. Cohesion and coupling are two measures of the interactions between components in a system. Cohesion is a measure of the degree to which components within a subsystem interact with each other to perform a single function or small set of related functions. Coupling is the degree of the interaction between subsystems. To paraphrase, cohesion is within a single subsystem and coupling is between subsystems. This discussion uses the generic term *interactions*; however, it is possible to define *cohesion* with respect to other characteristics such as engineering knowledge domains, type of material or manufacturing process, or the functions that the components perform. For example, the hydraulic subsystem in an airplane is defined to be cohesive in terms of the domain knowledge required to design and develop the hydraulics.

A heuristic is a rule of thumb that, in the context of architecture, describes a best practice that creates a modular and flexible architecture via architectural options. The heuristic to maximize the cohesion of subsystems and to minimize the coupling between subsystems has proven useful again and again. The reasons for this heuristic are to make an architecture that is more easily understood; to make partitioning the system into subsystems easier; to minimize the number of interfaces between subsystems; and to make changing, maintenance, and supportability of the system easier. Each of these objectives is discussed in this section. First, a system that has high cohesion within subsystems and low coupling between them is easier to understand because it has fewer interactions at the system level. The interactions are mostly within the subsystem level, which is hidden in the architecture level. The low coupling between subsystems means that there are fewer interfaces between subsystems. This makes the project easier to manage since interfaces are negotiated and then become configuration control items via the interface control document. Minimizing coupling works because the interactions between subsystems are generally more difficult to manage and control due to how most systems engineering projects are performed. In general, each subsystem is assigned to a subteam— a small group that is more easily managed by the project manager—for completion. All of the interactions inside of a subsystem are within the control of the subteam. The interactions between subsystems will involve two or more subteams. The coordination of the work of these subteams is more difficult and requires greater effort and negotiation. Consequently, by minimizing coupling, you minimize the need for coordination between subteams.

When subsystems are loosely coupled, one of the subsystems can be changed without or with only minimal need to change the other subsystem. In other words, the subsystems are highly independent. Changes to one do not necessarily infer changes to the other. In system development, this independence between subsystems is good because it reduces the need for coordination between the subteams developing each subsystem. This property is also beneficial to upgrades of the system, because one subsystem could be upgraded without necessitating upgrades to the other subsystem. In general, it is found that coupling is detrimental to system development because it prevents making changes to components independent of the whole.

Coupling between two components is due to the interaction between the components, classified per the types shown in Table 1. The interaction types are used to populate a design structure matrix (DSM). The DSM shows each component in what is essentially an N2 matrix and the interactions between them as either a 0 or a 1.

Table 1. Interaction Types

No interaction
Physical interaction (static)
Energy flow
Material flow
Information flow

Computer algorithms are needed to help identify potential modules because the size and complexity of system architectures preclude a manual approach. This paper adopts a clustering algorithm from Thebeau (2001), who defined a cost for each module based on interactions with penalties, adjustable by the user, for cluster size as well as a few other parameters to control the algorithm. The algorithm uses a bidding process with hill climbing to search for an optimal solution. The top graph of Figure 3 shows one of the DSMs evaluated in this paper; the bottom graph shows how the clustering algorithm formed modules. A good modularization has most of the interactions inside a module and very few interactions between modules. The results for the simple case show only ten interactions outside and between modules.

In the practice of forming modules, the algorithm is executed iteratively with the user changing parameters or the DSM, re-executing the algorithm, and repeating the cycle until a satisfactory clustering of modules is formed. The point of the algorithm is to speed up the generation of alternative architecture modularization concepts, but the algorithm does not necessarily automatically generate the modularization that is eventually used.

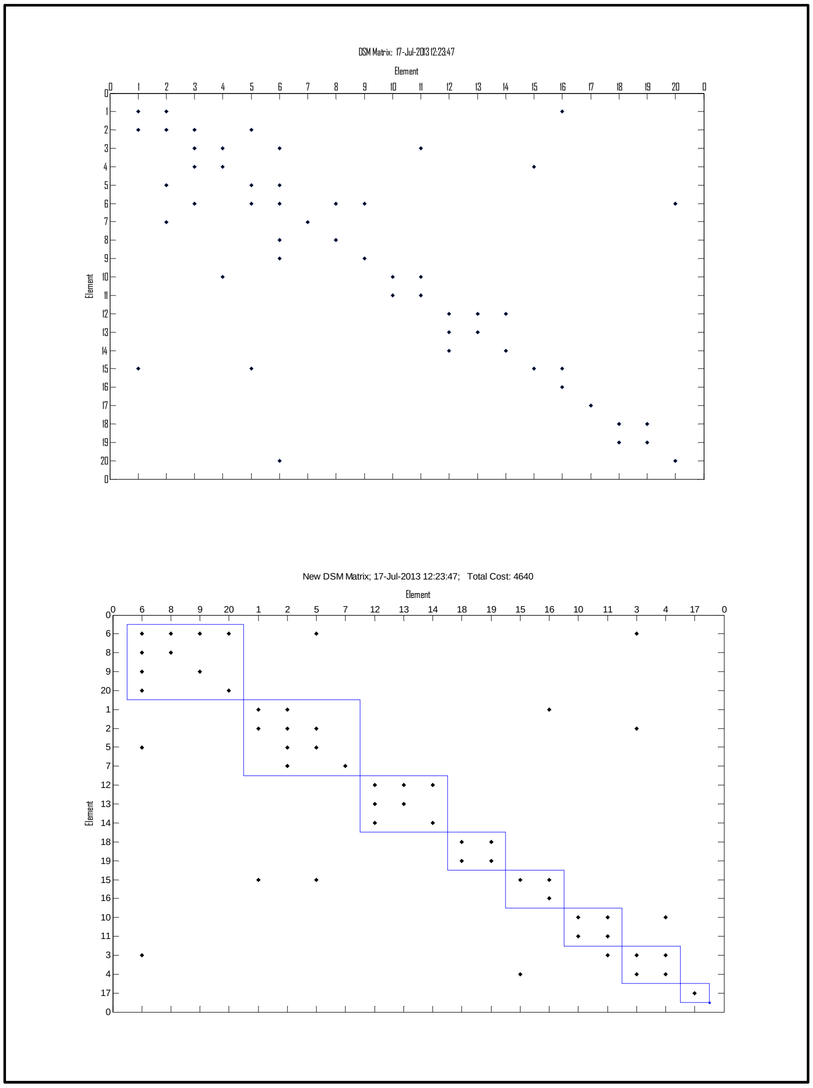

Figure 3. The Initial Design Structure Matrix and the System Clustered into Modules

Architecture Heuristics

Table 2 shows the main architecture heuristics. These heuristics are used to design system architectures to create architectural options.

Table 2. List of Architecture Heuristics

Heuristics
Architecture models to standardize data, processes, and structure
Function partitioning
Partition hardware and software
Partition high-risk technologies
Specialization versus generalization
Interfaces used industry-supported standards

The interface between modules is important; Table 3 shows the general types of interfaces. The architectural options require the interfaces between the modular subsystems to be defined appropriately.

Table 3. Interface Types

Interface Type	Description
Connector	Facilitates interaction of energy, material, or information flows
Isolator	Inhibits interaction of energy, material, or information flows
Converters	Alters the flow in the interaction

Scenarios

A scenario is a possible outcome, usually operational in nature, and is modeled as a node in a decision tree (see Figure 4). Scenario modeling is a standard approach in systems engineering.

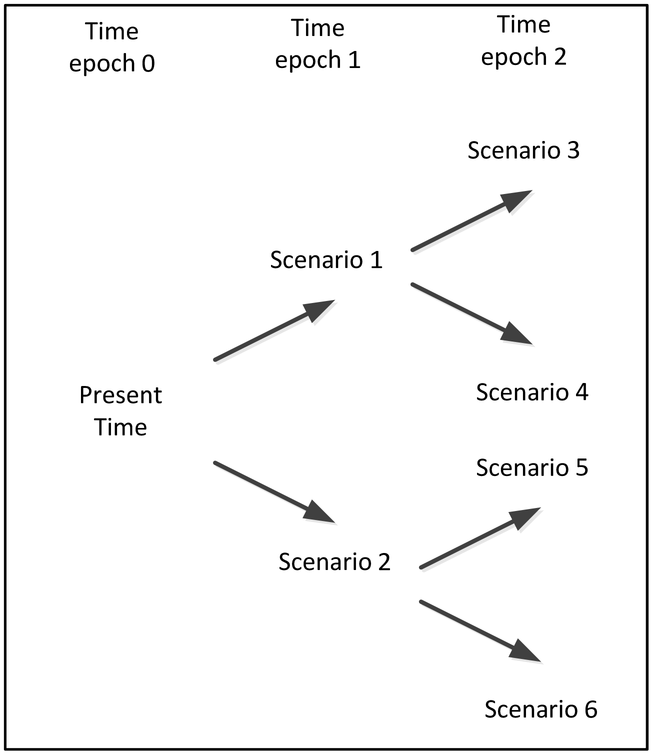

Figure 4. Scenarios in a Decision Tree

Valuation of Options

The valuation of architectural options is performed with a decision-tree structure because the uncertainty is defined by the future operational and technical scenarios. The decision tree is represented mathematically using set theory. Let t denote a time period in the set 1 … T. In each time period, the decision-maker makes a decision in whether to invest in an option. Let x_{ti} denote the execution of option i in time period t.

The objective is to maximize the MOP, which varies with time t, the operational scenario k that the system encounters, and which options i are active in the system. The real options model assumes that there is a fixed lower-level performance denoted by f_i and a variable component denoted by λ_{ti}. The objective function is

$$MAX\ MOP = \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{k=1}^{K} f_i + \lambda_{ti} x_{ti} s_{tk} \quad (1)$$

The decision-maker evaluates the values in the decision tree for all terminal nodes and then works backward until reaching the root node. The value at each node is represented with a value vector v_j that stores the accumulated benefits and costs from the downstream nodes.

Presentation of Results

The decision tree valuation results are best presented as architectural trade-off curves showing the capabilities measured by MOEs/MOPs and the cost. See Figure 5.

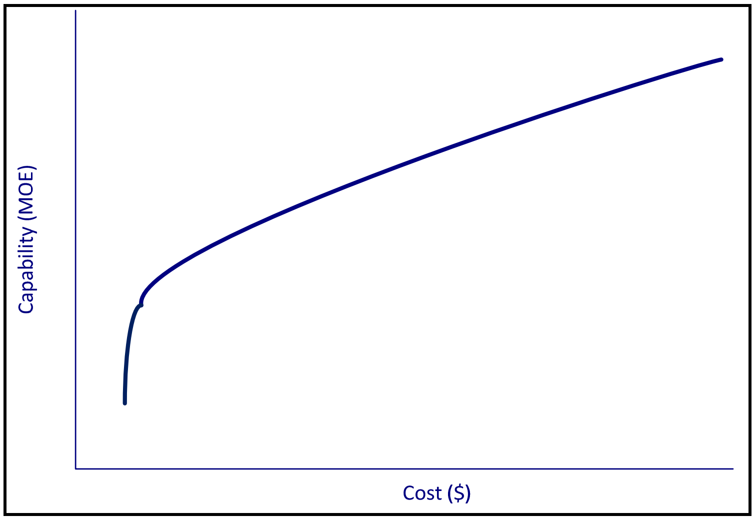

Figure 5. Notional Architecture Trade-Off Curve

Publications and Dissemination of Results

A paper will be published at the 2014 Acquisition Research Symposium to illustrate the method. Additionally, a journal article is in preparation on the valuation of real options for the phased acquisition of system capabilities.

Related Research Efforts

LCDR Heather Skowron, a student at the Naval Postgraduate School (NPS), is doing her master's thesis to specify a phased plan for the Coast Guard to develop and deploy a manpower determination system, which is a workflow system for the Coast Guard to analyze the workload requirements for ships and determine the type and number of crew. Skowron is designing a modular system architecture and mapping it to a schedule that will deliver capabilities in an evolutionary manner every six months. The architecture is designed to utilize commercial standards to preserve openness, and it allows Coast Guard decision-makers options on whether to implement certain system elements depending on their valuation of the capabilities provided. Skowron is expected to complete her thesis by May 2014. A second NPS student, LCDR Kara Lavin, is expected to continue this line of research for the Coast Guard when she does her thesis later in 2014.

Progam Executive Office Integrated Warfare Systems 1.0 is interested in combat system flexibility and system modularity. It presented this research topic during the 2014 Naval Research Requirements Fair. I spoke to the research sponsor and plan to submit a proposal to do this research, which will build upon the research conducted in this project.

Related Work

This research seeks to develop a model and method to use real options to value system architectural options and is consequently related to research in system flexibility and in real options. Flexibility has long been desired in the design of systems in order to deal with anticipated uncertainty in the system's development and operational lifetime (Giachetti, Martinez, Sáenz, & Chen, 2003; Ross, Rhodes, & Hastings, 2008). In the past decade, the theory of real options has increasingly been seen as a means to define and value flexible investment decisions in a project (Mun, 2006; Trigeorgis, 1996). Real options, inspired by the use of financial options, allow the option holder to exercise the option if conditions are favorable, but the holder is not obligated to exercise the option if conditions are unfavorable; the overall result of this process allows for upside potential and limiting the downside risk (Trigeorgis, 1996). These options have value because of the decision flexibility they provide (Brosch, 2008). To date, almost all applications of real options have been what is termed *options on projects* (Wang & de Neufville, 2006). Typical examples include the following: Giachetti (2012) described a scenario where real options to delay, scale up, scale down, or abandon the project are applied to enterprise system projects in the DoD. Pennock, Rouse, and Kollar (2007) applied the Black-Scholes equation to ship acquisition. Angelis, Ford, and Dillard (2013) described a case study of applying real options to the Army's acquisition of the Javelin anti-tank weapon system in which they considered three alternatives to provide the capability. Real options on projects are available in all projects and have been applied in the IT industry, in the oil and gas exploration industry, and to research and development portfolios.

What is far less common is the identification and application of options in the system architecture design itself. Wang and Neufville (2006) provided an example of a real option designed into a system, where they described the design of a bridge across the Tagus River in Portugal. The bridge was being designed for automobile traffic, yet the government realized that in the future, they might want to also have trains cross the Tagus River. Building two separate bridges, one for each mode of transportation, is more expensive than if a single bridge were designed to handle both. Yet, whether rail transport would ever be realized was uncertain. The engineers proposed a real option designed into the bridge of building supports capable of supporting two decks: one for automobile traffic and a second for rail traffic. The bridge would initially be built exclusively for automobile traffic, but the beefier supports created the system architectural option for adding the second deck for rail traffic. Real options valuation lets the decision-makers analyze whether the additional investment is warranted, and in this case, it was. This example illustrates a significant difference between real options on projects versus in projects. To obtain real options in projects, the systems engineers must identify future uncertainties and design the options into the system architecture so that the option for realizing that flexibility is available in the future. The research in identifying and designing options into system architecture is far less realized than the traditional stream of research into real options (Engle & Browning, 2008). Burrman, Zhang, and Babovic (2009) examined real options and applied them to the architecture of a maritime domain protection system in which the options are defined in terms of dollar value for costs and benefits. Engel and Browning (2008) examined how to define architectural options and show a valuation scheme of mapping the standard Black-Scholes equation to terminology for modular architectures. Mohr (2009) used real options to value the flexibility of modular cabins able to accommodate changing passenger demands. Silver and de Weck (2007) used a graph to model the switching cost between different architectural configurations. Their analysis used cost. What Silver and de Weck's research has in common is that the value of the option is entirely in financial terms.

An issue in the defense sector is how to value options in terms of capabilities. Mun and Housel (2010) presented a collection of tools based on real options that uses the concept of knowledge value added (KVA) as a surrogate for the benefits derived from an option. The KVA approach addressed the contradiction of using money to value options for the military. Ford, Housel, and Dillard (2010) used KVA in conjunction with simulation models for the analysis of alternative unmanned aerial vehicles, and they presented data where a Predator has a KVA of 943, versus a KVA of 1222 for Sky Warrior. The question is, what do these unitless KVA values mean to an acquisition program manager? The unitless KVA measures have no correspondence to how program managers, systems engineers, and other stakeholders think about the system's performance and capabilities, which severely limits their applicability. The paper determines that there is a need for valuation in terms already used within the acquisition community.

The majority of work on real options deals with options on projects, such as whether to delay, expand, contract, or make similar changes to the project dimensions. A few researchers have examined real options on the architecture, which are options designed into the architecture by engineers. Traditional options theory values the costs and benefits of options in terms of dollar values. However, military capabilities are measured in terms of MOEs and performance. A model of architectural options that deliver military capabilities needs to utilize units that have meaning to the stakeholders. Military stakeholders need to understand the trade-off between the architectural options and how it affects capabilities, as opposed to the industry practice of valuing options in strictly dollar terms.

In summary, the research on architectural options is underdeveloped, and incorporation of non-financial measures of the value of options has not been widely examined. Both these issues are critical to a more efficient acquisition process that emphasizes affordability.

Summary

The research project developed a method to identify and value architectural options. The approach is to identify uncertainty that the system will face, model it in a decision tree via scenarios, identify a means to measure system capabilities, define system modules and architectural options, apply real options to value the options, and then present the results to a decision-maker in the form of architecture trade-off curves. The intent of the research is to aid a decision-maker in identifying architectural options and defending their inclusion in the architectural design via the valuation.

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References

Angelis, D. Ford, D.N., & Dillard, J.T. (2013). Real options in military system acquisition: The case study of technology development for the Javelin anti-tank weapon system, Case Study. Retrieved from http://www.acquisitionresearch.net

Brosch, R. (2008). *Portfolio of real options*. Berlin, Germany: Springer Verlag.

Burrman, Zhang, & Babovic. (2009). Reducing risk through real options In systems design: The case of architecting a maritime domain protection system. *Risk Analysis* 29(3): 366-379.

Charette, R.N. (2008). What's wrong with weapons acquisitions? *IEEE Spectrum*. Retrieved from http://www.spectrum.ieee.org/magazine/2008/November

Engel, A., & Browning, T. R. (2008). Designing systems for adaptability by means of architecture options. *Systems Engineering*, *11*(2), 125–146.

Ford, D., Housel, T., & Dillard, J. (2010). Integrating system dynamic modeling and knowledge value added for improved analysis of alternatives: A proof of concept study. In *Proceedings of the Seventh Annual Acquisition Research Symposium* (Vol. 2, pp. 715–737). Retrieved from http://www.acquisitionresearch.net

Giachetti, R. E. (2012). Acquiring enterprise systems as a portfolio of real options. In *Proceedings of the Ninth Annual Acquisition Research Symposium* (Vol. 2, pp. 239–247). Retrieved from http://www.acquisitionresearch.net

Giachetti, R. E., Martinez, L. D., Sáenz, O. A., & Chen, C. (2003). Analysis of the structural measures of flexibility and agility using a measurement theoretical framework. *International Journal of Production Economics*, *86*(1), 47–62.

Koenig, P., Nalchajian, D., & Hootman, J. (2009). Ship service life and naval force structure. *Naval Engineers Journal*, *121*(1), 69–78.

Mohr, B. A. (2009, April). *Modeling the value of subsystem flexibility for aircraft financial evaluation using real options.* Paper presented at the Seventh Annual Conference on Systems Engineering Research, Loughborough University, Loughborough, England.

Mun, J. (2006). *Real options analysis: Tools and techniques for valuing strategic investments and decisions.* Hoboken, NJ: John Wiley & Sons.

Mun, J., & Housel, T. (2010). *A primer on applying monte carlo simulation, real options analysis, knowledge value added, forecasting, and portfolio* *optimization* (NPS-GSBPP-10-001). Monterey, CA: Naval Postgraduate School.

Pennock, M. J., Rouse, W. B., & Kollar, D. L. (2007). Transforming the acquisition enterprise: A framework for analysis and a case study of ship acquisition. *Systems Engineering*, *10*(2), 99–117.

Ross, A. M., Rhodes, D. H., & Hastings, D. E. (2008). Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value. *Systems Engineering*, *11*(3), 246–262.

Rowden, T. S. (2014, January). Building the surface fleet of tomorrow. *Proceedings Magazine*, *140*(1).

Silver, M. R., & de Weck, O. L. (2007). Time-expanded decision networks: A framework for designing evolvable complex systems. *Systems Engineering*, *10*(2), 167–187.

Thebeau, R. (2001). Matlab program code. Retrieved from http://www.dsmweb.org/?id=121

Trigeorgis, L. (1995). *Real options in capital investment: Models, strategies, and applications.* Westport, CT: Praeger.

Trigeorgis, L. (1996). *Real options: Managerial flexibility and strategy in resource allocation*. Cambridge, MA: MIT Press.

Trigeorgis, L. & Schwartz, E.S. (2001). *Real options and investment under uncertainty*. Cambridge MA: MIT Press.

Ulrich, K. & Eppinger, S. (2011). *Product Design and Development*. New York, NY: McGraw-Hill.

Wang, T., & de Neufville, R. (2006). *Identification of real options in projects.* Paper presented at the Fourth Annual Conference on Systems Engineering Research, Los Angeles, CA.

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