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Enabling Design for Affordability: An Epoch-Era Analysis Approach

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Preface & Acknowledgements

Welcome to our Tenth Annual Acquisition Research Symposium! We regret that this year it will be a "paper only" event. The double whammy of sequestration and a continuing resolution, with the attendant restrictions on travel and conferences, created too much uncertainty to properly stage the event. We will miss the dialogue with our acquisition colleagues and the opportunity for all our researchers to present their work. However, we intend to simulate the symposium as best we can, and these *Proceedings* present an opportunity for the papers to be published just as if they had been delivered. In any case, we will have a rich store of papers to draw from for next year's event scheduled for May 14–15, 2014!

Despite these temporary setbacks, our Acquisition Research Program (ARP) here at the Naval Postgraduate School (NPS) continues at a normal pace. Since the ARP's founding in 2003, over 1,200 original research reports have been added to the acquisition body of knowledge. We continue to add to that library, located online at www.acquisitionresearch.net, at a rate of roughly 140 reports per year. This activity has engaged researchers at over 70 universities and other institutions, greatly enhancing the diversity of thought brought to bear on the business activities of the DoD.

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

Unfortunately, what will be missing this year is the active participation and networking that has been the hallmark of previous symposia. By purposely limiting attendance to 350 people, we encourage just that. This forum remains unique in its effort to bring scholars and practitioners together around acquisition research that is both relevant in application and rigorous in method. It provides the opportunity to interact with many top DoD acquisition officials and acquisition researchers. We encourage dialogue both in the formal panel sessions and in the many opportunities we make available at meals, breaks, and the day-ending socials. Many of our researchers use these occasions to establish new teaming arrangements for future research work. Despite the fact that we will not be gathered together to reap the above-listed benefits, the ARP will endeavor to stimulate this dialogue through various means throughout the year as we interact with our researchers and DoD officials.

Affordability remains a major focus in the DoD acquisition world and will no doubt get even more attention as the sequestration outcomes unfold. It is a central tenet of the DoD's Better Buying Power initiatives, which continue to evolve as the DoD finds which of them work and which do not. This suggests that research with a focus on affordability will be of great interest to the DoD leadership in the year to come. Whether you're a practitioner or scholar, we invite you to participate in that research.

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

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Enabling Design for Affordability: An Epoch-Era Analysis Approach

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Abstract

Acquiring defense systems in the face of urgent needs, budget challenges, and scarce resources drives the need for designing affordable systems by anticipating uncertain futures and related mission volatility. Despite recent strategies to mandate *designing for affordability as a requirement* in acquisition management, current processes for performing early lifecycle affordability tradeoffs remain underdeveloped. Methods for exploring design tradespaces have matured but have lacked specific focus on evaluating affordability. Affordability tradeoffs have also largely been limited to static tradeoffs of systems in current operating environments, or in single point futures. Given that systems exist in a dynamic and uncertain world, designing for affordability necessitates a method capable of evaluating systems across many possible alternative futures. A new method that leverages both Multi-Attribute Tradespace Exploration and Epoch-Era Analysis is proposed to augment current practices in designing for affordability. This method can be applied to the evaluation of system concepts across multiple epochs (periods of fixed context and needs) and multiple eras (ordered sequences of epochs) and uses the Multi-Attribute Expense metric to provide a measure for aggregate costs and schedule considerations. This paper presents interim research outcomes of an ongoing research project, demonstrating the viability of the approach with a case study.

Motivation

With recent advances in technology and growing demand for enhanced warfighter capabilities, defense acquisition programs have become increasingly complex and costly to manage in the long term. Since the Department of Defense (DoD) is responsible for the research, development, production, and delivery of weapon systems on time and at a reasonable cost, there is an emergent need for the DoD to manage the cost, schedule, and performance of a major weapon system or program that typically runs into billions of dollars within its lifecycle.

With the prospect of slowly growing or flat defense budgets in coming fiscal years (GAO, 2011) and recent budget cuts, the DoD is seeking ways to yield better returns on its weapon system investments and find methods of delivering defense capabilities for less than it has in the past. It is well understood that mitigating uncertainty in estimating cost and schedule parameters that plague the early phases of program formulation would help to identify the true costs of a weapon system or program from the beginning and reduce overruns. This is also in consonance with the advent of capability-based planning, which aims to counter external threats with the best warfighter capabilities deliverable under constrained economic conditions and uncertainty (Patterson, 2012).

Efforts to improve cost and schedule estimation are ongoing, but there has been relatively little progress in addressing uncertainties related to costs stemming from alternative futures that the system may face. The research described in this paper is motivated by this specific aspect in the increasingly urgent need of designing for affordability.

Background

Buying strategies are continuously evolving to place more emphasis on cost in the decision process. With the launch of the Better Buying Power (BBP) initiatives and the Weapon Systems Acquisition Reform Act (WSARA), affordability has been mandated as a requirement at all milestone decision points of program development (Carter, 2010a, 2010b). Designing for affordability is thus imperative to early phase decision-making in the development of weapon systems and programs.

Affordability has become a design requirement due to multiple instances of failure in delivering expected technical performance, increased costs and schedule delays beyond program estimates, and the altering of requirements during program execution (GAO, 2011). The increasing prominence of affordability within the DoD and other working groups has led to the proposal of several notable definitions for the term *affordability*:

(i) The 2010 Carter memorandum defines affordability as “conducting a program at a cost constrained by the maximum resources the Department can allocate for that capability” (Carter, 2010a, 2010b).

(ii) INCOSE defines affordability as “the balance of system performance, cost and schedule constraints over the system life while satisfying mission needs in concert with strategic investment and organizational needs” (INCOSE, 2012).

(iii) NDIA defines affordability as “the practice of ensuring program success through the balancing of system performance (KPPs), total ownership cost, and schedule constraints while satisfying mission needs in concert with long-range investment, and force structure plans of the DOD” (NDIA, 2011).

(iv) The *Defense Acquisition Guidebook* defines affordability as "the degree to which the life-cycle cost of an acquisition program is in consonance with the long-range modernization, force structure and manpower plans of the individual DoD Components, as well as for the Department as a whole" (DoD, 2011).

As evidenced by this set of definitions, the concept of affordability not only incorporates cost but also schedule, performance, lifecycle, and all of these things relative to a larger set of possible investments. An affordable system is thus cost effective on its own—and relative to a larger system investment portfolio—in delivering value to the customer and relevant stakeholders. Affordability is enhanced if the system is capable of satisfying possible changing mission requirements over the system lifecycle. Consequently, a system developed without consideration for affordability is one that has been designed as a point solution in isolation, to meet a specific need at a specific time, possibly requiring the procurement of an entirely new system when customer needs evolve (Bobinis, Haimowitz, Tuttle, & Garrison, 2012).

Since the definitions of affordability also discuss costs relative to allocated budgets, affordability may also be analyzed at various levels of scope, as budgets can be allocated to systems, programs, and even portfolios of programs. Budgets and development timespans allocated to a program or portfolio may be partitioned into smaller packages in many different ways among its constituent systems or programs, respectively.

Affordability at a higher order program level may not necessarily equate to affordability at a lower order constituent system level and vice versa. Therefore, different measures may have to be applied to the design for affordability in an isolated system, program, or portfolio, as well as for the intended cascading of affordability considerations from higher to lower levels of acquisition management.

Higher order levels of affordability analysis will become increasingly important in the future, as they can stimulate an enterprise-driven effort to perform an architectural transformation of traditional engineering design methods that will eventually improve the affordable, full lifecycle operational effectiveness of customer solutions (Bobinis & Herald, 2012).

Past Failures

The consideration of affordability as a requirement during early phase design has become necessary in recent years due to prominent failures in system and overall program delivery. In fiscal year (FY) 2012 (GAO, 2012), nearly half of the DoD's 96 largest acquisition programs were failing to meet the "Nunn-McCurdy" cost growth and schedule standards that were earlier established to identify troubled programs (Schwartz, 2010, 2013). Despite active reductions in weapon unit quantities and reduced performance expectations, the cost overruns on major defense acquisition programs have grown to more than $300 billion over original program estimates (GAO, 2011).

Notable programs that experienced cost and schedule overruns were the Army's Comanche armed reconnaissance helicopter, the Navy's DDG-1000 next-generation surface combatant, and the Air Force's Transformational Satellite Communications System (TSAT; Cancian, 2010). The Comanche program commenced in 1982, but increasing unit costs resulted in a 10-year delay in schedule and its eventual cancellation in 2004. The $6.9 billion initially allocated for the procurement of 120 Comanche helicopters over five years could have been directed towards upgrading 350 AH-64 attack helicopters to deliver greater warfighter capability but was instead used to purchase 800 other helicopters (Cancian, 2010).

Similarly, the DDG-1000 program was cancelled in 2009 due to high costs and mission limitations, and funds were instead used to procure additional units of the older DDG-51 model. Unnecessary expenditures and schedule delays might have been averted if the Navy initially decided to purchase 13 units of the DDG-51 class for its $23 billion investment in only three DDG-1000 units. TSAT was also cancelled in 2009 due to rising costs and schedule slips. The Air Force might have used the $3.5 billion initial investment in TSAT to purchase seven units of the existing Advanced Extremely High Frequency (AEHF) satellites to avoid gaps in coverage (Cancian, 2010).

These high-profile failures accentuate the urgent need to reduce cost overruns and schedule delays, as well as the need to consider the impact of switching to alternatives later in the lifecycle, in the design of both current and future defense systems, programs, and portfolios. With recent strategies to mandate affordability as a requirement, establishing the preliminary design choice space for the system, program, or portfolio of interest through the generation of many possible alternatives has become imperative to increase insights in early phase decision-making, mitigate the risk of later costly changes, and maximize the value created for the stakeholders (Ross & Hastings, 2005).

Affordability and Tradespaces

The Carter memorandum (Carter, 2010a) stated that “the ability to understand and control future costs from a program’s inception is critical to achieving affordability requirements.” Since cost commitments and uncertainty are usually at their highest levels during early phase design (Blanchard & Fabrycky, 2006), implementing affordability tradeoffs in DoD systems and programs at their points of inception can actively reduce future cost overruns and schedule delays. To perform affordability tradeoffs early in the lifecycle, methods for systems engineering tradeoff analysis are required to demonstrate changes in costs as major decision parameters and time to completion are varied.

The minimization of system cost, while maintaining or increasing system capability across changing contexts over time, motivates the construction of system tradespaces with consideration of temporality. A tradespace is the space spanned by possible design alternatives and is bounded by utility and cost. As the alternatives are generated by enumerating design variables, expanding the tradespace requires a “creative recombination of current resources or systems to create a new system,” which would involve generation of either new design variables or reconfigurations of existing combinations of variables (Ross, Hastings, Warmkessel, & Diller, 2004).

Leveraging the increasing availability of computation power, tradespace exploration is the utility-guided, model-based search for better design solutions by avoiding premature fixation on point designs and narrow requirements (Ross et al., 2004). This allows a deeper and more holistic consideration of capabilities and mission utility instead of being locked too early into requirements and key performance parameters (Neches, Carlini, Graybill, Hummel, & McGrath, 2012).

The use of tradespaces instead of simple tradeoffs of several point designs can lead to better lifecycle results for the system or program of interest. The exploration of tradespaces also enables the promulgation of ilities, which are properties that often manifest and determine value in a system after it is put into use and which have ramifications with respect to time and stakeholders (de Weck, Ross, & Rhodes, 2012).

For example, flexibility allows for leveraging of emergent opportunities and mitigating risks such that the system is able to respond to changing contexts in order to retain or increase value delivery to system stakeholders over time (Viscito & Ross, 2009). As such, flexibility has become a desirable quality in long-lived systems. Due to increasing system costs and operational lifetimes of systems, various studies have already been conducted to incorporate flexibility into systems during the conceptual design phase (Saleh, Mark, & Jordan, 2009).

For the purposes of this paper, affordability will be a concept that provides explicit considerations for system cost and schedule constraints in value delivery and sustainment to stakeholders. Designing a system or program using affordability tradespaces will thus define its utility or performance space bounded by costs and time. Affordability studies can thus facilitate the attainment of better system, program, or portfolio lifecycle results while meeting budgetary and schedule constraints.

Applying Epoch-Era Analysis to Enable Designing for Affordability

The analysis of affordability tradespaces can become a multifaceted process when the impacts of uncertainties (including risks) inherent in alternative futures are incorporated into conducting tradeoffs during acquisition. To effectively evaluate the impact of dynamic variations in costs with tradeoffs in decision parameters and time to completion, an approach called Epoch-Era Analysis (EEA) can be applied to enhance the design for affordability (Ross, 2006; Ross & Rhodes, 2008).

EEA has been developed to consider and clarify the effects of changing contexts and needs over time on the perceived value of a system in a structured manner (Ross, 2006; Ross & Rhodes, 2008). Instead of discretizing the system lifecycle according to traditional system milestones, EEA discretizes the lifecycle according to impactful changes in the operating environment, stakeholders, or the system itself, through the constructs *epochs* and *eras*.

An epoch is a time period of fixed contexts and needs under which the system operates, and it can be characterized using a set of variables that define any factor, such as technology level and supply availability, which impacts the usage and value of the system. An ordered sequence of epochs constitutes an era and describes the potential progression of contexts and needs over time. Any futures relevant to system performance or costs can be described through assignments to the available epoch variables, providing a form of computational scenario planning (Roberts, Richards, Ross, Rhodes, & Hastings, 2009).

Figure 1 illustrates a notional system trajectory across an ordered sequence of epochs forming an era. In this illustration, the impact of changing contexts can be seen as a downward path on the system as it progresses across time. Rising expectations are also shown, illustrating how the perception of a successful system can be dependent not only on how the system performs within a context but also how that performance compares to changing expectations. In the final epoch of the illustrated era, the system must change in order to meet expectations. In this way, EEA can structure consideration of changing contexts and needs on system success and suggest strategies for how to sustain value in both the short run and the long run.

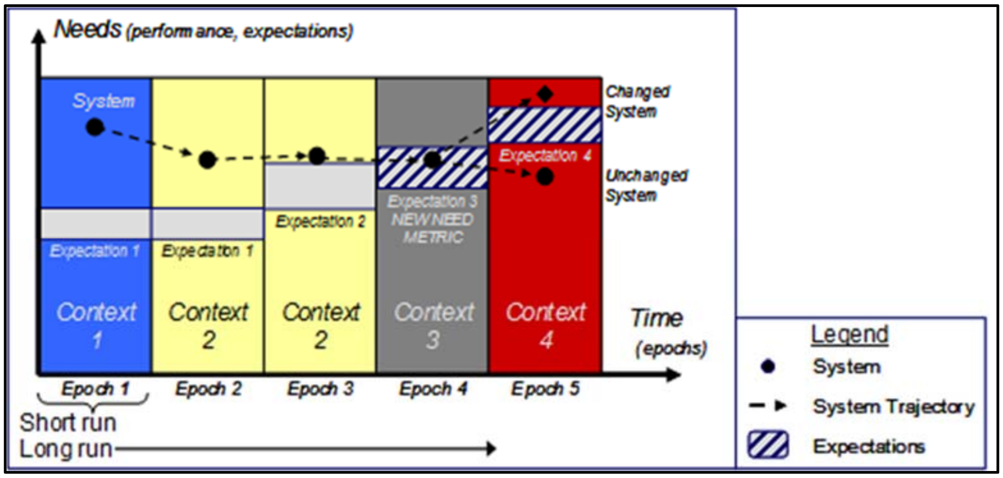

Figure 1. Partitioning Short Run and Long Run Into Epochs and Eras
(Ross & Rhodes, 2008)

EEA can be used with dynamic Multi-Attribute Tradespace Exploration (MATE), a conceptual design method that generates large numbers of designs through combinations of nonlinear functions of their performance attributes and compares their costs and utilities (Ross et al., 2004). Enumeration and evaluation of many alternative designs allow for a more complete exploration of a larger design tradespace. Evaluation of a single point design in which time-dependent performance variables are present can also be performed.

Therefore, the application of EEA to designing for affordability in a system, program, or portfolio can allow analysis of value delivery for single or multiple point designs across multiple epochs and multiple eras. System engineers can thus contribute to realizing better buying power by examining affordable systems previously overlooked or discarded (e.g., more affordable solutions may emerge from previously neglected regions of the tradespace).

Multi-Attribute Expense in Designing for Affordability

Designing for affordability is not only concerned with the monetary lifecycle cost of a system. While many definitions of *affordability* exist, there is general consensus that any evaluation of affordability must include a system's "schedule" of development and its responsiveness to emerging needs (Mallory, 2009; Herald, 2011; INCOSE, 2012). However, such temporal considerations are often difficult or impossible to represent in dollars. Non-monetary measures beyond traditional forms like lifecycle cost are thus required. An additional concern is that dollars for a system are often allocated from different budgets—for example, development versus operations. These different "colors" of money may be allocated (and spent) with differing degrees of ease. Analysis without aggregating these different types of dollar budgets may provide additional insights that would otherwise be lost if dollars were aggregated into a single monetary measure.

A possible measure capable of keeping track of both monetary and non-monetary considerations, as well as keeping different colors of money separate, is the Multi-Attribute Expense (MAE) function, which has previously been used in a satellite system design case study as an independent variable in tradespace exploration to capture both a system's development time and initial operating costs (Diller, 2002). MAE is formulated similarly to a Multi-Attribute Utility (MAU) function (Keeney & Raiffa, 1993). *Expense* refers to aspects of the system design and development that the designer wants to keep at low levels, a concept akin to the notion of negative utility. Expense is principally focused on "what goes into a system," in contrast to utility, which is focused on "what comes out of a system." Typically quantified on a zero to one scale, where an expense level of one denotes complete dissatisfaction and an expense level of zero denotes minimal dissatisfaction. As such, a stakeholder typically demands maximal utility and minimal expense in an ideal design (Nickel, 2010).

An MAE function requires careful construction through stakeholder interviews to elicit informed responses and aggregate preferences to capture articulated value. Because MAE is a dimensionless, non-ratio scale metric, an entity with twice the MAE number over another does not imply that it is twice as expensive in terms of monetary value.

Since temporal elements like schedule constraints and time-to-build have extensive leverage on the different colors of money, the MAE can be extended to affordability applications in federal acquisition processes. Instead of comparing monetary costs against utility, EEA can be modified to compare MAE against MAU in order to perform affordability-driven analysis that captures the elements of both time and costs.

A method that leverages the EEA approach and MAE metric can allow for the effective comparison of benefits and costs across a range of alternative futures. Also, this method may transform traditional engineering practices in acquisition management if it is able to account for system changes due to shifts and perturbations, manage lifecycle differences between subsystem or subprogram components, evaluate feedback, and be adaptive to evolving system behaviors (Bobinis et al., 2012). Since affordability is a concept evaluated over time, such a method can provide structured options for improvement to enable enhanced design for affordability.

Proposed Method Based Upon Epoch-Era Analysis

A new method that leverages the EEA approach and MAE metric is proposed to help enable the design of affordable systems, allowing for the structured evaluation of design alternatives across many alternative futures and helping to ensure that a potential design's cost is acceptable across the entire lifecycle. The proposed method is inspired by the Responsive Systems Comparison (RSC) method, which was developed earlier to support designing for changeability (Ross et al., 2008). RSC is a prescriptive operationalization of MATE and EEA. RSC has been previously applied to the design of a satellite radar system (Ross, McManus, Rhodes, Hastings, & Long, 2009).

RSC is designed to "guide the … practitioner through the steps of determining how a system will deliver value, brainstorming solution concepts, identifying variances in contexts and needs (epochs) that may alter the perceived value delivered by the system concepts, evaluating key system tradeoffs across varying epochs (eras) to be encountered by the system, and lastly developing strategies for how a designer might develop and transition a particular system concept through and in response to these varying epochs" (Ross et al., 2008). It is hypothesized that through modifying several original processes in RSC, incorporating recent refinements to EEA, and utilizing MAE to better capture the diversity of expenditures on a given system, the proposed method can more effectively address the time and resource-centric approach of designing for affordability.

Overview of Proposed Method

The overall structure of the proposed method consists of nine processes, which are grouped into three distinct parts: information gathering (Processes 1 through 3), alternatives evaluation (Process 4), and alternatives analysis (Processes 5 through 9). A graphical representation of the method is shown in Figure 2. The information-gathering portion, Processes 1 through 3, consists of defining the context and problem statement, stakeholders and respective needs, and contextual variables. The alternatives analysis portion, Processes 5 through 9, compares the dynamic properties of potential designs across the potential futures that the system may encounter. These two main portions of the proposed method are bridged by Process 4 (Design-Epoch Tradespaces Evaluation), which can provide feedback to decision-makers and stakeholders, creating an opportunity to revisit the information-gathering processes. Process 4 also provides cursory analysis of potential designs in preparation for the more in-depth alternatives analysis in the second half of the method.

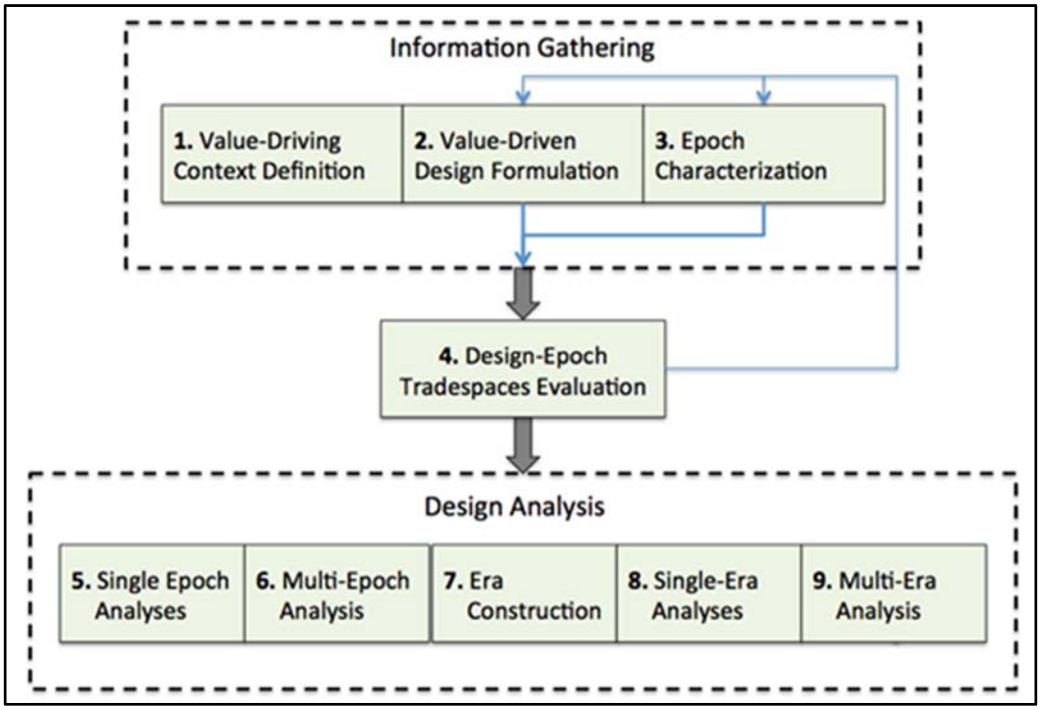

Figure 2. A Graphical Overview of the Gather-Evaluate-Analyze Structure of the Method

The processes of the proposed method, with brief descriptions of the activities involved, are as follows, with modifications to the prior RSC method emphasized (in italics):

Process 1: *Value-Driving Context Definition*

The first process of the proposed method involves development of the basic problem statement. The stakeholders are identified, relevant exogenous uncertainties are elicited, and an initial value proposition is formed. *The resources available to each stakeholder are examined along with the associated uncertainties.*

Process 2: *Value-Driven Design Formulation*

The second process begins by defining the needs statements for all stakeholders, which become the attributes of system performance, along with utility functions describing each stakeholder's preference for each attribute. *The stakeholder resources statements are also elicited (with corresponding expense functions), which then become the attributes of the system's expense function.* The system solution concepts are proposed from past concepts or expert opinions. These concepts are decomposed into design variables of the system.

Process 3: *Epoch Characterization*

In this process, the key contextual uncertainties are parameterized as epoch variables, and possible future contexts are identified. Uncertainties in stakeholder needs are elicited*. Uncertainties in resource supply and availability are also identified, along with changes to stakeholder preferences on resource usage*.

Process 4: *Design-Epoch Tradespaces Evaluation*

This process utilizes modeling and simulation to map the design and epoch variables to system performance attributes *and expense attributes*. Stakeholders' utility *and expense* functions are then used to generate the MAU *and the MAE* for each design, within each epoch.

Process 5: *Single Epoch Analyses*

This process includes the analysis of MAU *and MAE* of alternatives within particular epochs, including designs graphically compared on an MAU versus MAE scatterplot for any given epoch (time period of fixed operating context and stakeholder needs). Within-epoch metrics, such as yield, give an indication of the difficulty of a particular context and needs set for considered designs.

Process 6: *Multi-Epoch Analysis*

After completing the traditional tradespace exploration activities of Process 5, in which the practitioner compares potential designs within a particular epoch, metrics are derived from measuring design properties across multiple (or all) epochs to give insight into the impact of uncertainties on potential designs, including the evaluation of short run passive and active strategies for affordability (i.e., efficient MAU at MAE*). In addition, resource usage can be analyzed to identify designs that are robust to the factors identified in Process 3 (e.g., decreasing budgets or labor availability).*

Process 7: *Era Construction*

This process constructs multiple sequences of various fixed duration epochs together to create alternative eras, which are long-term descriptions of possible futures for the system, its context, and stakeholder needs. This process can be performed with the aid of expert opinion, probabilistic models (e.g., Monte Carlo or Markov models), and scenarios of interest to stakeholders.

Process 8: *Single-Era Analyses*

This process examines the time-dependent effects of an unfolding sequence of future epochs created in Process 7. By examining a particular series of epochs for a given length of time, decision-makers can identify potential strengths and weaknesses of a design and better understand the *potential impact of path-dependent, long-run strategies for affordability.*

Process 9: *Multi-Era Analysis*

This process extends Process 8 by evaluating the dynamic properties of a system across many possible future eras, *identifying patterns of strategies that enable affordability across uncertain long-run scenarios.*

In the remainder of the paper, the first three processes are described in more detail for the purposes of the demonstration case (as of the date of this paper), with the modeling and simulation and the analysis processes to be applied later in the ongoing effort.

Offshore Patrol Cutter Acquisition Demonstration Case

The case chosen for an initial demonstration of the proposed method is drawn from Schofield (2010), who described an $8 billion Coast Guard Offshore Patrol Cutter (OPC) acquisition program for over 20 ships, each with a service life of around 30 years. For this paper, only the acquisition of one ship will be considered, and the alternatives will be limited to a few point designs rather than an exhaustive tradespace of alternative designs. A brief description of the project is given. Ongoing work will extend the analysis to the program level to examine measures of affordability on multi-year and multi-unit acquisitions.

The OPC operates in a variety of areas to perform many different missions, including ports, waterways, and coastal security (PWCS), search and rescue (SAR), drug interdiction (DRUG), migrant interdiction (AMIO), living marine resources (LMR), other law enforcement (OLE), and defense readiness (DR; Fabling, 2010). These mission areas include autonomous operations as well as cooperative missions with other vessels, requiring endurance and maneuverability, respectively.

Process 1: *OPC Value-Driving Context Definition*

The value-driving context for the OPC is made up of the value propositions as well as the key stakeholders involved in decision-making and funding. The basic stakeholder relationships present for the OPC system are depicted in Figure 3. As shown in the figure, the internal stakeholders are the entities between which the primary exchanges of value occur.

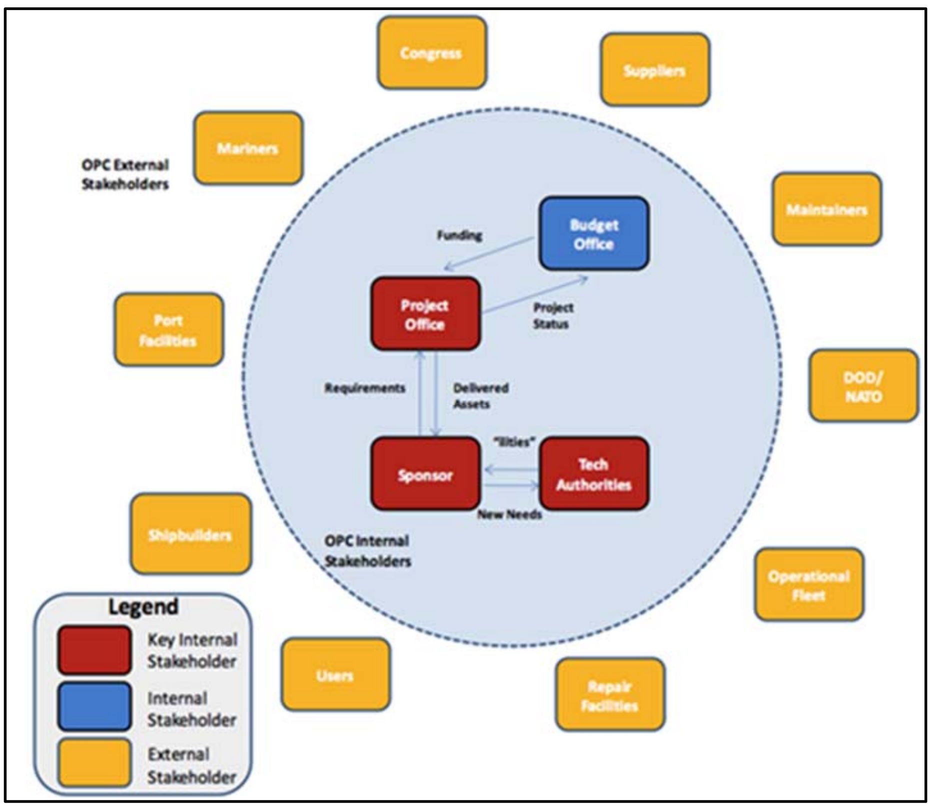

Figure 3. A Graphical Depiction of the Stakeholders and Their Relationships in the OPC System
(Schofield, 2010)

Schofield (2010) defined the value propositions for each stakeholder as follows:

> **Project Office:** Provide a new cutter fleet meeting operational requirements within a defined budget level and delivery to coincide with decommissioning of current WMEC fleet.
>
> **Sponsor:** Develop operational requirements that meet the mission needs of the Coast Guard and Coast Guard user requirements.
>
> **Technical Authorities:** Ensure new developed system meets legacy, external constraints, and design standards with technologies that maximize capability within established risk requirements. (p. 82)

It is clear from the value propositions that concern for resource usage is not consistent across stakeholders; as one might expect, each stakeholder has different expectations and goals with regard to resources involved in the project. The Project Office specifically addresses two standard resources: budget ("defined budget level") and schedule ("delivery to coincide with ..."). The Sponsor appears to be primarily concerned with the mission needs and user requirements of the organization, and resource usage is not of primary concern. The Technical Authorities' value statement includes the aspect of technological resources that enable core capabilities. In the second process of the proposed method, interviews of each stakeholder will better reveal their preferences on the usage of the resources with which they are concerned.

Process 2: *Value-Driven Design Formulation*

The second process builds upon the initial system context definition by first proposing the system design concept and then eliciting the performance attributes desired by the stakeholders. The design concepts are then partitioned into potential design variables for the proposed system. To better identify the key design drivers, the relationships of design variables to performance attributes are then assessed qualitatively by the values "none," "low," "medium," or "high" impact, using a Design-Value Matrix (DVM) as a visual aid for this activity. Schofield (2010) decomposed the value propositions generated in Process 1 to infer the performance attributes and then map them to the design variables of the system.

For the present study, a new matrix is created to map the impact of design variables to the resource expenditures of the system, qualitatively assessing each design variable's impact on each expense attribute. In this way, an alternative DVM can be generated, focused on expense attributes, and is shown in Figure 4 with purely notional data. By summing the rows and columns, the practitioner can quickly determine which design variables have the most impact on general resource usage (in the notional example, the length and propulsion type are the most impactful), as well as which resources are more sensitive to the present design choices (again, from the notional data, the Operations Cost is the most sensitive, followed by Blue Money and Acquisition Cost). Generating an enhanced DVM, with both utility attributes and expense attributes, provides an expanded cost and benefit perspective on the ramifications of various design decisions.

Expense-Focused DVM (Notional Values)							
Key Internal Stakeholder: Sponsor							
Expense Attributes / Design Variables	Length (ft)	Power (hp)	Propulsion Type (Diesel, CODOG, CODAG, Turbo)	Antennae Space (cub. Ft)	Crew size (#)	...	Total Impact
Acquisition Cost	9	3	3	3	1	...	24
Operations Cost	9	3	9	1	9	...	32
Acq. Schedule	1	1	3	1	0	...	15
Red Money	3	1	1	9	1	...	19
Blue Money	9	3	9	3	1	...	25
Total	31	11	25	17	12	...	

Figure 4. A Design-Value Matrix Reflecting the Notional Impact of Design Variables on System Expense Attributes

Process 3: *Epoch Characterization*

After identification of the design variables, performance and expense attributes, and their corresponding relationships, the internal and external uncertainties are added into the analysis. The prior study (Schofield, 2010) listed the external uncertainties (in the associated categories) related to the OPC as follows:

> **Technology:** VUAV integration; major C4ISR system upgrade; and new and more capable (size, range, personnel carried) small boats.
>
> **Policy:** Marine engine emission reductions; reduced copper content from shipboard systems (sea water systems); increased intelligence gathering into government-wide system.
>
> **Budget:** Loss of acquisition budget prior to IOC; increase in operational funding for increased operational usage.
>
> **Systems of Systems:** Deploying with National Security Cutters; new cutter-deployed helicopters.
>
> **Missions:** Support of arctic region for fisheries; adding environmental cleanup response capability; more frequent international presence particularly for peacekeeping missions. (p. 93)

Epoch variables are generated from these uncertainties by determining the primary source of the possible changes in operating context. For instance, Schofield (2010) used the marine engine emission reductions uncertainty in the Policy category to generate the "Engine Emissions Rating" epoch variable, which has an integer value range from 2 to 4. Once each epoch variable is created, the impact of the epoch variables on each of the design variables, performance attributes, and resource attributes can then be depicted with an Epoch Descriptor Impact Matrix, similar to the DVM in Process 2. An example Epoch Descriptor Impact Matrix with notional values is shown in Figure 5.

Epoch Descriptor Impact Matrix

Epoch Variables	VUAV	C4ISR Racks	Small Boat Size	Engine Emissions	SCIF Size	...	Total Impact
Design Variables							
Length (ft)	1	9	3	1	3	...	**47**
Power (hp)	1	3	9	1	3	...	**54**
... ...	...	...	...	...	...	...	**...**
Total	**15**	**24**	**32**	**31**	**29**	**...**	
Utility Attributes							
Air Cap	9	1	0	3	3	...	**31**
Range	1	3	9	1	9	...	**43**
... ...	...	...	...	...	...	...	**...**
Total	**27**	**23**	**28**	**21**	**32**	**...**	
Expense Attributes							
Acq. Schedule	1	1	3	1	0	...	**25**
Red Money	3	1	1	9	1	...	**39**
Blue Money	9	3	9	3	1	...	**45**
Total	**24**	**21**	**18**	**20**	**16**	**...**	

Figure 5. A Matrix Reflecting the Notional Impact of Epoch Variables on Design Variables, Utility Attributes, and Expense Attributes

Similar conclusions can be drawn as in Process 2; for example, it is clear from the sums of rows in Design Variables that Power is the variable most impacted in general by all uncertainties. Likewise, Range is the performance attribute most impacted by the uncertainties, and Blue Money is the most impacted expense attribute. Conversely, the Small Boat Size epoch variable (with Engine Emissions not far behind) is the most impactful on all design variables, the SCIF Size is most impactful on the utility attributes, and the VUAV is most impactful on the expense attributes. Gaining an understanding of these relationships early in the design process allows the practitioner to begin considering how a design should be oriented to cope with uncertainties as well as to keep in mind those contexts which are especially detrimental to the utility or expense of the system, whether directly or through opportunity costs.

Next Steps: *Processes 4–9*

The study is continuing beyond this paper with the application of the second half of the proposed method. Process 4, the Design-Epoch Tradespaces Evaluation, will use the information generated thus far to calculate the expense measurements for each design, allowing a partial tradespace to be shown on a standard utility-versus-expense scatterplot. Preliminary results can be shown to stakeholders and decision-makers, allowing feedback to Processes 2 and 3, if necessary, to update the design variables and epoch variables under consideration (see Figure 2). Upon completion of Process 4 and any necessary iteration, Process 5 (Single-Epoch Analyses) will then begin to look at the designs' relative resource utilization in different epochs, allowing the practitioner to begin understanding the dynamic expense properties of each alternative under consideration as well as to pick relevant *point futures* in which to compare alternative designs.

The application will continue with the Multi-Epoch Analysis of Process 6, measuring the designs' expenses across all relevant epochs. Established metrics such as the Fuzzy Pareto Number, Filtered Outdegree, and others will be calculated to help identify designs that are insensitive to the impact of uncertain operating environments and missions (Fitzgerald & Ross, 2012a). Multi-epoch affordability metrics will also be introduced to help identify and rank designs based on resource usage, including those which best adapt to decreasing budgets, those which do not vary widely in resource usage, and those which can best capitalize on increasing technology and spending levels.

In addition to observing design properties across many alternative point futures, it is also informative to analyze design properties through the long run using an ordered sequence of different epochs (i.e., an era). A particular era can be created by combining epochs through expert opinion, random generation, and other means. During Process 7 (Era Construction), one or more of these methods will be used to generate and name possible eras for the OPC. In Process 8 (Single-Era Analyses), metrics of the alternative designs will then be compared for a given era as an indication of design resource usage in one possible long-run future, potentially revealing the path-dependent sensitivity of a particular design (Fitzgerald & Ross, 2012b). This analysis will be broadened to identify patterns across multiple possible long-run epoch sequences in Process 9, Multi-Era Analysis, wherein further insights into the long-term resource behavior of the OPC under many different scenarios will be gained. These insights will be aided through the application of existing and proposed metrics to compare properties such as the stability of operating costs, stability of manpower requirements, and adaptation to budget variation.

Discussion

Designing for affordability throughout the acquisition process, but especially in the early phases, can expedite significant reductions in cost and risk and enable the value delivery of either effective systems or programs within economically frugal and risk-averse environments. By applying the proposed method to a demonstration study, we intend to illustrate how affordable solutions within fluid tradespaces can be identified in a systematic and informed manner, accounting for changing sets of mission requirements, operating contexts, and available budgets.

As the preceding demonstration begins to illustrate the application of affordability considerations to a single acquisition program, the same method can also be applied at the levels of systems, programs, and portfolios of programs. Introducing different levels of scope to affordability studies necessitates clear distinctions among systems, programs, and portfolios in future work.

For the purposes of the current discussion, the distinction between system, project, and program is now described. A system is typically defined to be a combination of interacting elements organized to achieve one or more stated purposes (INCOSE, 2012), whereas a project can be defined as the enveloping process that encompasses the socioeconomic and technical considerations in delivering the system. A program can be defined as a group of related and interdependent projects managed together to obtain specific benefits and controls that would likely not occur if these projects were managed individually (KLR, 2008).

Program-level affordability can be achieved through either a top-down or bottom-up approach. A top-down approach entails the application of affordability considerations at the program level such that its effects potentially cascade down to its constituent systems. A bottom-up approach conversely demands the aggregation of system-level affordability for each constituent system in order to establish program-level affordability. These two approaches may not yield the same results, and it is an avenue worth exploring to determine the more effective or viable option.

Another paradigm for exploration is that of portfolio-level affordability. A portfolio can be defined as a collection of projects or programs grouped together to facilitate the effective management of efforts to meet strategic business objectives (KLR, 2008). These projects or programs are not necessarily interdependent or directly related. Portfolio-level affordability analysis may involve applying affordability considerations across multiple projects, programs, and possibly even portfolios. Given that the DoD has been evaluating the expenditures for both defense acquisition programs and portfolios, a portfolio-level affordability study can provide overarching guidance to architecting entire defense capabilities within realistic bounds of cost and time. Similarly, top-down and bottom-up approaches can also be taken to achieve portfolio-level affordability.

Quantitative measures of cost, schedule, and performance can also be derived at system, program, and portfolio levels to serve as vital health indicators at different tiers of acquisition processes. By assessing the performance of an individual system or program as well as entire defense portfolios, the return on investment that the current defense acquisition system delivers to stakeholders can be accurately measured and analyzed. Systems, programs, and portfolios can then be individually or collectively calibrated based on a multitude of affordability indicators in order to fulfill evolving cost and schedule constraints.

As a starting point, affordability requirements have already been mandated at current program milestone reviews and at the inception of new programs in consonance with the Carter memorandum. Designing for affordability can be extended to all levels in acquisition management in order to ensure that value delivery in systems, programs, and portfolios can be sustained. The method described in this paper could potentially be used to gain insights at each of these levels of acquisition management.

Another avenue for study is the concurrent application of affordability with other ility considerations. Research on the tradeoffs for changeability (Fitzgerald & Ross, 2012b), survivability (Richards, Ross, Hastings, & Rhodes, 2009), and evolvability (Beesemyer, Fulcoly, Ross, & Rhodes, 2011) in previous case studies may possibly be repeated with affordability considerations, and results may yield "affordably changeable," "affordably survivable," or "affordably evolvable" systems that were previously overlooked or discarded. For such change-related ilities, existing methods such as the Epoch Syncopation Framework (ESF) can also be utilized to account for cost, performance, schedule, and uncertainty factors regarding experienced epoch shifts in the analysis of design tradespaces (Fulcoly, Ross, & Rhodes, 2012). This can promote the development of rules and strategies to execute change mechanisms with explicit considerations for cost and time across a system lifespan.

Conclusion

Current strategies to mandate designing for affordability as a requirement in acquisition management are still at their infancy stages. A particularly challenging aspect of designing for affordability is to make decisions not only for today's mission and operating context but also for alternative futures where budgets and missions may change and contexts may shift. We propose a method that can enable practitioners to design for affordability in a more effective and comprehensive manner, given this challenge of a dynamic world. By leveraging the EEA approach and the MAE metric, tradespaces containing many possible design alternatives can be explored with stronger considerations of aggregated costs, time, and performance in order to focus specifically on evaluating affordability. This will facilitate the conduct of affordability tradeoffs in dynamic operating environments with many possible alternative futures and eliminate design restrictions to only single point futures. The viability of this method has been preliminarily demonstrated with the OPC acquisition case study. It will be further elaborated in the course of ongoing research. Inspired by the existing Responsive Systems Comparison method, this method places increased emphasis on tradeoffs important to managing changes in available and expended resources over time. It is anticipated that the method could be applied to ascending levels of acquisition considerations, from systems to programs to portfolios. Program-level affordability analysis might consider the acquisition management of the entire OPC acquisition program for over 20 ships, while portfolio-level affordability analysis might entail the concurrent acquisition management of the OPC program with other related or unrelated naval programs. With this method, the concept of affordability may be considered simultaneously with other ilities, providing synergistic insights from other existing methods such as the ESF to enhance the design of affordable systems. Based on early results, the method appears to show promise as an enabler for better design for affordability in systems, programs, and portfolios in the future.

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