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Procedia Computer Science 00 (2014) 000–000

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## Conference on Systems Engineering Research (CSER 2014)

Eds.: Azad M. Madni, University of Southern California; Barry Boehm, University of Southern California;  
Michael Sievers, Jet Propulsion Laboratory; Marilee Wheaton, The Aerospace Corporation  
Redondo Beach, CA, March 21-22, 2014

# A Method for Selecting Affordable System Concepts: A Case Application to Naval Ship Design

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### Abstract

The current defense acquisition environment includes much uncertainty regarding future budgets, political developments, and global geopolitical events. With affordability of systems now mandated by the US Department of Defense, it is imperative to ensure that future acquisitions will be feasible from their inception given resource considerations, and can remain feasible given various future perturbations of those resources. This paper introduces a method for early conceptual development (inception) of major defense systems and demonstrates the method's application to a case study of a hypothetical naval ship acquisition. The results of the application and the implications of the method for system development are discussed.

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Selection and peer-review under responsibility of the University of Southern California.

*Keywords:* affordability; systems engineering; tradespace exploration; utility; expense; epoch; era

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### 1. Introduction

The increased focus on affordable defense systems over the past several years is a result of US Department of Defense (DoD) mandates with regard to budget considerations. This paper uses a resource-centric approach to affordability, and introduces a composite method which is applied to the early-lifecycle conceptual design of a

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hypothetical naval frigate, the Next Generation Combat Ship (NGCS), which is described as a hybrid between the Navy's Littoral Combat Ship (LCS) and the Coast Guard's Offshore Patrol Cutter (OPC). The method's processes are briefly described and demonstrated, with each process showing the (representational) results from its application to the NGCS system. A discussion of the affordable design choice follows, as well as a discussion of the value of the method for any system's early lifecycle stages of conceptual planning and design. It should be noted that the method is designed to be applicable to complex systems across engineering domains. The paper's goal is to illustrate the various processes and constructs involved in the proposed method, not necessarily to gain insight into the design of a naval frigate. For more details on the case application beyond the scope of this paper, please see Schaffner 2014<sup>1</sup>.

### 1.1. Motivation

In past years, the performance of a potential system was of chief concern, but the amount of resources committed to a program is increasingly becoming the primary driver of decisions regarding future acquisitions. Because of relatively flat projected defense budgets in future years<sup>2,3</sup>, the DoD is seeking methods of delivering defense capabilities for less resource expenditure than traditionally required. One such method for reduction in DoD expenses was revealed in the Carter Memorandums of 2010, which mandated that affordability be instituted as a requirement for future acquisitions<sup>4,5</sup>. With regard to helping define affordable decisions, Tuttle and Bobinis<sup>6</sup> describe the Affordability Triangle, shown in Fig. 1, with required capabilities (i.e., determined by stakeholder needs) forming the base of the triangle, and the affordability decision criteria comprising cost, schedule, and performance. It is clear that examining each of these latter multi-criteria considerations in multi-year, billion-dollar weapons systems and programs adds several layers of complexity to a standard trade study. In addition, Tuttle and Bobinis note that an affordability trade study must “extend the time horizon” of the traditional analyses. In order to extend the time horizon of analysis, any study must address the contextual and capability developments over time, along with their potential impacts to the performance, cost, and schedule of the system (whether the impacts are objective or subjective). The dual motivations for this paper, then, are the analysis of uncertainty over a system lifecycle combined with the analysis of the multi-criteria considerations of cost, schedule, and performance meeting required capabilities. The ultimate goal is to design affordable systems that meet the needs of warfighters – *and remain affordable* – regardless of future circumstances. To achieve such a goal, efforts toward affordability must begin in the earliest phases of system planning, when resource commitments and solution-constraining decisions are not yet present. Performing such analysis at this stage allows design engineers to “see, evaluate, accept and reject a large number of courses of action...without actually committing resources”<sup>7</sup>, potentially elevating system-specific knowledge to better inform the high-impact decisions made at the earliest stages of the system lifecycle. For the purposes of this paper, the affordability of a system is defined as the property of becoming or remaining feasible relative to resource needs and resource constraints over time.

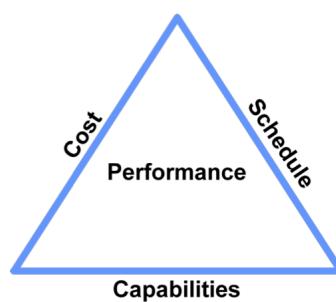


Fig. 1: The Affordability Triangle from Tuttle and Bobinis<sup>6</sup>.

## 2. Development of a Composite Method for Affordability

The analysis of system affordability covers many aspects, including the system development schedule, various types of expenses, and the level of those expenses in dynamic operating environments over the system lifecycle. Ideally, these expenses must be balanced with the value delivery of the system, since a system providing minimal performance might be affordable but not very desirable. This paper builds upon an established method for early-lifecycle conceptual system design to balance all of these factors, and introduces several metrics to cover the resource-centric concerns of stakeholders. The first measure introduced is the Multi-Attribute Expense (MAE) function, intended to aggregate stakeholder preferences on individual resource consumption. The second measure introduced is the Max Expense metric, which gives the maximum resource expenditure for any resource across the various futures considered. The third measure is the Expense Stability metric, which reflects the stability of individual resource consumption over time. Each of these metrics helps reveal the individual aspects of a system's affordability, informing analysts and decision makers of the relative feasibility of each potential design under consideration, whether relative to one another or to established/projected future budgets.

The Responsive Systems Comparison (RSC) method was developed to aid in the design of complex systems, allowing effective anticipation of future contexts and needs relevant to system design choices early in the lifecycle through the Epoch Era Analysis (EEA) approach<sup>8</sup>, where an *epoch* is a time period of fixed context and needs, and an *era* is an ordered sequence of finite-duration epochs. RSC has been applied to several case applications ranging from satellite systems<sup>9</sup> to an upcoming Coast Guard ship<sup>10</sup>. The method applied in the present study is a 9-process variant of RSC and is described in the next section.

### 2.1. 2.1 Overview of the Composite Method for Affordability

The overall structure of the composite RSC-based 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 below in Fig. 2.

The information-gathering part, Processes 1 through 3, consists of defining the context and problem statement, stakeholders and respective needs, and contextual variables. The alternatives analysis part, Processes 5 through 9, compares the dynamic properties of potential designs across the potential futures that the system may encounter. These two parts of the method are bridged by Process 4 (Design-Epoch Tradespaces Evaluation), which provides evaluation data of potential designs, giving early feedback and thereby creating an opportunity to revisit the information gathering processes. These processes and their representational outcomes for the NGCS study are described in Section 3.

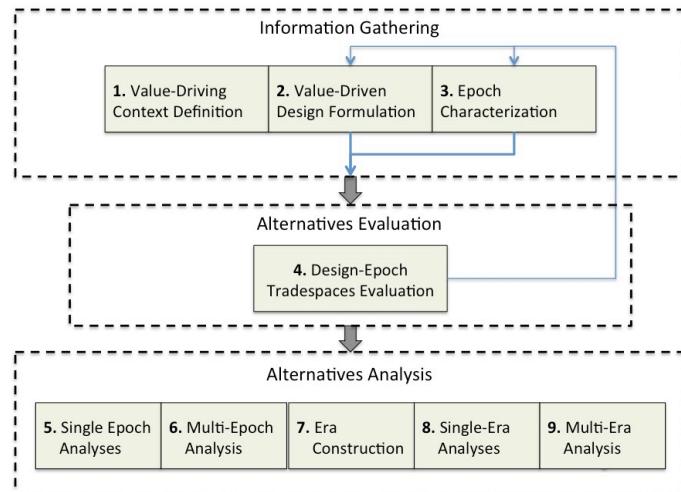


Fig. 2: A graphical overview of the Gather-Evaluate-Analyze structure of the method.

### 3. Demonstration Case: NGCS

This paper demonstrates the method as applied representationally to a Next-Generation Combat Ship (NGCS), which is described as a larger version of the Navy's current Littoral Combat Ship (LCS) that would support air and sea operations over diverse areas of interest for the next 30 years. Schofield's<sup>10</sup> application of the original RSC method was to a smaller naval application, the Coast Guard's Offshore Patrol Cutter (OPC). The current case combines the design variables, attributes, and epochs from Schofield's OPC study with the evaluated outputs of the MIT Math Model<sup>11</sup>, a standard naval modeling tool regularly used for the evaluation of potential designs for Naval frigates (slightly larger than the LCS).

The proposed NGCS requirements, therefore, reflects some similarity with both the OPC and LCS. For example, the OPC is designed to operate in a variety of mission areas, including ports, near shore, and open sea, with a range in excess of 8,500 nautical miles and endurance minimum of 45 days<sup>10</sup>. The LCS is designed to have a range in excess of 3,500 nautical miles and an endurance of 21 days. The NGCS that is the focus of this study, meanwhile, is required to operate in mission areas at least as varied as the OPC, have a minimum endurance of 30 days, and have a range in excess of 4,000 nautical miles. The operating context of the NGCS is also largely unchanged from that of the OPC, with many of the NGCS's contextual variables borrowed from the OPC study.

#### 3.1. Process 1: Value-Driving Context Definition

The first process of the 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.

*Representational Outcome:* For the Offshore Patrol Cutter, Schofield<sup>10</sup> defines Value Propositions for each of three Stakeholders. Because each of these value propositions reveal the different priorities of their respective organizations, the present case of the NGCS combines them into one representative stakeholder for analysis. This stakeholder desires to provide a new fleet of USN frigates for use in air and sea operations across a variety of operating areas, and controls the acquisition and operating budgets, labor expenses, and development schedule.

#### 3.2. 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. Multi-attribute aggregation functions are chosen for both utility and expense. Potential system solution concepts are proposed from past concepts or expert opinions, and are then decomposed into design variables of the system.

*Representational Outcome:* The attributes of the system (both utility and expense) are shown in Fig. 3, with units, desired acceptance range, and weight (reflecting contribution within aggregate utility and expense functions). Preferences on each attribute levels were captured in single-attribute utility and single-attribute expense curves (not shown, but available in Schaffner 2014<sup>1</sup>). A linear weighted sum aggregation function was chosen for each multi-attribute utility (MAU) and multi-attribute expense (MAE).

<b>Mission Statement:</b>		Provide new frigate fleet for the USN.		
<b>Objective:</b>		Provide defense, air, and sea support across the defined mission areas.		
Attribute (Acronym)	Units	Range ["worst" to "best"]	Weight (0.1 to 1)	
Range	nm	4500 10000	0.2	
Speed	kts	12 40	0.1	
Displacement (Disp.)	cubic ft.	11000 4000	0.2	
Air Capability (Air Cap)	hrs/day	2 12	0.2	
Endurance (Endr)	days	30 60	0.1	
Small Boat Capability (SBCap)	#ppl-hrs/day	20 100	0.2	
Acquisition Cost (Acq.)	\$ million	1500 500	0.4	
Lifecycle Cost (LC)	\$ million	7500 3000	0.3	
Initial Operating Cap. (IOC)	year	2020 2018	0.2	
Crew Size (Crew)	# persons	250 200	0.1	

Fig. 3: Decomposition of mission statement into representational attributes of the NGCS system.

### 3.3. Process 3: Epoch Characterization

In this process, the key contextual uncertainties are parameterized as epoch variables, and specific 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.

*Representational Outcome:* Five epoch variables (EVs) – shown in Fig. 4(a) – were chosen from four different categories of uncertainty (Technology levels, Policy Developments, integration with SoS, and Mission required capabilities). The epoch variable VUAV represents the size of unmanned aerial vehicles in operation (either small or large, as shown), and the variable Small Boat Size represents the size of deployable boats stored on-board the NGCS. In the Epoch Descriptor Impact Matrix of Fig. 4(c), the four possible estimated levels of impact are 0,1,3, and 9. The increasing difference between each level helps practitioners better differentiate the low, medium, and high impact an epoch variable will have, which is intended to lead to more accurate estimation. The six representative epochs are shown in Fig. 4(b), which displays each epoch variable's levels in the respective epochs.

(a)

Levels			
EV Category	Epoch Variable	[Range]	Units
EV -- Tech	VUAV	[Small, Large]	Storage Level
EV -- Tech	Small Boat Size	[24, 35]	ft
EV -- Policy	Engine Emissions	[2, 3, 4]	(Tier)
EV -- SoS	Range Increase	[0, 10, 20]	%
EV --Mission	Ice Region Use	[Low, Med, High]	Level

(b)

Epoch Name	VUAV	Small Boat Size	Engine Emissions	Range Increase	Ice Region Use
<b>Conflict</b>	Large	35	4	20	High
<b>Mothership</b>	Large	35	2	10	Low
<b>Sojourning</b>	Small	24	2	20	High
<b>Sea Support</b>	Small	35	3	10	Medium
<b>Non-Polluter</b>	Small	24	4	0	Low
<b>Baseline</b>	Small	24	2	0	Low

(c)

Epoch Descriptor Impact Matrix						
	VUAV	Small Boat Size	Engine Emissions	Range Increase	Ice Region Use	Total Impact
Range	1	1	1	9	9	21
Speed	1	1	9	9	3	23
Displacement	1	1	0	3	3	8
Air Capability	3	3	0	3	3	12
Endurance	1	1	1	9	3	15
Small Boat Capability	1	9	1	3	3	17
<b>Total</b>	<b>8</b>	<b>16</b>	<b>12</b>	<b>36</b>	<b>24</b>	
Utility Attributes						
Range	1	1	1	9	9	21
Speed	1	1	9	9	3	23
Displacement	1	1	0	3	3	8
Air Capability	3	3	0	3	3	12
Endurance	1	1	1	9	3	15
Small Boat Capability	1	9	1	3	3	17
<b>Total</b>	<b>8</b>	<b>16</b>	<b>12</b>	<b>36</b>	<b>24</b>	
Expense Attributes						
Acquisition Cost	3	3	3	1	0	10
Lifecycle Cost	3	3	1	9	3	19
IOC	1	0	3	1	3	8
Crew Size	3	3	1	3	1	11
<b>Total</b>	<b>10</b>	<b>9</b>	<b>8</b>	<b>14</b>	<b>7</b>	

Fig. 4: (a) The contextual uncertainties of the NGCS captured in epoch variables; (b) The six epochs created for the case study from assignments to the epoch variables; (c) The impacts of the epoch variables on the attributes of the NGCS.

(a)

Design #:	EPOCH: Baseline					
	Blue Diam.	Red Square	Green Triangle	Purple X	Blue X	Yellow Circle
Range	4500	6500	4500	6500	8000	6500
Speed	20	20	30	30	30	40
Displacement	7663	8143	4654	7734	8639	9800
Air Capacity	8	4	2	8	8	12
Endurance	50	50	30	45	45	60
SB Capacity	60	20	20	60	40	100
Acquisition	1156	968	627	1011	1009	1230
Lifecycle	5086	4364	3244	4510	4505	5263
IOC	2018	2018	2018	2018	2018	2018
Crew Size	225	230	200	225	220	250
MAE:	0.36	0.28	0.13	0.29	0.28	0.41
MAU:	0.59	0.51	0.31	0.73	0.73	0.90

(b)

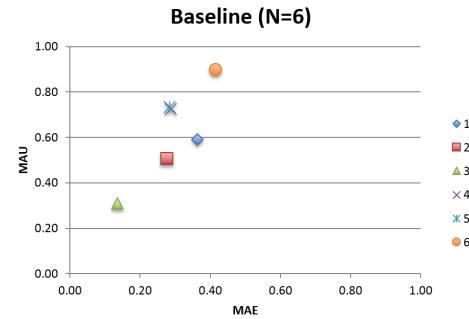


Fig. 5.(a) the six representative designs in the Baseline epoch; (b) the visual tradespace (MAU v. MAE).

### 3.4. Process 4: Design-Epoch Tradespaces Evaluation

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

*Representational Outcome:* The evaluated designs in the Baseline epoch are shown below in Fig. 5. This evaluation process was performed for the six designs in all six epochs considered using the MIT Math Model with appropriate revisions to reflect the epoch changes. The MIT Math Model evaluates the actual performance of each design within each epoch, while the acceptance ranges in Fig 3 illustrate what the stakeholder wants the performance to be.

### 3.5. 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 vs. 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.

*Representational Outcomes:* This case study analyzed the designs in six representative epochs (see Fig. 4(b)) of the 108 possible epochs; two of these epochs are shown below in Fig. 6. This shows that context can determine the performance (MAU), affordability (MAE), and feasibility of the designs. For example, Design 3 ends up infeasible in both of the epochs shown, and designs in Sea Support epoch are much more expensive (shifted to right in MAE).

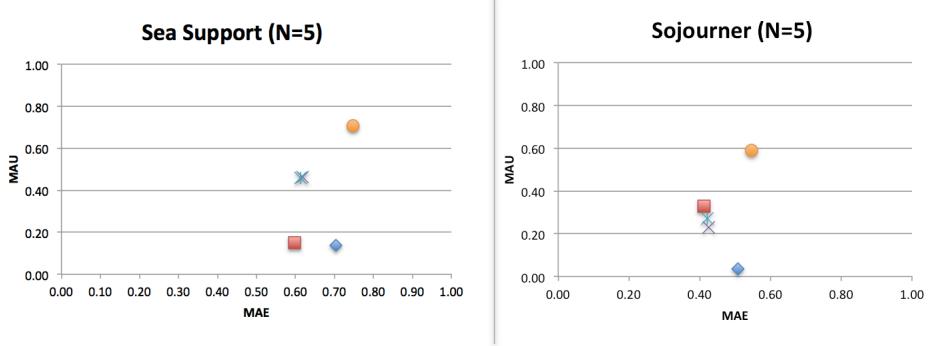


Fig. 6: The designs evaluated in the Sojourner and Sea Support epochs.

### 3.6. Process 6: Multi-Epoch Analysis

After comparing potential designs within a particular epoch, metrics are derived from measuring design properties across all epochs to give insight into the impact of uncertainties on potential designs, including 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).

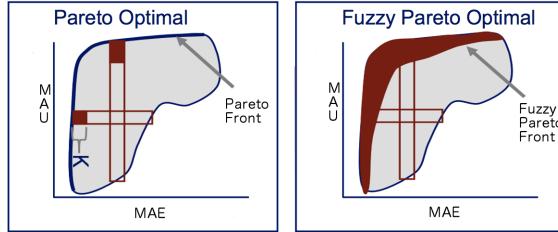


Fig. 7. A general illustration of the fuzzy Pareto metric, where K is the level of “fuzziness” applied to the traditional Pareto front.

Table 1: The NPT and fNPT measures of the six NGCS designs over the six representative epochs

Design #	NPT	5% fNPT	10% fNPT	20% fNPT
1	0	0	0	0.17
2	1	1	1	1
3	0.33	0.33	0.33	0.33
4	0.5	1	1	1
5	0.67	1	1	1
6	1	1	1	1

#### Representational Outcomes:

The Normalized Pareto Trace<sup>9</sup> (NPT) is a metric developed to measure the percentage of all epochs in which a design is Pareto optimal. This is shown for each design in the second column of Table 1. The fuzzy version of this metric – fNPT, where 0% fuzziness is identical to the NPT metric – is shown for various fuzziness levels in the columns to the right of the NPT. Fig. 7 illustrates the idea of fuzzy Pareto optimality, where K is the fuzziness level.

Two resource-centric metrics that can be calculated as part of this process are the Max Expense metric and the Expense Stability metric. The former is simply the maximum cost (with respect to a single resource) that a design will incur over all of the epochs, while the latter measures the variance of the design’s cost (again with respect to a single resource) across all epochs. These metrics are shown in Table 2 for some of the resources considered.

Table 2: Affordability metrics including the maximum of expenses such as Lifecycle Cost, Crew Size, and standard deviation of Lifecycle Cost (LCC) of the designs across all epochs.

Metric Type	Metric	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Max Expense	Max Lifecycle Cost (\$ mil.)	7093	6087	4524	6290	6284	7340
Max Expense	Max Crew Size	260	265	235	260	255	285
Expense Stability	Std. Dev. LCC (\$ mil)	2156	1850	1375	1912	1910	2231

### 3.7. 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.

*Representational Outcomes:* Two eras were manually created for the present case study, each covering a possible 10-year sequence of epochs that the NGCS might encounter. One such era is made up of the following sequence:

**Era 1:** Baseline (36 mos), Sea Support (36 mos), Baseline (24 mos), and Non-Polluting (24 mos)

### 3.8. 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.

*Representational Outcomes:* Using the two eras created in Process 7, the MAU and MAE values were examined, and are shown in Fig. 8 and Fig. 9. The stakeholder value models in Era #1 do not change on either the utility attributes or the expense attributes, allowing the MAE and MAU values to be compared directly between epoch.

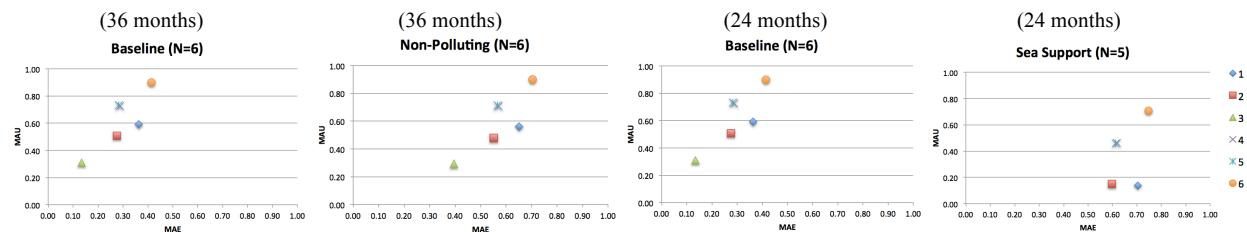


Fig. 8: The four epochs of Era #1 and their durations.

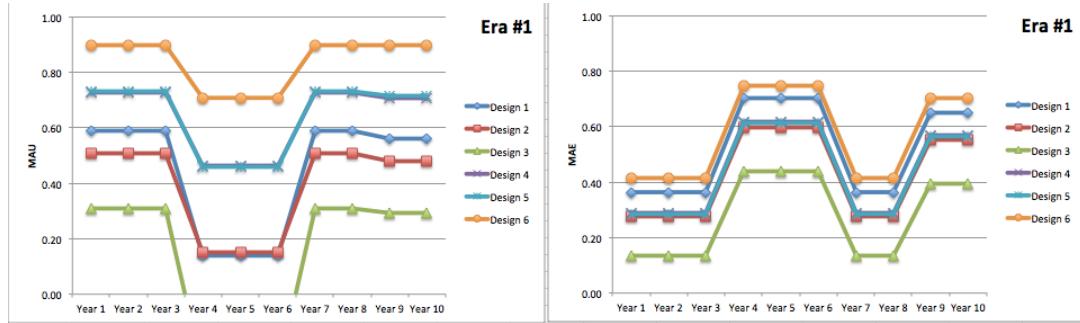


Fig. 9: Left, the MAU values of each design during Era #1; Right, the MAE values of each design in Era #1.

The same metrics used in Process 6 also apply in this process (e.g., NPT/fNPT for Pareto analysis, Max Expense and Expense Stability for expense analysis), as each can be calculated using only the epochs in this particular era. The Pareto metrics would deem Design 3 unaffordable, as it becomes infeasible in the second epoch of this era. The results of the resource-centric metrics for Era #1 are shown in Table 3.

Table 3: Affordability metrics in Era #1, including maximum yearly operations cost, NPV maximum operations cost., and standard deviation of operations costs.

Metric Type	Metric	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Max Expense	Max Ops Cost (\$ mil/yr)	154	133	102	137	137	158
Max Expense	Max Ops Cost (NPV \$ mil/yr)	131	113	87	117	117	134
Expense Stability	St.Dev. (\$ mil)	11.0	9.5	7.1	9.8	9.8	11.4

### 3.9. 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. Any number of eras can be generated through the means noted in Process 7, since there are infinite combinations of epochs and their respective durations. Once a sufficient number of eras have been generated, many of the metrics used in the Multi-Epoch Analyses of Process 6 carry over to the analysis of designs throughout all of the eras created. These metrics include the NPT and fNPT, Max Expense, Expense Stability, and changeability-focused metrics (which are not discussed in the current paper). The reader is directed to Schaffner and Wu<sup>12</sup> for more explanation on this step.

### 3.10. Discussion of the “Affordable” NGCS Design

Since affordability has been defined in terms of feasibility, several observations can be made regarding affordable design choices for the NGCS system. Design 3 was consistently the lowest-resource design, and might have been the “affordable” choice if only the Baseline Epoch was considered. However, its lack of feasibility in many of the epochs makes it a poor design choice, since its performance does not enable the minimum required capabilities in those epochs. First, the MAE metric shows that Designs 2, 4, and 5 all have similar resource expenditures in most epochs, while Designs 1 and 6 require relatively more. These observations could provide good motivation for selecting the lower-expense designs (2,4,5) as designs of interest as early in the method as Process 6. The Max Expense metric applied in Process 6 reveals that Design 2 could require slightly more crew (265 crewmen) than Designs 4 and 5 (260 and 255, respectively); but Design 2 could also cost less (albeit not by much) over its lifecycle (\$6.1 billion). Finally, when Expense Variability is considered, it shows that the designs currently under consideration all behave similarly throughout the epochs. Keeping in mind the definition of affordability as feasibility, it can be concluded that these three designs are indeed affordable choices. Accordingly, other measures (e.g., stakeholder satisfaction) can be used to downselect from the initial designs of interest. Observing Design 5’s decreased value in the Conflict epoch (epoch tradespace not shown in the present paper) could result in selecting only Design 4, which requires similar expenditures but provides more stable value delivery throughout Conflict and other epochs. Designs 2 and 4 can be compared to identify the design variables and attributes that potentially enable affordability in these designs. For example, two common design variables are length (520–530 feet) and levels of Anti-Surface/Anti-Aircraft capabilities (both medium level). These common traits can be studied to provide the general interaction between these particular variables, the resulting ship attribute levels, and the stakeholder preferences on those attributes. The affordability analysis performed through the application of this method thus naturally leads into a study of the common traits of affordable NGCS solutions. Rather than concluding the study with one solution deemed “most affordable,” the NGCS stakeholder can gain a better idea of early design decisions’ impacts on the lifelong affordability of the chosen system design.

## 4. Discussion of the Method Application to Early-Lifecycle Conceptual Design

As noted in the introduction, the application of this composite method in the conceptual design phase informs the analysis of system affordability for design selection and resulting design decisions. By incorporating the MAE function, the stakeholder preferences on various resources are represented: in the case of NGCS, these included development schedule (IOC) with monetary (e.g., acquisition and lifecycle) and non-monetary (e.g., labor) expenses. By examining the Maximum Expense incurred by each design over many possible futures, individual designs can be selected for further study. Likewise, Expense Stability can help guide analysts and decision makers to individual designs of interest. Perhaps even more useful is the additional knowledge gained of the relationship between specific design variables and their resulting effects on the affordability of the system. This knowledge can be gained whether designs are studied due to their lower expenses (to study the traits of affordable designs) or

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\* Process not demonstrated by the current study due to the representative nature of the analysis, but described here for completeness.

designs are studied due to their higher expenses (to better understand design decisions that may result in an unaffordable design). This comprehensive approach provides stakeholders with a deeper perspective on the affordability of systems while still in the conceptual design phase – *before major commitment of resources has occurred*. Stakeholders are thus enabled to better understand the system behaviour across environments as well as the trades at play between design variables and resulting expenses. Such an understanding naturally leads to capable and responsible design decisions that set the system up for affordable success from its inception.

## 5. Conclusion

The increased focus on affordable defense systems over the past several years is a result of US DoD mandates with regard to budget considerations. To aid in this focus, this paper describes and demonstrates a composite method for early-lifecycle conceptual design of the hypothetical NGCS system, with an emphasis on resource commitments required for each of the six design alternatives. The alternatives are evaluated in different epochs, various utility- and resource-centric metrics are discussed, and the resulting affordable design alternatives are noted. Some preliminary analysis is presented of specific design choices that enable affordability in the NGCS system. The final process of the method, Multi-Era Analysis, could be extended through automated generation of epoch sequences, providing further insight into long-term strategies for affordability.

## Acknowledgements

This material is based upon work supported by the Naval Postgraduate School Acquisition Research Program under Grant No. N00244-12-1-0060.

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