SEAri Working Paper Series

Title: *RSC-based Method Case Summary: Next Generation Combat Ship*

Paper Number: **WP-2014-1-1**

Revision Date: January 23, 2014

Author: M.A. Schaffner and A.M. Ross

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RSC-Based Method Case Summary: Next Generation Combat Ship

Michael A. Schaffner and Adam M. Ross
Systems Engineering Advancement Research Initiative (SEAri)
Massachusetts Institute of Technology,
E38-575, 77 Massachusetts Ave,
Cambridge, MA 02139
mschaff@mit.edu

Introduction and Background

The analysis of system affordability covers many of the aspects previously discussed, 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 factors must be balanced with the value delivery of the system, since a system providing minimal performance might be affordable but not desirable. In this case study, an established method for conceptual system design is used to consider all of these factors, augmented by several metrics introduced to cover resource-centric concerns. The first of these measures is the Multi-Attribute Expense (MAE) function, intended to aggregate stakeholder preferences on resource consumption. The second is the Max Expense metric, which gives the maximum resource expenditure for any resource across time. The third is the Expense Variability metric, which reflects the stability of resource consumption over time. The incorporation of all of these metrics enables the design method to directly inform analysts and decision makers of the relative affordability of each potential design under consideration, whether relative to one another or to established or projected budget levels.

The Responsive Systems Comparison (RSC) method was developed to aid in the design of complex systems across many domains, allowing effective anticipation of future contexts and needs relevant to system design choices early in the lifecycle through the Epoch Era Analysis (EEA) approach (Ross and Rhodes, 2008). RSC has been applied to several case applications ranging from satellite systems (Ross et al., 2009a) to an upcoming Coast Guard ship (Schofield 2010). The method applied in the present study is a 9-process variant of RSC applied 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 (2010) 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, 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 (Schofield). 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.

Overview of the 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 below in Figure 1. 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.

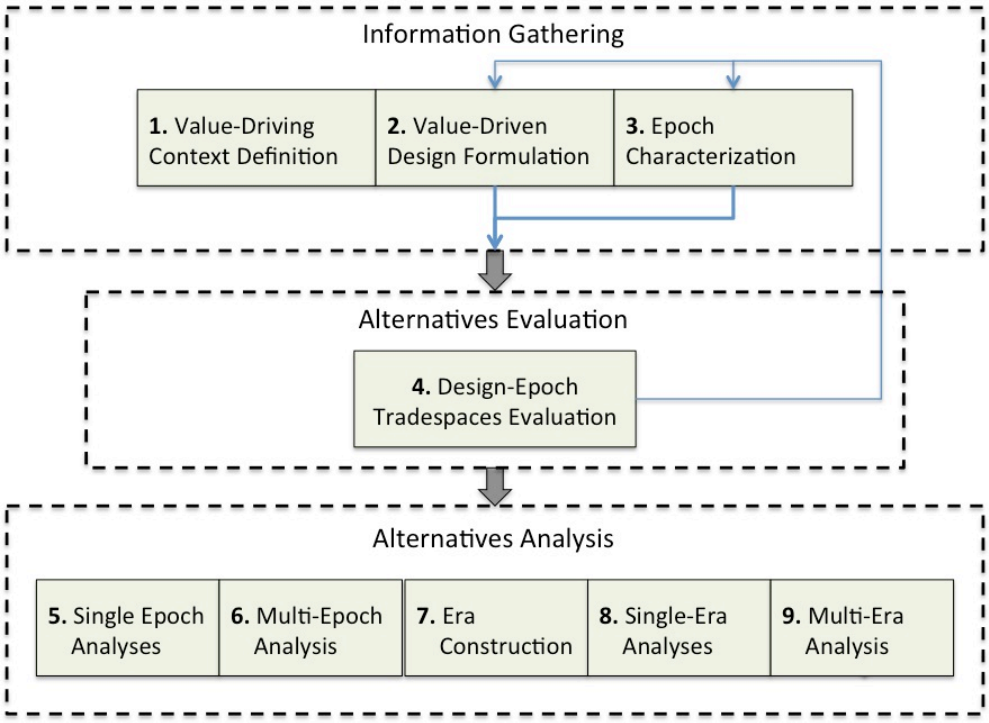

Figure 1. A graphical overview of the Gather-Evaluate-Analyze structure of the method.

The processes of the proposed method, with brief descriptions of the activities involved, are as follows, with modifications to the original 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 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.

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 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*[1]

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

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*.

3. Application of the Proposed Method to the NGCS

While the OPC and LCS systems are designed for many-unit acquisitions occurring over a period of several years, the present study examines only a single unit acquisition for the purposes of demonstrating the salient points of analysis.

Process 1: 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. Schofield (2010, p.82) defines 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.

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.

Because each of the stakeholders' value propositions reveal the different priorities of their respective organizations, the present case of the NGCS combines the various points of view into one representative stakeholder for simplicity of analysis. This stakeholder desires to provide the new fleet of USN frigates for use in air and sea operations in a variety of operating areas. In the second process of the proposed method, interviews with this stakeholder will better reveal the relevant preferences on the usage of the resources.

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 attributes desired by (as well as expense attributes of importance to) the stakeholder. Through stakeholder

interviews, the attributes' characteristics can be determined and weighted according to the preferences revealed. In this case, the weights placed on each attribute reflect the "combined" stakeholder from Process 1. Two types of attributes are delineated in the results: those attributes which represent resources that would ideally be conserved from the stakeholder's perspective, or "expense" attributes (e.g., acquisition cost, crew size), and those attributes which represent performance that would ideally be maximized, or "utility" attributes (e.g., range, speed). The results of this activity can be seen below in Figure 2.

Mission Statement:	Provide new frigate fleet for the USN.			
Objective:	Provide defense, air, and sea support across the defined mission areas.			
Attribute (Acronym)	**Units**	**Range**		**Weight**
		["worst" to "best"]		**(.1 to 1)**
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
Displacement (Disp.)	cubic ft.	11000	4000	0.2
Range	nm	4500	10000	0.2
Speed	kts	12	25	0.1
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

Figure 2. Decomposition of mission statement into attributes.

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 utility attributes and expense attributes are then assessed qualitatively by the values 'none', 'low', 'medium', or 'high' impact, using a Design-Value Matrix (DVM) with values of 0, 1, 3, and 9, as a visual aid for this activity. Following Schofield's (2010) example of decomposing the value propositions generated in Process 1 to infer the utility attributes, the present study creates a DVM mapping the impact of design variables to the resource expenditures of the system. Thus the impacts are assessed of each design variable on each expense attribute in addition to the utility attributes, generating the DVM shown below in Figure 3.

Design-Value Mapping (Notional Values)												
Representative Stakeholder												
Expense Attributes	**Design Variables**	Length	Beam	Draft	Prop Type	Hull Material	Deckhouse Material	Defense Cabability	Helos	ASUW	AAW	**Total Impact**
Acquisition Cost		9	3	3	3	3	3	3	3	3	3	**36**
Lifecycle Cost		9	3	3	9	1	1	1	1	1	1	**30**
IOC		1	3	1	3	1	0	3	1	1	1	**15**
Crew Size		3	1	1	1	1	1	3	3	3	3	**20**
Total		**22**	**10**	**8**	**16**	**6**	**5**	**10**	**8**	**8**	**8**	
Utility Attributes												
Displacement		9	9	3	3	9	3	3	3	1	1	**44**
Range		9	3	1	9	3	1	1	3	1	1	**32**
Speed		9	3	3	9	3	1	3	1	1	1	**34**
Air Capacity		3	3	1	0	1	1	3	9	3	3	**27**
Endurance		1	3	1	3	1	1	3	3	3	3	**22**
Small Boat Cap.		3	3	1	0	1	1	3	3	3	3	**21**
Total		**34**	**24**	**10**	**24**	**18**	**8**	**16**	**22**	**12**	**12**	

Figure 3. A Design-Value Matrix reflecting the notional impact of design variables on attributes.

Several benefits exist from creating such a DVM. First, by summing the rows and columns of the DVM, a practitioner can quickly determine which design variables have the most impact on general resource usage (in the notional example, the length and propeller type are the most impactful), as well as which resources are more sensitive to the present design choices (again, from the notional data, the Acquisition Cost is the most sensitive, followed by Lifecycle Cost and Crew Size). 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. Second, if low-impact design variables are identified (e.g., Draft, Deckhouse Material in Figure 3), they can be removed from the analysis to simplify the process going forward and concentrate effort on the design drivers. Finally, these impacts can be used to inform the modeling and simulation of the system necessary to evaluate system attributes in Process 4, Design-Epoch Tradespaces Evaluation.

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. (Schofield, 2010) lists 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 (SoS)**: 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 uses 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. Due to the similarities of operating contexts and missions, the epoch variables chosen for the NGCS are a subset of those outlined for the OPC. The epoch variables chosen are shown below in Figure 4, with the corresponding category, associated ranges of values, and corresponding units.

		Levels	
	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

Figure 4. A list of the epoch variables modeled for the NGCS context and needs.

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. The complete Epoch Descriptor Impact Matrix with values (both notional and taken from Schofield's (2010) OPC study) is shown below in Figure 5.

Epoch Descriptor Impact Matrix						
	Epoch Variables	VUAV	Small Boat Size	Engine Emissions	Range Increase	Ice Region Use	**Total Impact**
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**
Total		**8**	**16**	**12**	**36**	**24**	
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**
Total		**10**	**9**	**8**	**14**	**7**	

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 Speed and Range are the utility attributes most impacted by the uncertainties, and Lifecycle Cost is the most impacted expense attribute. Conversely, the Range Increase epoch variable (by quite a margin) is the most impactful on all attributes, with Ice Region Use heavily impacting performance. Gaining an understanding of these relationships early in the design process allows a 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. In addition, this mapping will aid in the evaluation of designs in each epoch and era in the subsequent processes of the method.

Process 4: Design-Epoch Tradespaces Evaluation

Once the value-driving context has been defined, along with the value-driven designs (variables and attributes) and epochs, a practitioner is ready to begin evaluating candidate designs in all epochs. The evaluation of the potential designs' attributes in the case of the NGCS was achieved through use of the MIT Math Model, which is a set of mathematical relationships developed at MIT and used for over 20 years in the design of Navy frigates for academic and government studies. The

model's inputs and outputs include length, beam, draft, crew size, weapon packages and many other factors (around 50 in all). It incorporates detailed calculations of payload size, hull geometry, machinery, power and space requirements, weight, stability, and a simplified cost model. Using the model, a naval subject matter expert generated six feasible ship designs based on the design variables provided, producing the attributes of Acquisition and Lifecycle Costs, Crew Size, Range, Speed, Displacement, and IOC for the 6 representative NGCS designs. These attributes were combined with several others – Air Capability, Endurance, and Small Boat Capability – along with the notional impacts of the epoch variable levels from Process 3. The resulting (adjusted) attribute levels were mapped to stakeholder preferences through the use of single attribute utility functions. The utility curves for the levels of each attribute – normally captured through stakeholder interviews, but here generated through assessment of current capabilities and the concepts of loss aversion and anchoring in prospect theory (Kahneman and Tversky 1979, 1984) – provide a single attribute utility value for each system attribute's level. The utility curves defined for all attributes in the Baseline epoch are shown below in Figure 6.

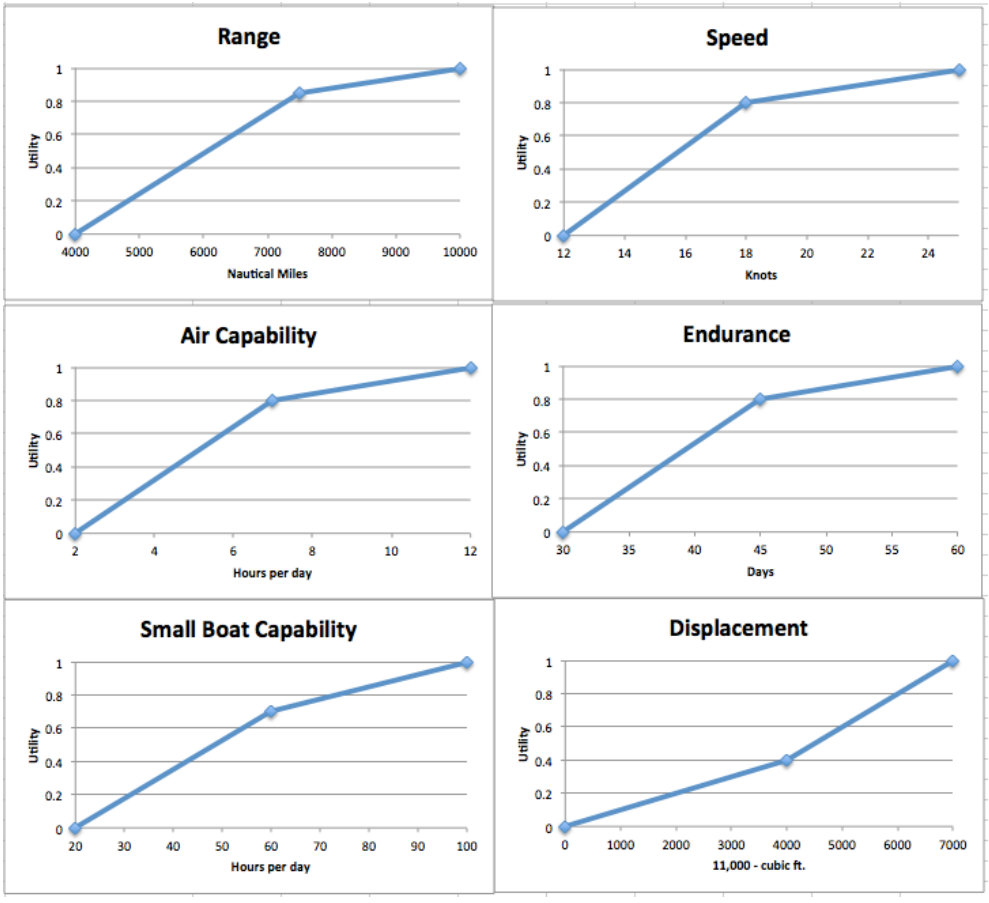

Figure 6. Single Attribute Utility (SAU) curves on each system attribute. The leveling off of stakeholder satisfaction/dissatisfaction occurs around levels established by previous systems.

All of the single attribute utility values are then aggregated into a Multi-Attribute Utility (MAU) value for each design point. Two key assumptions are made during this step: preferential independence among attributes and utility independence

among attributes. If each attribute of the system contributes independently to utility, then the *swing weights* (relative ranking of an attribute's importance when it is at its best values and all others are at their minimally acceptable values) on each attribute sum to 1. These assumptions allow the MAU to be calculated using a simple weighted sum of the single attribute utilities:

$$\sum_{i}^{N} k_i U_i(X_i)$$

where

$$\sum_{i}^{N} k_i = 1$$

The MAU metric is commonly plotted against each design's monetary cost to help visualize a tradespace. As the present study is focused on resource usage, however, monetary cost is replaced with the Multi-Attribute Expense (MAE) metric, which captures stakeholder preference on other resource usage in addition to financial cost (e.g., initial operating capability, crew size) through the use of Single Attribute Expense (SAE) functions, akin to the SAU and MAU functions from above. These preferences are shown below Figure 7.

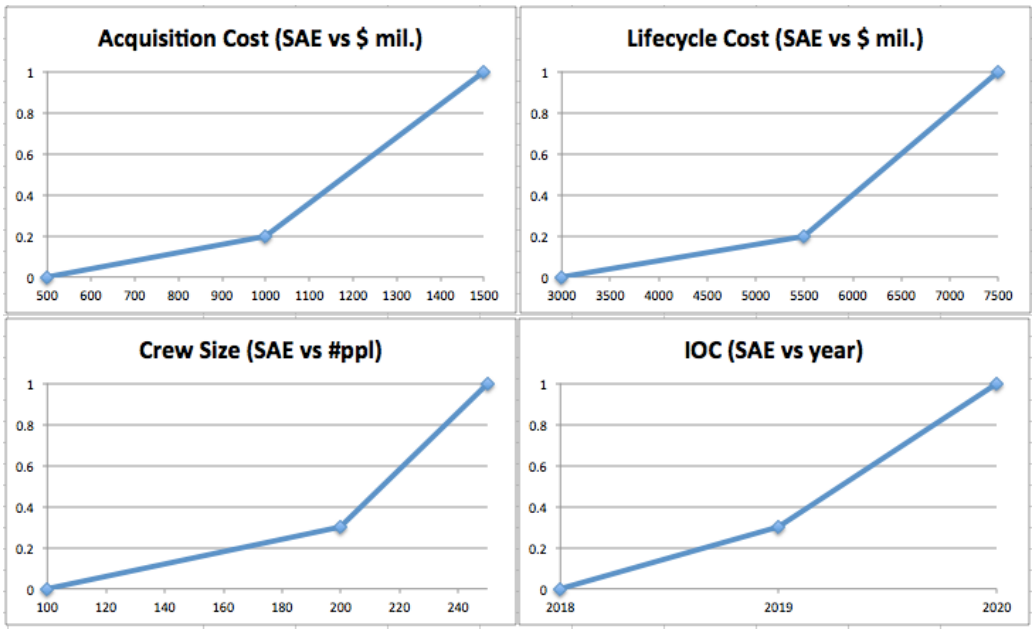

Figure 7. SAE functions for the expense attributes of the NGCS, where a value of 1 represents complete dissatisfaction. The "knees" in the curves represent anchoring from similar expenses of previous systems.

For the present study, six representative designs were chosen for evaluation throughout epochs, shown below in Figure 8. The resulting evaluations of these designs in the Baseline epoch is shown in Figure 9, which lists all of the attribute

values and the resulting MAE and MAU values for each design. One of the visual results of the MAU and MAE evaluations in the Baseline Epoch is a tradespace plotting the MAU vs. MAE metrics for the handful of NGCS designs, shown below in Figure 10. These evaluations are performed for all designs in all epochs (a representative six epochs, in the case of the NGCS), providing the metrics necessary for the remaining steps of the method. Different sets of stakeholder preferences on utility attributes were used in addition to those shown in Figure 6, depending on the epoch.

Design #:	1	2	3	4	5	6
Length (ft)	519	530	440	521	510	562
Beam (ft)	59.8	59	51.1	57.5	56.8	62.2
Draft (cu.ft.)	19.1	18.8	16.3	18.3	20.3	19.4
Prop Type	CRPP	CRPP	CRPP	CRPP	CRPP	CRPP
Hull Material	OS	OS	HTS	HTS	OS	OS
DH Material	Aluminum	Steel	Aluminum	Aluminum	Steel	Aluminum
Def Capability	Low	High	Low	Low	High	Low
Helos	2	1	1	2	2	2
ASUW	High	Medium	Low	Medium	Medium	High
AAW	High	Medium	Low	Medium	Medium	High

Figure 8. The six representative designs (with corresponding design variable levels) for the initial concept selection of the NGCS.

			EPOCH: Baseline			
	Blue Diam.	Red Square	Green Triangle	Purple X	Blue X	Yellow Circle
Design #:	1	2	3	4	5	6
Acquisiton	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
Displacement	7663	8143	4654	7734	8639	9800
Range	4500	6500	4500	6500	8000	6500
Speed	20	20	30	30	30	40
AIR CAP	8	4	2	8	8	12
ENDRNC	50	50	30	45	45	60
SB CAP	60	20	20	60	40	100
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

Figure 9. The evaluated attributes of the six representative designs in the Baseline Epoch, with aggregated MAE and MAU values. (See Figure 2 for units of measurement.)

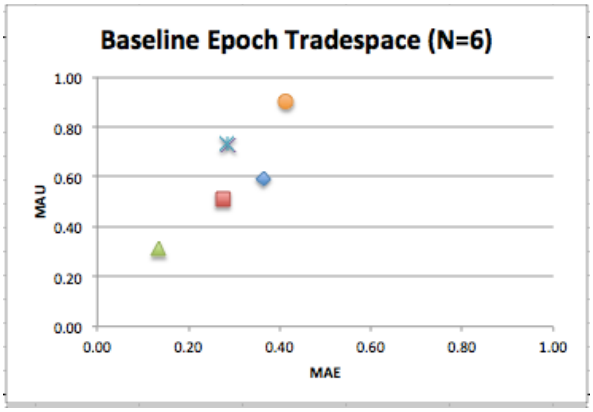

Figure 10. One of the results of attribute evaluation through the Math Model, epoch variable impacts, and single/multi-attribute utilities: a tradespace (MAU vs MAE) of 6 NGCS designs operating in the Baseline Epoch.

The six epochs evaluated for the NGCS study are shown below in Figure 11. They represent all of the 108 possible epochs from the combinations of the epoch variable levels (see Figure 5).

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

Figure 11. The six representative epochs constructed for the NGCS study (of 108 possible).

Process 5: Single-Epoch Analyses

Once the evaluations of Process 4 are complete for all designs in all epochs, analyses can begin of design characteristics in single epochs. In addition to the MAU and MAE metrics, the present case considers the monetary cost of each design as well as each design's Pareto efficiency in the tradespace. This analysis can be repeated for any number of epochs of interest, which can be chosen through various means – those most likely to occur, those most likely to hinder value delivery, or those of concern for other reasons to stakeholders and analysts. The present study chooses only a few of the epochs created in Process 4: Mothership, Sea Support, and Conflict.

Mothership is an epoch characterized by Large VUAVs and 35ft Small Boats, with a 10% increase in Range of mission over the Baseline Epoch. This combination of epoch variables represents a period in which stakeholders would desire the NGCS to support air and sea operations over non-Arctic waters. The evaluated designs for this epoch are shown below in Figure 12, and the corresponding tradespace is depicted below in Figure 13.

			Mothership			
	Blue Diam.	Red Square	Green Triangle	Purple X	Blue X	Yellow Circle
Design #:	1	2	3	4	5	6
Acquisiton	1274	1067	691	1115	1112	1356
Lifecycle	6167	5293	3934	5470	5464	6382
IOC	2018	2018	2018	2018	2018	2018
Crew Size	250	255	225	250	245	275
Displacement	7663	8143	4654	7734	8639	9800
Range	4500	6500	4500	6500	8000	6500
Speed	18	18	27	27	27	36
AIR CAP	0	-4	-6	0	0	4
ENDRNC	45	45	25	40	40	55
SB CAP	50	10	10	50	30	90
MAE:	0.47	0.36	0.21	0.39	0.38	0.51
MAU:	0.38	0.18	infeasible	0.54	0.53	0.75

Figure 12. The evaluated attributes of the 6 representative NGCS designs in the Mothership epoch. (See Figure 2 for units of measurement; negative attribute values are treated as 0.)

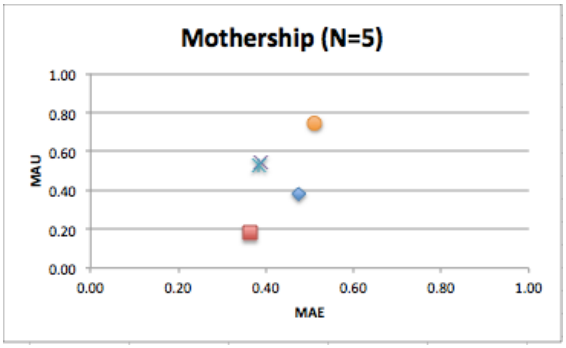

Figure 13. The 6 potential NGCS designs in the Mothership epoch.
(One design is below minimum acceptable utility, leaving the 5 feasible designs.)

It is important to note that in general, the MAU and MAE values cannot be compared between epochs, since stakeholder preferences may change between epochs (i.e., changed what the 0-to-1 scale represents, as it is not a universal scale). The yields of the tradespaces can always be compared, however, providing the number of designs at or above the minimum acceptable utility and at or below maximum acceptable expense. While six designs were evaluated in each epoch, only five are feasible in the Mothership epoch, indicating that this epoch provides some challenges for at least one potential design to provide minimum acceptable utility and/or operate below maximum acceptable expense. The table in Figure 12 shows that Design #3 does not provide

Because acquisition and lifecycle costs can be limiting factors compared to the other expenses (e.g., crew size) rolled up in the MAE metric, the monetary costs of each design are briefly observed in each epoch of interest. Design #6 has an acquisition cost of $1.3 billion and a lifecycle cost of $6.4 billion, while Design #2 design's acquisition cost is 30% less (~$1 billion), and its lifecycle cost is around 15% less ($5.3 billion). The other designs' costs are in the middle of these two designs. If budget levels were established for the stakeholder in this epoch, those considerations could aid in the comparison of these costs. In addition, Process 6 will examine more informative cost metrics over all epochs, with or without established budget levels.

The Fuzzy Pareto Number (FPN) is a metric developed to indicate a design's relative value in a given epoch, as it measures how far from Pareto-optimality that design lies in the tradespace of that epoch (Fitzgerald and Ross, 2012). Since it represents a percentage of deviation from cost/utility Pareto efficiency, it is measured from 0 to 100; in addition, since it is a percentage, it can be compared across epochs as an indicator of relative efficiency differences. In the Mothership Epoch, the FPN for 4 of the designs is 0 due to their locations on the Pareto front. The remaining design, Design #1, has an FPN number of 20, meaning that it is 20% "inefficient" compared to the Pareto front in this epoch.

These analyses are now briefly discussed for the rest of the epochs of interest.

Sea Support is an epoch during which the NGCS would be required to support extended missions with very capable small boats over a wide range of global waters.

It assigns the following values to the epoch variables (various possible levels described in Process 3): Small Boat Size of 35ft, Emissions standards at Level 3, Range Increase of 10%, and High Ice Region Use. The evaluated attributes of all designs are shown in Figure 14 below; the tradespace of MAU vs. MAE follows in Figure 15.

			Sea Support			
	Blue Diam.	Red Square	Green Triangle	Purple X	Blue X	Yellow Circle
Design #:	1	2	3	4	5	6
Acquisiton	1274	1067	691	1115	1112	1356
Lifecycle	5887	5052	3755	5221	5216	6092
IOC	2020	2020	2020	2020	2020	2020
Crew Size	240	245	215	240	235	265
Displacement	7663	8143	4654	7734	8639	9800
Range	3600	5200	3600	5200	6400	5200
Speed	15	15	23	23	23	31
AIR CAP	2	-2	-4	2	2	6
ENDRNC	40	40	20	35	35	50
SB CAP	40	0	0	40	20	80
MAE:	0.70	0.60	0.44	0.62	0.61	0.75
MAU:	0.14	0.15	infeasible	0.46	0.46	0.71

Figure 14. The evaluated attributes of each design in the Sea Support epoch. (See Figure 2 for units of measurement; negative attribute values are treated as 0.)

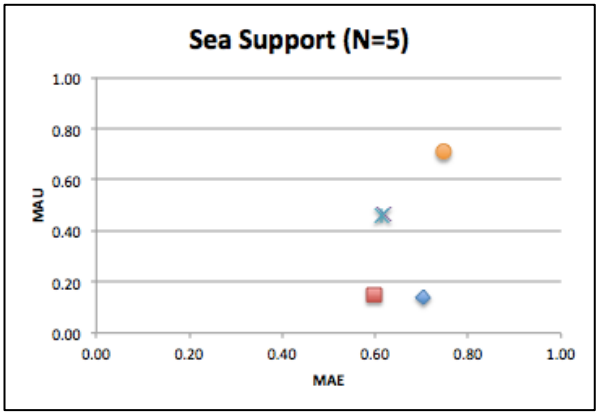

Figure 15. The 4 feasible NGCS designs in the epoch Sea Support.

The yield of this epoch is again five out of the six evaluated designs. From Figure 14, we can see that the acquisition costs are similar to that of the Mothership epoch, but the lifecycle cost is slightly less in this epoch. We can also see that the IOC is pushed back to the year 2020 for all designs. The FPNs for Designs #2, #4, #5 and #6 are once again 0, while the FPN for Design #1 is 38.

The third epoch of interest considered, Sojourner, is defined by a Range Increase of 20% plus High Ice Region Use. The stakeholder's preferences in this epoch are agnostic of the air and small boat capabilities of each design. Figure 16 displays the evaluated attributes of each design in this epoch, and the tradespace of MAU vs. MAE is shown below in Figure 17.

			Sojourner			
	Blue Diam.	Red Square	Green Triangle	Purple X	Blue X	Yellow Circle
Design #:	1	2	3	4	5	6
Acquisiton	1156	968	627	1011	1009	1230
Lifecycle	6141	5270	3917	5446	5440	6355
IOC	2019	2019	2019	2019	2019	2019
Crew Size	245	250	220	245	240	270
Displacement	7663	8143	4654	7734	8639	9800
Range	3600	5200	3600	5200	6400	5200
Speed	15	15	23	23	23	30
AIR CAP	2	-2	-4	2	2	6
ENDRNC	30	30	10	25	25	40
SB CAP	35	-5	-5	35	15	75
MAE:	0.51	0.41	0.27	0.43	0.42	0.55
MAU:	0.04	0.33	infeasible	0.23	0.27	0.59

Figure 16. The evaluated attributes of each design in the Sojourner epoch.
(See Figure 2 for units of measurement; negative attribute values are treated as zero.)

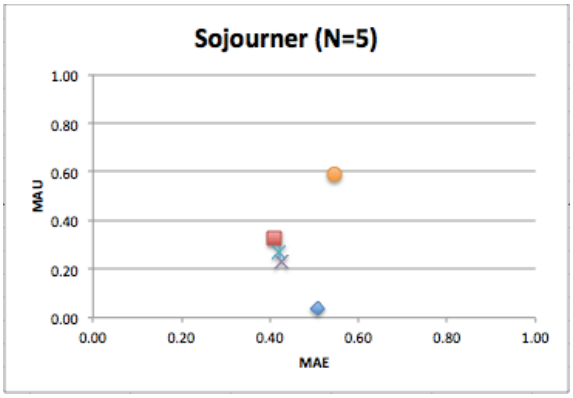

Figure 17. The 5 feasible potential NGCS designs in the Sojourner epoch.

The yield of this epoch is five of the six designs; only Design #3 is infeasible. From Figure 16, we can see that the acquisition costs are similar to that of the previous epochs considered, but the lifecycle costs of all designs are around the Mothership epoch's levels. It is of interest to note that only two designs remain on the Pareto front: Designs #2 and #6. The FPN for Design #4 is 4, the FPN for Design #5 is 3, and Design #1's FPN is 23.

Process 6: Multi-Epoch Analysis

The analyses of Process 5 can be enlightening regarding the behavior of individual designs and the impacts of individual epochs, but the observations can be time-consuming (and the resulting data overwhelming) for any significant number of designs and/or epochs. The analyses can also allow undue weight to be placed on the epochs of interest over those omitted from explicit consideration, even though all epochs represent possible operating environments. For this reason, Process 6 focuses on several summary metrics to gain a higher-level view of all designs' characteristics *over all epochs*. (Since only 6 epochs are used as representative of all epochs in this study, their tradespaces are shown side by side for easy comparison in the attached Technical Appendix.) No weight is given to epochs based on likelihood of occurrence, as the purpose of this analysis is simply to cover all

possible scenarios the system might encounter. The first of the metrics designed for this purpose is the Normalized Pareto Trace.

The Normalized Pareto Trace (NPT) reflects the percentage of all epochs for which a given design is Pareto efficient (Ross et al., 2009b). A higher NPT indicates higher Pareto efficiency for a design over *all* epochs, rather than higher Pareto efficiency in only one epoch (like the FPN). It is calculated for any design by counting the number of epochs in which that design has an FPN of zero and then dividing by the total number of epochs. The six potential NGCS designs and their corresponding NPTs across the six representative epochs (shown in Figure 11) are listed below in Figure 18.

	Design #	**NPT**
Blue Diamond	1	0
Red Square	2	1
Green Triangle	3	0.33
Purple X	4	0.5
Blue X	5	0.67
Yellow Circle	6	1

Figure 18. The NPTs for the 6 NGCS designs across the 6 representative epochs. An NPT value of 1 represents Pareto efficiency in 100% of the epochs.

Clearly Designs #2 and #6 would be good choices when high priority is placed on Pareto efficiency, as they remain on the Pareto front no matter which epoch encountered. Design #6 is the most expensive and brings the most utility in every epoch, while Design #2 is one of the lower expense designs and is closer to minimal acceptable utility in most epochs.

The somewhat simplistic measure of NPT can be extended by allowing some "fuzziness" threshold in the evaluation of efficiency. The fuzzy Normalized Pareto Trace (fNPT) is a metric that does precisely this – applies a specified fuzziness percentage to the Pareto front in each epoch, where 0% is a normal Pareto front, and 100% includes the entire range of both the MAU and MAE of the designs in a given epoch (Fitzgerald et al., 2012a). The fNPT of each design at several fuzziness levels is shown below in Figure 19.

	Design #	**0% fNPT**	**5% fNPT**	**10% fNPT**	**20% fNPT**
Blue Diamond	1	0	0	0	0.17
Red Square	2	1	1	1	1
Green Triangle	3	0.33	0.33	0.33	0.33
Purple X	4	0.5	1	1	1
Blue X	5	0.67	1	1	1
Yellow Circle	6	1	1	1	1

Figure 19. The fuzzy NPTs of the 6 NGCS designs for several levels of fuzziness. A value of 1 represents fuzzy Pareto efficiency in 100% of the epochs.

The results of the fNPTs show that with a small amount of fuzziness – around 5% – most of the NGCS designs have maxed out their fNPT number (due in part to the

small number of designs considered). Design #1 remains inefficient even after the fuzziness level approaches 20%, decreasing this design's attractiveness compared to the others. With more designs under consideration, the benefits of the fNPT metric should be evident: helping identify designs that may be near-Pareto efficient in many epochs and resultantly missed by the original NPT (such as Designs #4 and #5 in this case).

(Aspects of changeability)

The metrics shown so far do not take into consideration the possibility of changing from one design to another in a given epoch. This possibility is usually present in some form, however, and as a result it helpful for multi-epoch analyses to evaluate a design based on the strategies used for change – that is, an original design can be evaluated in multi-epoch analyses by evaluating the *target design* (to which the original changes, if applicable) in each epoch. Strategies can be defined to guide the change behavior; for the NGCS case, the strategy chosen was "Maximize Efficiency" (i.e. move to the Pareto front if not already there). Transition rules were created such that any design could be discarded and any design purchased in any epoch. A transition matrix was then constructed to reflect the resulting target design (dictated by the chosen strategy) in each epoch from each original design in that epoch. With this additional information on the anticipated transitions and resulting designs in each epoch, modified forms of the previous metrics were constructed and are now discussed.

The *effective* NPT (eNPT) and *effective* fNPT (efNPT) metrics evaluate a design across all epochs in the following way: if the change strategy dictates that a (original) design changes to another (target) design in a given epoch, then the target design is evaluated; if the change strategy dictates that a starting design does not change in that epoch, then that starting design is evaluated (Fitzgerald et al., 2012b). The eNPTs for the NGCS designs, generated by the change strategy "Maximize Efficiency" discussed above, are shown below in Figure 20.

	Design	**eNPT**	**eNPT, with $ budget (notional)**	**eNPT, with time budget (notional)**
Blue Diamond	1	1	0.3	0.17
Red Square	2	1	0.5	0.67
Green Triangle	3	1	0.5	0.5
Purple X	4	1	1	1
Blue X	5	1	0.67	1
Yellow Circle	6	1	1	1

Figure 20. The eNPTs for the NGCS designs with the change strategy "Maximize Efficiency".

As the table shows, most designs' base eNPT is a great improvement over the NPT. In fact, it appears that every design can achieve Pareto efficiency in every epoch. This is true because of the transition rules defined and the transition strategy chosen. Recall that the transition rules defined for the NGCS case state that every design can be discarded and any other design purchased in its place in any epoch, while the transition strategy dictates movement to the Pareto front in every epoch.

If smaller-scale changes than discard/replace were available (e.g., "add UAV storage", "remove crew", etc), rules could be established to represent the feasibility/infeasibility of changing from one design to another in any epoch, thereby limiting the improvement of a design's eNPT over its NPT. Likewise, transition costs of money and time could be defined for any of the transitions between designs, and these costs could be used to limit feasibility (depending on the budget/goal of the transition strategy defined) as well as to track the total expenditures necessary to achieve a given eNPT. In the notional columns on the right of Figure 20, it can be seen that budgets of time or financial costs would prevent Design #1, for instance, from improving very much. Likewise, the other designs may improve or not. (The effective fNPT (efNPT) metric can also be constructed, but is left out of the present study due to the already-maximized eNPT values above.)

(Additional aspects of affordability)

In addition to the efficiency of a design relative to other designs in each epoch, it can be useful to consider the resource expenditures of a design in various operating environments. Two ways of measuring expenditures across all epochs are applied to the NGCS case: one tracks the maximum amount required of each resource for a given design, and the other tracks the stability of resource consumption throughout all epochs. The first metric can help identify designs that would be unsustainable given the right conditions, while the second metric can identify designs for which allocating resources in the future (e.g., Congressional budget requests) may prove easier due to consistency through changing operational environments. In the case of the NGCS, the highest levels of expense for each design's Lifecycle Cost and Crew Size in all (6 representative) epochs are shown below in Figure 21.

Max Expense	Design					
	1	2	3	4	5	6
Lifecycle Cost ($ mil.)	7,093	6,087	4,524	6,290	6,284	7,340
Crew Size	260	265	235	260	255	285

Figure 21. The highest levels of Lifecycle Cost and Crew Size across all epochs.

Recalling the Normalized Pareto Trace from earlier, efficient designs #2 and #6 can be selected for comparison of their respective maximum expenses incurred. While Design #2 could cost a maximum of just over $6 billion in its lifetime, Design #6 could cost over 20% more in one possible scenario. In addition, Design #6 could require 25 more crewmen depending on the epoch encountered. Note that multiple designs' maximum expenses are not all necessarily from the same epoch, as epoch variables impact individual designs differently. (Likewise with a design's multiple expense attributes: each of a design's attributes are impacted differently by the epoch variables, so that the lifecycle cost may be highest in one epoch, while maximum crew size is required in another.)

The standard deviation of each design's lifecycle cost is shown below in Figure 22. Continuing our analysis from the Max Expense, it can be seen that Design #2 has somewhat less variability across epochs than Design #6, by around $400 million. If budget forecasts were known at the time of this analysis, such information could be

used effectively to choose a design that fit within the expected variability of the budget for the timeframe of the forecast.

Expense Stability			Design			
(St.Dev. in $ mil.)	1	2	3	4	5	6
Lifecycle Cost	2,156	1,850	1,375	1,912	1,910	2,231

Figure 22. The standard deviation of Lifecycle Cost for each design across all epochs.

These considerations, when combined with previous analyses, help outline the impact of the risks involved for any initial concept selection, and they can help analysts and decision makers alike understand the traits behind design concepts that would be affordable in all futures.

Process 7: Era Construction

The analysis up to this point has evaluated NGCS designs in epochs, or short-run periods of fixed contexts and needs. By combining these short-run fixed periods into a sequence over a longer period of time, an *era* is created – allowing a practitioner to study the attributes of designs over one possible development of the operating environment, as well as the effects of path dependence through epochs (Ross and Rhodes, 2008). Two eras were manually constructed for the present study, each representing a ten-year sequence of epochs that the NGCS may encounter (taken from the six representative epochs from Process 4, c.f. Figure 11). The first era considered consists of the following sequence:

Baseline for 36 months, Sea Support for 36 months, Baseline for 24 months, Non-Polluting for 24 months.

The second era considered consists of:

Sojourning for 24 months, Conflict for 36 months, Mothership for 36 months, and Sojourning for 24 months.

Process 8: Single-Era Analyses

The first era comprises epochs in which stakeholder preferences do not change. As a result, the MAE and MAU values can be compared directly. The era is shown below in Figure 23 (each tradespace) and Figure 24 (line graph view).

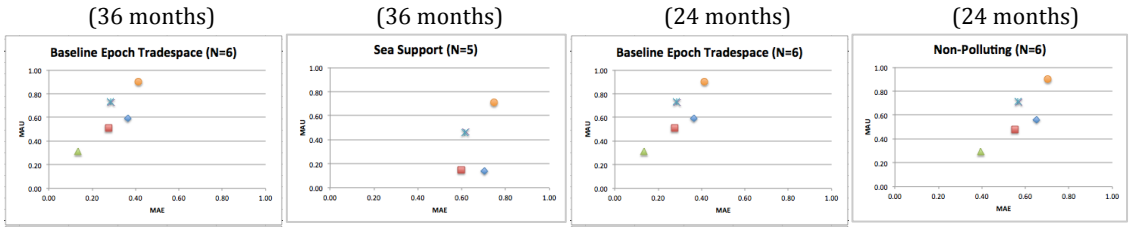

Figure 23. The four epochs of Era #1 and their durations. Stakeholder preferences remain constant; as a result, MAU and MAE values can be directly compared across epochs.

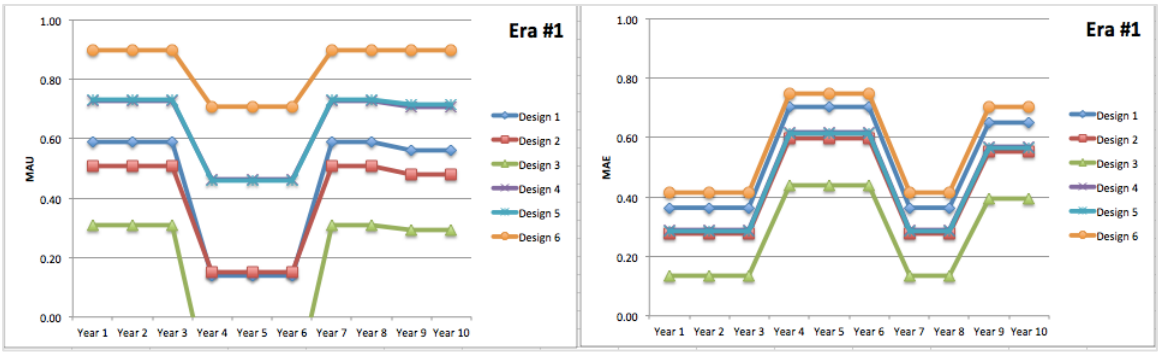

Figure 24. Left: the MAU values of each design during Era #1.
Right: the MAE values of each design in Era #1.

Before proceeding, it is noted that Design #3 is infeasible in the Sea Support epoch, meaning that design cannot provide minimum acceptable utility throughout this era. If a decision maker believes this era to be one of the more likely narratives to play out for the NGCS, then that design should be removed from consideration.
Using the concept of time value of money, the NPV of each design's operations cost can be calculated for the entire era. (To obtain the operations cost for a given timeframe, the acquisition cost was subtracted from the 30-year lifecycle cost, and the result divided into the appropriate number of months.) For instance, Design #1's yearly operations cost in the Baseline Epoch is $131 million; this amount is used as the input to the final NPV calculation. This same calculation is performed for each design in each epoch in the era, and a 10% discount rate is assumed. The intermediate values and final calculation are shown below in Figure 25.

			Era #1			
($ millions)	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
NPV Ops Yr. 1	131	113	87	117	117	134
NPV Ops Yr. 2	119	103	79	106	106	122
NPV Ops Yr. 3	108	94	72	96	96	111
NPV Ops Yr. 4	116	100	77	103	103	119
NPV Ops Yr. 5	105	91	70	93	93	108
NPV Ops Yr. 6	95	82	63	85	85	98
NPV Ops Yr. 7	74	64	49	66	66	76
NPV Ops Yr. 8	67	58	45	60	60	69
NPV Ops Yr. 9	59	51	40	53	53	61
NPV Ops Yr. 10	54	47	36	48	48	55
NPV Total:	**929**	**803**	**618**	**827**	**826**	**953**

Figure 25. Calculation of the net present value ($ millions) of designs' operations costs for Era #1.

From these numbers, it appears that Designs #2, #4, and #5 form one group with similar NPV operations costs, and that Designs #1 and #6 form another similar group. While these numbers reflect the same grouping of designs as the MAE suggests in the tradespace plots, it is important to note that the MAEs could be similar for certain designs whose operations cost's NPV are vastly different. For this reason, it can be necessary to consider these costs separately from the MAE score itself if information about the operations budget is known at this stage.

The additional affordability considerations from Process 6 can also be repeated at this point: the maximum values of the operations costs of each design are shown below in Figure 26, and the standard deviation of operations costs throughout the era is shown in Figure 27.

($ million / yr)	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Max Ops Cost:	154	133	102	137	137	158
Max Ops Cost (NPV):	131	113	87	117	117	134

Figure 26. The maximum yearly operations cost of each design throughout Era #1, compared with the NPV maximum operations cost.

(St.Dev. in $ mil.)	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Expense Variability	11.0	9.5	7.1	9.8	9.8	11.4

Figure 27. The standard deviation of each design's operations costs throughout Era #1.

In this case, the results from the era analysis reflect the same conclusion as Process 6 (over all epochs): the more expensive designs have slightly more variance than the less expensive designs. If more designs were under consideration, it may be possible to find a more expensive design that is more cost-stable across all epochs (and/or in a particular era), which may give incentive to include it when considering designs for final selection. Of course these metrics can be considered for any resources of particular concern, but are only applied here to operations cost for demonstration purposes.

The second era, shown in Figure 28 below, consists of epochs with changing stakeholder preferences, and so the MAU and MAE values cannot be compared directly across epochs.

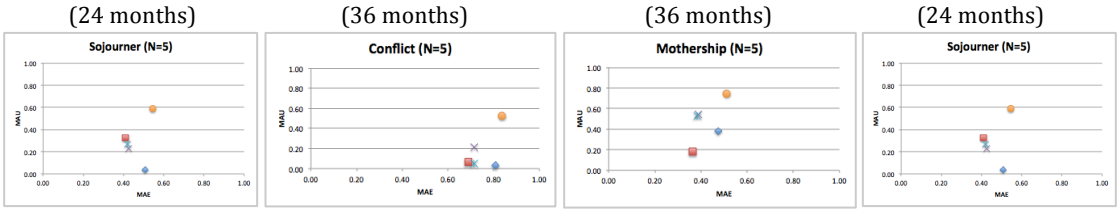

Figure 28. The four epochs of Era #2. The MAU and MAE values cannot be compared between epochs due to changing stakeholder preferences.

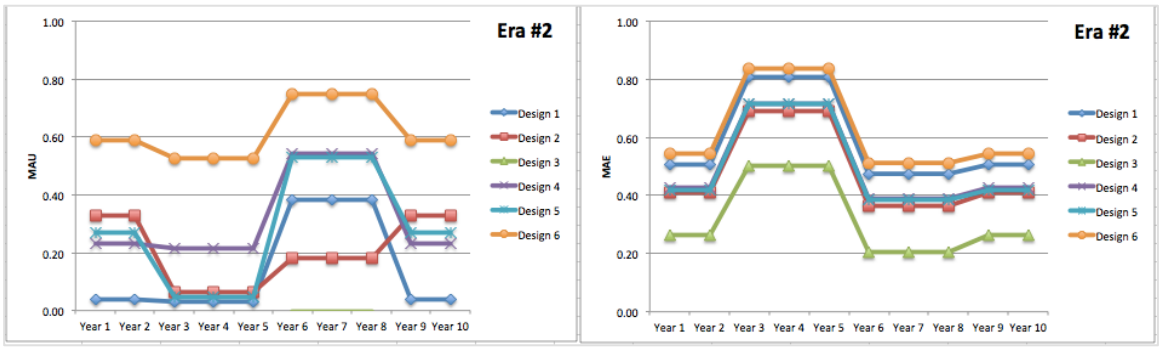

Figure 29. Left: the MAU of each design through Era #2. Right, the MAE of each design during the same ten-year period. Note that stakeholder preferences change between epochs.

It is again noted that Design #3 is infeasible in this era; in fact, it is not feasible in even one of these epochs. Design #2, while starting the era highly ranked in the MAU measurement, makes its way to the least favorable ranking for a short time. Its expenses remain least dissatisfying, however, among feasible designs in this era. The NPV calculations for all designs in this era are shown below in Figure 30.

			Era #2			
($ millions)	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
NPV Ops Yr. 1	166	143	110	148	148	171
NPV Ops Yr. 2	151	130	100	134	134	155
NPV Ops Yr. 3	157	135	104	140	139	161
NPV Ops Yr. 4	143	123	94	127	127	146
NPV Ops Yr. 5	130	112	86	115	115	133
NPV Ops Yr. 6	101	87	67	90	90	104
NPV Ops Yr. 7	92	80	61	82	82	95
NPV Ops Yr. 8	84	72	55	74	74	86
NPV Ops Yr. 9	78	67	51	69	69	80
NPV Ops Yr. 10	70	61	47	63	63	72
NPV Total:	**1171**	**1011**	**774**	**1042**	**1041**	**1204**

Figure 30. Calculation of the NPV operations costs of each design in the 10-year Era #2.

It should be obvious that this era represents a particularly challenging environment for the designs, with two of them exceeding one billion dollars for the NPV operation costs. The maximum values and the standard deviations of operations costs for all designs are shown below in Figure 31 and Figure 32.

($ million / yr)	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Max Ops Cost:	190	164	125	169	169	195
Max Ops Cost (NPV):	166	143	110	148	148	171

Figure 31. The maximum operations cost incurred by each design throughout Era #2, compared with the maximum NPV operations cost.

(St.Dev. in $ mil.)	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Expense Variability	11.5	9.9	7.6	10.2	10.2	11.8

Figure 32. The standard deviation of operations cost throughout the 10 years of Era #2.

Process 9: Multi-Era Analyses

While certain insights can be gained by inspection of individual eras such as those in Process 8, it is also instructive to observe alternatives' behavior across the era space, i.e., in all of the eras constructed by Process 7, since large numbers of eras can be constructed through combinatorics, probabilistic state transitions, and other means. Process 9 focuses on these analyses across all eras, which are somewhat analogous to the Multi-Epoch Analyses of Process 6.

Most of the metrics of Multi-Epoch Analyses carry over, including the NPT, fNPT, eNPT, efNPT, and Expense Variability, with slight differences in calculation. For example, the NPT/fNPT of each design in an era are calculated using only the epochs in that era, and the Pareto trace is normalized by the total amount of time in the era (rather than the total number of epochs). Once calculated for each design in each

era, the NPT values can be compared in various ways. One could look for the extreme NPT values, whether high or low, leading back to Process 8 and observation of the properties and interactions of the specific design and era that cause these extreme values. (In the NGCS case, for example, it might be discovered through this activity that Design #3 performs very poorly in eras with long durations of the Conflict epoch. Further investigation could lead to the insight that the lack of UAV capacity drastically reduces satisfaction in eras involving Conflict.) One could also look for the highest average NPT over all eras to identify a design that consistently delivers value across all identified possible futures.

The effective versions of the NPT and fNPT can become more informative in this process as well. Because transition rules and costs can depend directly on contextual uncertainties (whether epoch variables or stakeholder needs), the eNPT/efNPT metrics can help identify *path-dependent* weaknesses of particular change strategies. The eNPT/efNPT metrics of Process 6 only considered transition costs and rules for one epoch, but analyzing these same metrics through sequences of epochs can reveal particularly devastating (or beneficial) contextual developments. For example, in the NGCS case: assume Design #3 started in the Baseline epoch, followed by a change to Design #5 in the Mothership epoch based on the rule "Maximize Efficiency". That sequence appears to satisfy stakeholder needs very well relative to the other designs. If the Mothership epoch were followed by the Conflict epoch, however, and no change was allowed from Design #5 to any design on the Pareto front – whether due to the transition budget or established transition rules – the eNPT of Design 3 in the era would be resultantly lower (how much lower depends on the duration of the epochs and era). This consequence is only one example of many path-dependent behaviors that emerge from the incorporation of change strategies over the long run.

As noted, the Expense Variability metric can also be applied during this process, identifying contextual sequences that provide for either stable or turbulent expenses relative to other eras. The goal of all the analyses of Process 9 is to identify those designs and change strategies that result in efficient value delivery at low and stable costs throughout the entire system lifecycle.

Discussion of Impact on Development Cycle

The epoch variables analyzed thus far in the current study have focused primarily on the post-acquisition phases of the system lifecycle (e.g., technology levels of UAVs, emissions regulations, mission parameters). One natural extension of the Epoch-Era approach is to model the epoch variables of the development cycle itself – that is, to model each stage of development in one or more possible epochs comprised of budget level, material and labor availability, political relations, etc. Example epoch variables in such a study are shown below in Figure 33.

Epoch Variable	[Range]	Units
Subsystem1	[4,6,8]	TRL Level
Labor available	[Nominal, Low]	Level
Acq. Budget	[80%,90%,100%,110%]	Baseline Adj.
Ops Budget	[80%,90%,100%,110%]	Baseline Adj.

Figure 33. Example epoch variables with notional ranges for describing development cycle environments.

In the example variables shown above, several types of resources are modeled: subsystem availability, labor, and budgets. These types of variables could be modeled at any level of detail desired – instead of an overall budget number, for example, colors of money could be used to represent specific capability or operations. The epochs formed by the combinations of these variables' levels could then be sequenced, creating eras describing possible developments of the environment throughout preliminary design, detailed design, and construction/production. Such an approach could efficiently encapsulate much of the uncertainty present throughout the long development lives of major systems and programs.

This encapsulation would provide several strategic benefits for decision makers. First, it would allow easy identification of systems that require total commitment – those with no adequate "fall-back" plan in the case of falling budgets, infeasible subsystems, or other resource perturbations that might occur before the system production and use. Second, and inversely, it would help identify system choices that would limit expansion of quantity or capabilities, should such expansion be desired in the case of a new threat or political development (e.g., the increasing budgets in Figure 33). Third, decision makers could potentially identify the common capabilities of a number of highly desirable systems, allowing production of those core capabilities to begin while deferring the final configuration decisions until later in the development cycle, when the system's initial operational context can be more accurately determined. According to Blanchard and Fabrycky, "50% to 75% of the projected life cycle cost for a given system can be committed…during the early stages of conceptual and preliminary design" (1998, p.48). This commitment of resources is reflected in Figure 34 below; each of the three strategic benefits above relates directly to narrowing the gap between the "Commitment" curve and the "System-Specific Knowledge" curve depicted.

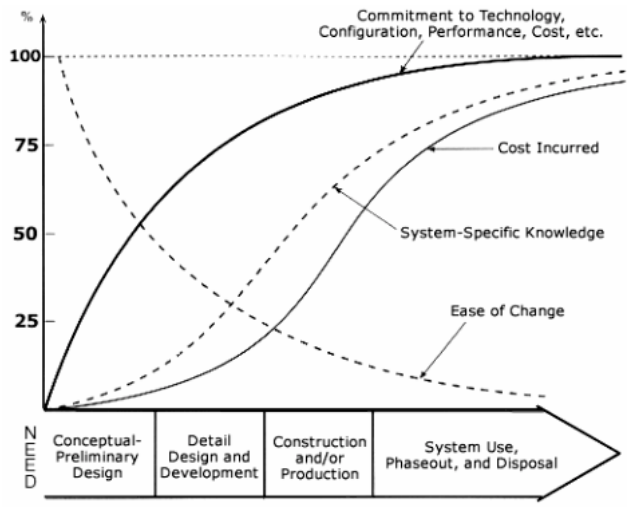

Figure 34. Levels of Knowledge and Cost through the lifecycle (Blanchard and Fabrycky 1998, p.49).

Conclusion and Discussion

In this study, the proposed design method is demonstrated on the NGCS, an illustrative case of the Navy's next multi-purpose fleet comprising frigates slightly larger than the current LCS. An overview of the method is given, outlining the nine processes involved. Processes 1, 2, and 3 are then demonstrated, resulting in the identification of stakeholders, needs, design attributes and variables, and contextual variables involved in the study. Process 4 evaluates each of the six representative NGCS alternatives in each of the six representative epochs, and Processes 5 and 6 compare designs with metrics including FPN, NPT, and fNPT. Aspects of changeability are discussed, and notional eNPT numbers given. Affordability measures such as Max Expense and Expense Variability are introduced to provide insight into the various levels of designs' resource usage in different scenarios. Processes 7 and 8 demonstrate two possible eras with corresponding measures of designs. The activities of Process 9 are outlined, and potential results from the analyses are discussed. The method's potential application to the development cycle is briefly shown and the strategic benefits are discussed.

As noted in the introduction, the application of this design method directly informs the analysis of system affordability for the potential NGCS designs. By using the MAE function, the stakeholder preferences on various resources are combined: development schedule (IOC) with monetary (e.g., acquisition and lifecycle) and non-monetary (e.g., labor) expenses. Using this metric, it can be seen that Designs 2, 4, and 5 all have similar resource expenditures in most epochs, while Designs 1 and 6 are somewhat higher. This measurement alone could provide a good starting point for selecting Designs 2, 4, and 5 as designs of interest. The Max Expense metric from Process 6 shows that Design 2 could require slightly more crew (265) than Designs 4 and 5 (260 and 255), but Design 2 could also cost less (albeit not by much) over its lifecycle ($6.1 billion vs. $6.3 billion). Finally, the Expense Variability metric from Process 6 shows that these designs' expenses vary in similar ways over the epochs.

Since all three of these designs appear to be affordable alternatives, other measures (such as stakeholder satisfaction) can be used to further restrict the number of designs under consideration. Observing Design 5's drop in utility in the Conflict epoch (see Era #2, for instance) could result in it being removed from consideration, since it has the same level of expense as Design 4, which has more stable value delivery throughout Conflict and other epochs. Designs 2 and 4 can be further examined, then, to identify the design variables and attributes that enable these to be affordable choices in the design of the NGCS system. For example, both of these designs are of length 520-530 feet with Medium levels of Anti-Surface and Anti-Aircraft capabilities. These common traits could be further investigated to gain insight into the interactions between these particular variables, the ship attributes they most influence, and the stakeholder preferences on those attributes. In this way, the affordability analysis performed through the application of this method leads into a study of the common traits of affordable NGCS solutions. Rather than pointing to one solution deemed "most affordable", this approach provides stakeholders with a new perspective on the affordability of systems during the conceptual design phase, allowing them to better understand the complex including the behavior of the system and the trades at play.

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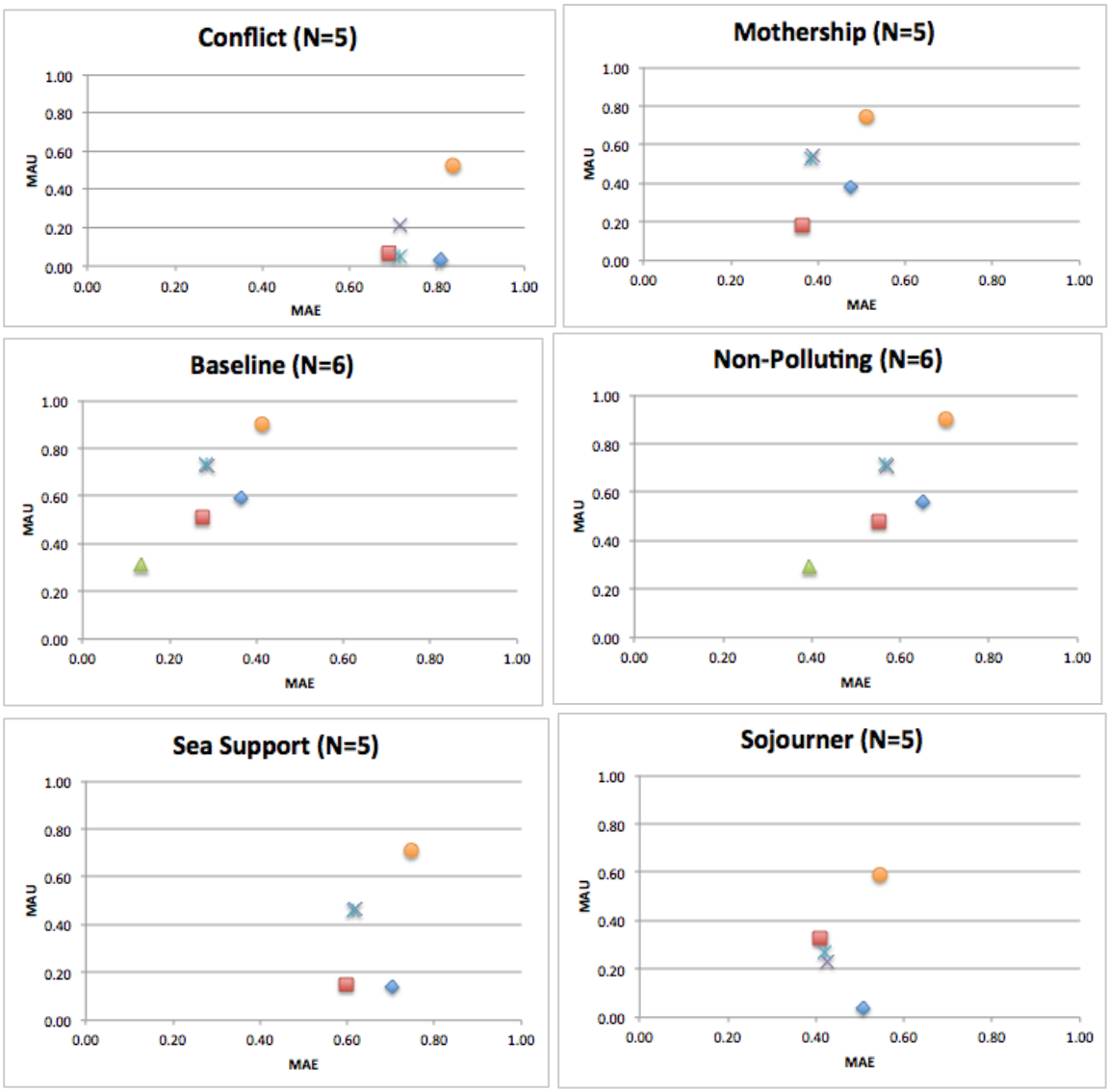
Technical Appendix

All epoch tradespaces of the potential NGCS designs