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Program and Portfolio Affordability Tradeoffs Under Uncertainty Using Epoch-Era Analysis

Parker D. Vascik
Massachusetts Institute of Technology
77 Massachusetts Avenue, E38-575
Cambridge, MA 02139
pvascik@mit.edu

Adam M. Ross
Massachusetts Institute of Technology
77 Massachusetts Avenue, E38-574
Cambridge, MA 02139
adamross@mit.edu

Donna H. Rhodes
Massachusetts Institute of Technology
77 Massachusetts Avenue, E38-572
Cambridge, MA 02139
rhodes@mit.edu

Abstract. The design, acquisition and stewardship of large scale, sociotechnical programs and portfolios faces new challenges as constituent systems evolve in sophistication and interconnectedness, all while exogenous factors become more volatile. However, advances in computational capabilities and uncertainty modeling better enable systems engineers to evaluate value tradeoffs in early phase conceptual design. This paper extends prior work that explored system design tradespaces for affordability under uncertainty to the program and portfolio level. Time-varying exogenous factors, such as resource availability, stakeholder needs, or technology obsolescence may influence value contribution of constituent systems over the lifecycle of a portfolio, potentially making an initially attractive design less attractive over time. This paper introduces a method to conduct portfolio design for affordability by leveraging Epoch-Era Analysis with aspects of Modern Portfolio Theory. The method is demonstrated through the design of a carrier strike group portfolio involving the integration of multiple legacy systems and newly acquired vessels.

Introduction

A recently developed approach, *Epoch-Era Analysis* (EEA), enables the conceptual design of systems that are resilient to potential changes in context and needs (exogenous uncertainties) throughout the system lifecycle. EEA provides quantitative support for the design of time-contingent system properties such as survivability, flexibility, and affordability (Ross et al., 2010). When combined with Tradespace Exploration (TSE), EEA empowers engineers to consider more potential designs than possible with traditional analysis of alternatives methods.

Since the issuance of the 2010 memo Better Buying Power (BBP) and the implementation of the Department of Defense (DoD) Efficiency Initiative (Carter, 2010), a significant body of research has been generated to support *design for affordability*. In this vein, EEA was adapted to support affordability analysis for naval acquisitions through the introduction of aggregate cost and schedule considerations (Schaffner et al., 2013). As system interconnectedness and interdependence continues to increase, there is a need to expand the scope of EEA and other design for uncertainty techniques to support affordability tradeoffs at the multi-system level; this necessitates consideration of two related concepts: *system of systems* (SoS) and *portfolios*.

A SoS is a dynamic network of constituent systems that exhibit varying levels of operational and managerial independence, but operationally interact to achieve mutually desired, oftentimes emergent, capabilities (Maier, 1998). A portfolio is a construct that describes a collection of assets simultaneously invested in to exploit qualities of the set, regardless of whether the assets are operationalized independently or as participants in a SoS.

This paper presents an effort to modify a resource-centric approach of EEA developed by Schaffner, Ross and Rhodes (2014) to be used for affordable portfolio design through the integration of elements of *Modern Portfolio Theory* (MPT) and the SoS design literature. The proposed method is demonstrated in a case study on the acquisition of a portfolio of assets from which a carrier strike group (CSG) may be assembled. Insight is provided into CSG lifecycle affordability by revealing changes in portfolio utility and costs in response to uncertainty in future context, such as unit availability, budget constraints, capability requirements, strategic threats, and technology development. The method is proposed to support affordability tradeoffs for complex programs and portfolios under uncertainty.

Background

Efforts to Stem Program Cost Growth through Affordability Analysis. According to the Government Accountability Office (GAO), many of the 74 Nunn-McCurdy program unit cost breeches that occurred between 1997 and 2011 corresponded to *context* changes in the environment surrounding the acquisition programs (US GAO, 2011). Spurred by the "affordability mandate" of BPP 1.0, 2.0, and now 3.0, a variety of approaches were developed to support affordability definition and consideration. Bobinis, et al. (2013) developed metrics to assess the contextual and dynamic attributes of affordable systems. Siedlak et al. (2015) introduced a parametric design and visualization environment to conduct either multi-objective optimization or manual trade-off analyses for system affordability under demand uncertainty. Finally, Wu, Ross, & Rhodes (2014) employed EEA to explore system affordability under a variety of uncertainty factors to provide insight into changing contexts in potential futures.

These advances, however, address only a portion of the challenge of achieving affordability for the DoD as they do not explicitly consider the higher order complexities inherent to multi-system acquisition and operations (Wu, 2014). Current resources available to the DoD capabilities-development process, such as the *Systems Engineering Guide for Systems of Systems* (2008) and portfolio-analysis methods proposed by Davis, Shaver, and Beck (2008), provide a framework for the conceptual design and acquisition of large programs or portfolios. The latter of these works suggests that economic based methods and advanced approaches for sensitivity analyses are necessary to better identify "flexible, adaptive, and robust (FAR) solutions."

In line with this sentiment, Komoroski et al. (2006) sought to adapt existing system affordability techniques to multi-system situations through the use of real options analysis, specifically to identify long-term SoS acquisition strategies for information technology. Similarly, Davendralingam, Mane, and DeLaurentis (2012) explored initial pathways to adapt concepts from Modern Portfolio Theory (MPT) to SoS acquisition. This research proposes that Epoch-Era Analysis complements these previous efforts by adding the ability to assess the influence of changing contexts on the affordability of potential portfolios, thereby directly considering exogenous uncertainties and revealing portfolio sensitivities to these uncertainties.

Characterization of Tiers of Design Abstraction. To clarify the terminology used in this paper and link it to trends in the SoS literature, three "tiers" of design abstraction are proposed to classify the unique properties, literature and approaches associated with multi-system design and acquisition.

System-Level: System design occurs at a "level of decomposition that is inclusive of a major architectural element and is semi-independent from the rest of the architecture" (Walton, 2002, p. 20). The designer of a system typically has full design authority, and although a system may be composed of multiple components (such as a launch vehicle) it is not considered a SoS as the sub-elements are not managerially independent (Maier, 1998).

Program-Level: Program design is distinguished from system design in that it requires joint consideration of multiple constituent elements (typically systems themselves). Two program types may be distinguished through attributes of their constituent systems. *Type I* programs are composed of homogeneous constituent systems and typically are designed and operated under centralized control. *Type II* programs are composed of heterogeneous constituent systems that complete similar missions and are evaluated by a common set of value metrics. Type II programs frequently involve semi-independent or fully-independent constituent systems and therefore encounter SoS design challenges as described by (Eisner et al., 1991).

Portfolio-Level: A portfolio is a collection of selected assets (potentially new and legacy programs) that are simultaneously invested in to collectively provide a set of heterogeneous capabilities. A portfolio designer does not necessarily have a significant level of control over the design of the constituent programs, or their ultimate operationalization in a SoS.

Efforts to Expand EEA to Portfolio-Level Design. Previous research leveraged EEA for program and portfolio-level affordability analysis through a bottom-up "survival of the fittest" approach (Wu, 2014). While this approach is effective for Type I program-level design, it may prematurely discard potentially valuable designs that do not appear attractive in lower levels of design abstraction, but produce a favorable overall portfolio. In fact, an application of portfolio theory to tradespace analysis for a space science mission found that the most promising portfolio of assets to minimize uncertainty was not consistently a constellation of the most promising single satellite design(s). Rather, the designs that minimized portfolio-level uncertainty included sub-par, system-level solutions that interacted to exhibit emergent benefits and enhanced portfolio-level utility (Walton, 2002). This research seeks to address the limitations of Wu's approach to portfolio-level affordability analysis by applying elements of top-down design through the integration of aspects of MPT with TSE and EEA.

EEA-Based Approaches for Design for Affordability. Portfolio design with affordability considerations requires analysis of factors such as system development schedules, legacy hardware and operations, resources, and political capital. Furthermore, these factors must be considered with respect to the dynamic environments the portfolio may experience over its lifecycle. Epoch-Era Analysis is an effective mechanism to evaluate design options in anticipation of future context shifts. An *epoch* is a time period of static context and stakeholder expectations, like a snapshot of a potential future. An *era* is an ordered sequence of epochs with finite durations that describes a potential progression of contexts over the system's lifecycle.

EEA consists of several distinct, but related analysis techniques. In *single-epoch analysis*, potential portfolios are evaluated in individual epochs to determine the portfolio's relative position to the Pareto front. When the performance of the same portfolio is compared in different epochs through *multi-epoch analysis*, the various influences of contextual uncertainties may be perceived and shifts in portfolio proximity to the Pareto front may be observed. If multiple epochs are ordered together into an era, changes in the value of proposed portfolios over time becomes apparent, and portfolios that become unaffordable are identifiable. Figure illustrates how this final technique, called *single-era analysis*, may reveal lifecycle deficiencies in initially promising portfolio designs (Ross & Rhodes, 2008).

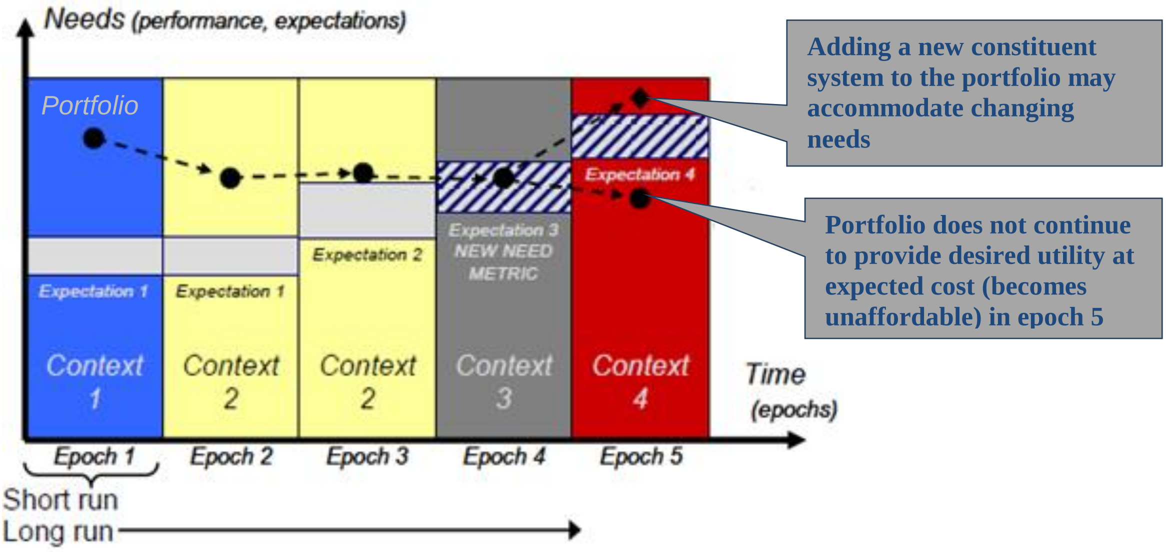


Figure 1. Epoch-Era Analysis reveals the performance (including affordability) of a portfolio through a sequence of varying contexts thereby illustrating potential lifecycle value

Combination with EEA with Generalized MPT. Modern Portfolio Theory has ubiquitous impact on financial investment strategies. As a methodology, MPT identifies efficient frontiers of portfolio investments by comparing the performance forecasts for potential assets with the elicited values and preferences of the investor(s). A MPT Pareto frontier consists of potential portfolios of investments that maximize the return on investment for a given level of risk. MPT assumes groups of investments with negative trending covariance exhibit a portfolio risk that is less than the average of the risks of each constituent investment (Amenc & Sourd, 2005).

While MPT and EEA share a variety of commonalities including value elicitation from stakeholders/investors, the use of models to describe investment/system value, and a foundation in utility theory, there are also fundamental differences in the design of engineering systems that violate assumptions necessary for MPT. Ricci and Ross (2012) reviewed the similarities and differences of MPT and EEA and proposed a variety of modifications to MPT that address asset availability, diversification costs, carrying costs, and switching costs. However, the non-normal performance distributions and non-linear relationships of constituent systems in engineering portfolios violate MPT assumptions and are yet to be addressed. This paper supplements EEA with two possible constructs, the *capability tree* and *combination coefficients*, to address these two challenges of constituent system modeling and interaction.

Method for Portfolio Affordability Tradeoffs under Uncertainty

Multi-Attribute Tradespace Exploration (MATE) is a method that has been used extensively in system-level design. When used with EEA, MATE facilitates design for a variety of "ilities," including affordability. Previous research developed Responsive Systems Comparison (RSC) to formally combine MATE with EEA to consider dynamic uncertainty of contexts and needs (Schaffner et al., 2014). Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) is proposed in this paper as a new method that builds upon RSC to support portfolio affordability analysis. PLEEAA extends RSC with two new constructs to enumerate viable portfolios: a *portfolio selector* and a *portfolio design tool*. Additionally, a "portfolio capability tree" is also implemented to link system performance to portfolio utility. The key innovative feature of PLEEAA is the fusion of elements from Modern Portfolio Theory with the capabilities of Epoch-Era Analysis. Figure 2 presents a graphical representation of how this is achieved.

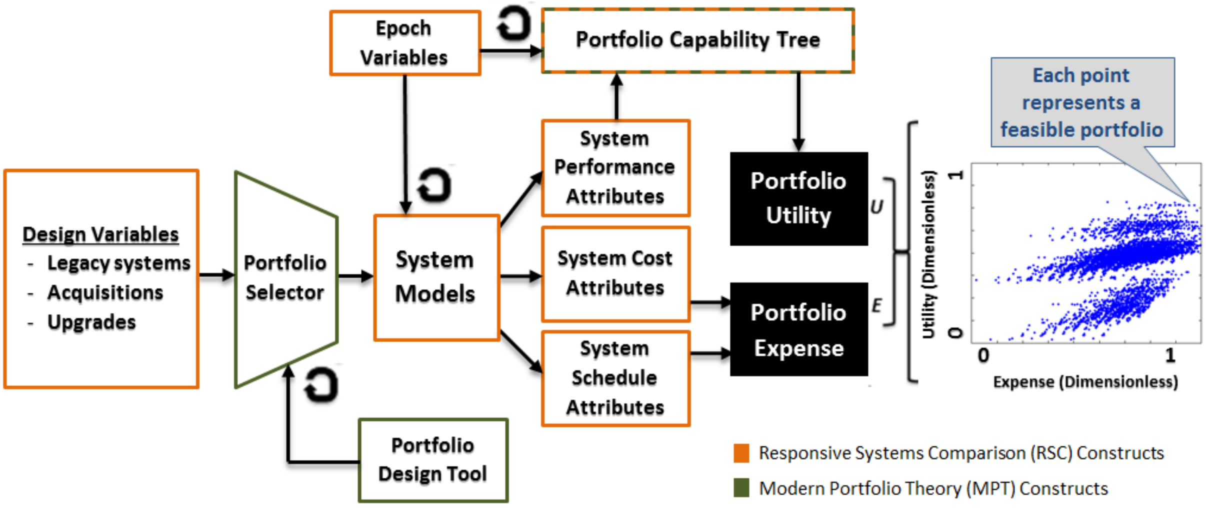


Figure 2. Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) process model

Portfolio Design Tool and Portfolio Selector. A fundamental element of MPT is "asset allocation," or the identification of potential asset classes that a portfolio designer (the systems engineer applying PLEEAA) desires to consider for inclusion in the portfolio. In finance, these assets may be stocks, bonds, or cash (Amenc & Sourd, 2005). For Navy portfolios, asset allocation may involve identifying fundamental categories of assets such as cruisers, destroyers, aircraft, and submarines, for example. The portfolio designer may apply specific constraints to each class, such as a maximum number of units (or funds) they are willing to allocate to that class; these *class constraints* mirror investment thresholds in financial portfolios. Alternative approaches could be employed to create the initial portfolios such as the Building Blocks to Composite Options Tool (BCOT) developed by Davis et al. (2008).

Portfolio Capability Tree. A key challenge of tradespace-based portfolio analysis is linking constituent system performance attributes with portfolio-level capabilities. This research uses a capability-based value mapping called a *capability tree* to convey portfolio designer needs down through the portfolio management hierarchy to the constituent system managers and then aggregate system-level performance attributes back up to define portfolio-level utility. The structure and inspiration of capability trees are rooted in *means-ends objectives networks* as developed by Keeney (1992). Means-ends objectives networks link decision alternatives to their impact on the overall objective to enable quantitative modeling. Capability trees link portfolio asset options to their impact on the overall portfolio utility for the same purpose.

To develop the capability tree, a portfolio designer decomposes the elicited strategic objectives of the portfolio-level stakeholders into a set of desired capabilities, or performance attributes. Each portfolio performance attribute is communicated to a unique program-level manager who is the decision maker for programs that contribute value to that portfolio-level performance attribute. The process is then repeated where the program-level manager decomposes their values into a set of program-level performance attributes that are communicated to another program-level manager; this process terminates with the constituent system managers.

It is important to recognize that the portfolio designer and program-level managers at each level in the portfolio hierarchy are empowered to develop their own performance attributes and mental value models to measure the operation and utility of the systems (or programs) in their subtree. The utility measurement developed is then shared by the in-level manager with the manager one level above in the capability tree hierarchy. Therefore, the assigned utility of a program must be effectively communicated at the interface of the two managers, referred to as a "node". The capability tree model, as described here, is an imposed constructed value model. Illustrated in Figure 3, nodes of the capability tree are represented by collate symbols, and the multi-document symbol represents the unique value and performance models of managers.

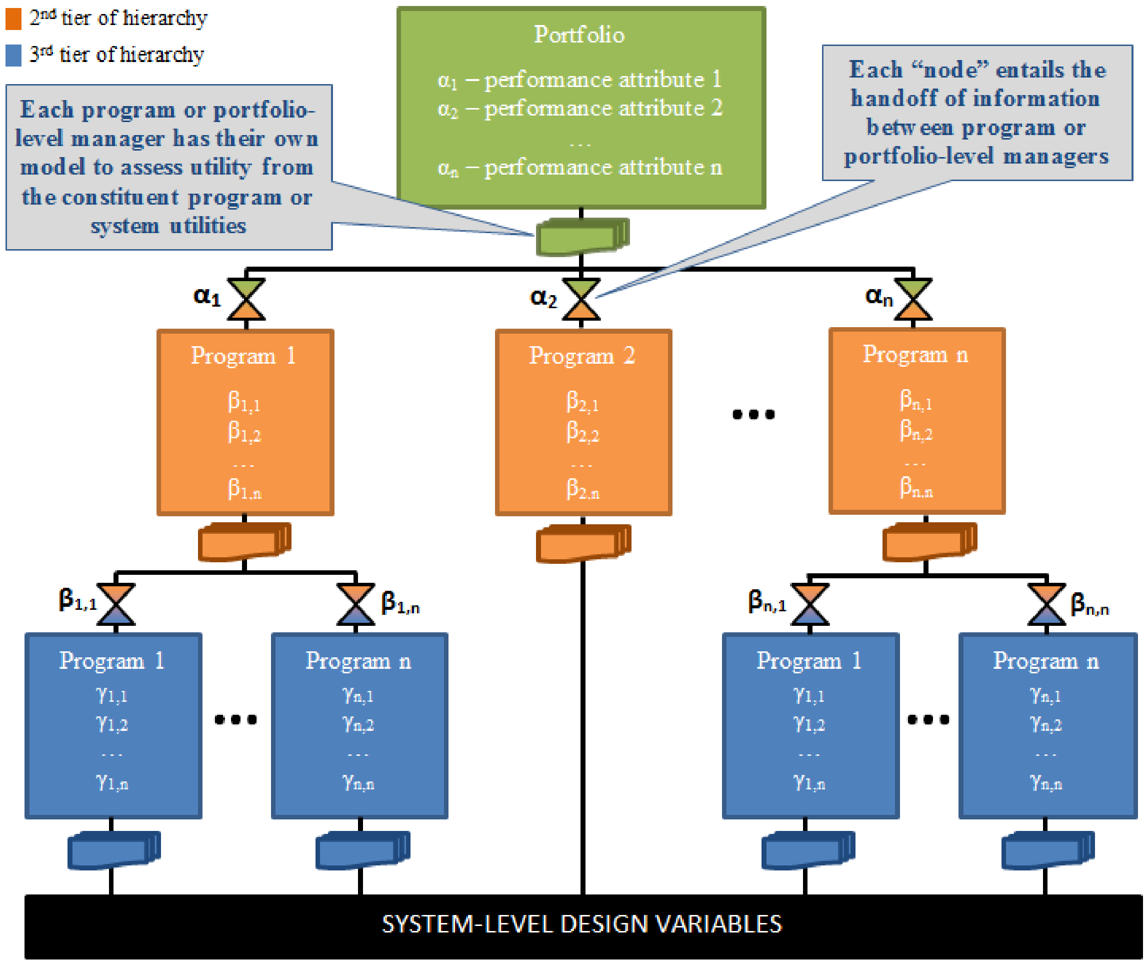


Figure 3. PLEEAA "capability tree" portfolio design architecture

Through the capability tree, desired portfolio strategic objectives flow down to lower-level program managers as performance attributes. A capability tree is extendable to multiple levels of programs: three have been shown in Figure 3. Each additional level of the portfolio hierarchy allows for the design of more intricate portfolios through TSE techniques, but will also increase the analysis complexity. All "branches" of the tree do not need to have the same number of hierarchy levels. Some capabilities will naturally terminate in system-level attributes directly from the portfolio-level, while others may require multiple levels of decomposition to equate to system-level performance attributes. A portfolio objective is fully decomposed when the system-level "leaf node" performance attribute is readily described by a metric of the potential component systems, such as the number of missiles on a ship.

Complementary and Substitute Systems. A fundamental challenge unique to engineering portfolios as opposed to financial portfolios is that portfolio-level capability may not simply be an aggregate sum of the constituent assets' capabilities. The capability tree framework supports the consideration of utility and cost variations due to complementary and substitute systems by empowering bottom-level portfolio managers to identify commonalities between constituent system performance. However, this approach requires the decision making models of each manager to be well represented at every node. For this initial CSG case study, and indeed for many conceptual design or acquisition programs, this assumption is not realistic. Therefore, this research adopts the concept of "level of attribute combination complexity" introduced by Chattopadhyay (2009) as a first order approximation to manage complementary and substitute systems. PLEEAA elicits bottom-level portfolio hierarchy managers to characterize a low, medium or high "combination coefficient" with respect to potential constituent system interactions for each performance attribute in their area of responsibility.

Overview of PLEEAA. PLEEAA is a variant of the RSC method for affordability analysis. The Gather-Evaluate-Analyze structure of RSC, developed by Schaffner et al. (2013), was supplemented with additional steps necessary for portfolio design. Specifically, the *value-driven design formulation* now occurs with multiple groups of stakeholders corresponding to different levels of the portfolio hierarchy. The 11 processes of PLEEAA are represented in Figure 4, and each process is described and demonstrated through the CSG demonstration case.

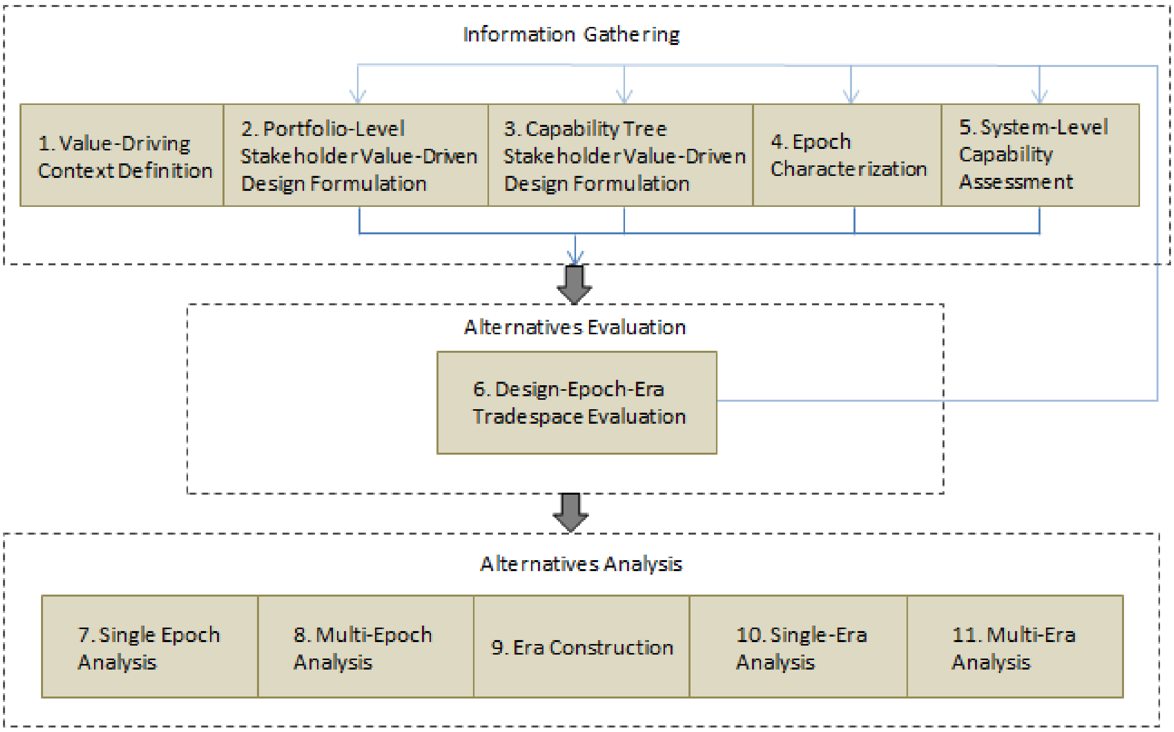


Figure 4. A graphical overview of the Gather-Evaluate-Analyze structure for PLEEAA

Demonstration Case: Carrier Strike Group Design for Affordability

The following sections briefly describe each process in PLEEAA. A *representational outcome* is included that displays a first pass, high-level application of PLEEAA to CSG portfolio design. The values of stakeholders, models for performance aggregation, and system performance parameters were notionally created from publically available information and feedback from experts familiar with the systems. For a full discussion of the CSG PLEEAA case study, please see (Rhodes, Ross, and Vascik, in press).

Process 1: Value-Driving Context Definition. PLEEAA begins by identifying the basic problem statement and design space for the proposed portfolio. The portfolio-level stakeholders are selected and engaged as necessary to formulate relevant exogenous uncertainties and outline initial value propositions. An inchoate set of potential constituent systems is constructed, and the portfolio designer's degree of influence over these systems is determined. A significant limitation of this initial form of PLEEAA is an inability to consider numerous stakeholders with diverse interests. However, recent efforts by Fitzgerald & Ross (2016) present approaches to conduct multi-stakeholder negotiations through TSE that may potentially be applied to the portfolio space to address this limitation of the PLEEAA method.

Representational Outcome: The value proposition for a CSG is articulated as a "responsive, flexible capability for sustained maritime power projection and combat survivability to shape the operation environment, respond to crises, and protect the United States and allied interest in any threat environment" (Chief of Naval Operations, 2010, p. 2). The instruction designates the combatant commander and operational commander of the naval group as the primary portfolio-level stakeholders. An initial set of 12 potential constituent systems is provided in the instruction. This research added an additional six Next Generation Combat Systems (NGCS) as well as the new Zumwalt-class destroyer to create the pool of potential constituent systems.

Process 2: Portfolio-Level Stakeholder Value-Driven Design Formulation. The portfolio designer elicits a variety of information from the portfolio-level stakeholders to establish the portfolio (top) level preferences of the capability tree and clarify constraints on the portfolio composition and costs.

1) <u>Performance Attributes</u>: A set of overarching capabilities that the portfolio must be able to fulfil to meet the strategic objectives. These capabilities, or performance attributes, are assigned weights to reflect the stakeholder preferences based on elicited information. Utility functions are developed to capture these preferences.

2) <u>Expense Attributes</u>: The set of limited resources available to portfolio stakeholders is elicited. Expense functions are created to characterize the attractiveness of levels of potential portfolio usage of these resources, and acceptable thresholds are identified.

3) <u>Portfolio Investment Strategy Constraints</u>: Constraints are set concerning viable portfolio composition. These constraints may define limitations on resources, types of constituent systems, and acceptable risk. They could also be more specific and govern internal investment strategy decisions such as the maximum number of component systems allowed or the minimum resource allocation allowable to any single system.

Representational Outcome: Five notional, portfolio-level performance attributes for a CSG portfolio were developed; four accompanying portfolio-level expense attributes were also defined. For this initial case study, the nine single-attribute performance and expense attributes result in multi-attribute utility and multi-attribute expense through linear weighted sum aggregation functions. The value weights at each node sum to one. This requires an assumption that the performance and expense attributes contribute independently to aggregate value. While this is not necessarily a realistic assumption for a CSG portfolio, it is a sufficient first order estimation for the demonstration purposes of this case study.

Process 3: Capability Tree Stakeholder Value-Driven Design Formulation. From the information gathered in the previous processes, the portfolio designer creates a notional structure of the capability tree by identifying specific program managers at each node. The portfolio designer elicits information from each program manager and continues the process until all branches have terminated into the system-level attributes, or leaf nodes.

Representational Outcome: The capability tree for the CSG case study attests to the inherent complexity of portfolio analysis. Although the representation of the CSG has been simplified, the resultant capability tree contains five branches (corresponding to the five portfolio-level performance attributes from process 2) and, through up to four levels of decomposition, 91 distinct system-level performance attributes. For the sake of brevity, the capability tree has not been included in this paper but may be found in (Rhodes, Ross and Vascik, in press).

Process 4: Epoch Characterization. The portfolio designer engages a wide breadth of salient stakeholders to identify and characterize the uncertainty of key future contexts the portfolio may encounter. It is anticipated that a core set of contextual uncertainties will emerge from the stakeholders that may be parameterized by a common set of epoch variables. Contextual changes in stakeholder preferences (e.g., performance attribute weightings) are also elicited.

Representational Outcome: Seven epoch variables were identified from five major categories of uncertainty including technology levels for advanced energy weapons (AEW) and unmanned aerial systems (UAS), maintenance events, policy environment, managerial control, and threats. The seven epoch variables were enumerated independently and combined to produce a total of 2,187 potential epochs. For the sake of simplicity, five possible epochs that represent recognizable potential futures were initially extracted from this set in a “narrative” sampling approach. These five epochs and their epoch variable levels are provided in Table 1.

Table 1. Epoch description using epoch variables for five selected epochs

Epoch Names	*Epoch Variables*						
	AEW	UAS	Maint.	Budget	Mgmt. Control	Symm. Threat	Asymmetr. Threat
Baseline (BL)	Low	Low	Low	Med	Med	Low	Med
Small Navy (SN)	Low	Med	Low	Low	Low	Low	Low
War on Terror (WoT)	Med	High	Low	Med	High	Low	High
Major Conflict (MC)	High	High	Low	High	High	High	Med
Peacekeeping (PK)	Med	Low	Med	Med	Med	Med	Med

Process 5: System-Level Capability Assessment. Each potential constituent system must be evaluated for its performance in each system-level performance attribute. This “capability assessment” may take a variety of forms. In some cases, the bottom-level capability tree hierarchy managers may utilize unique performance models or integrated campaign models (such as those proposed in the *DoD Acquisition Modeling and Simulation Master Pl*an) to computationally assess the constituent systems’ performance. In other cases, such models may not exist and the bottom-level managers, or an appropriate subject matter expert, may be engaged to assess system performance qualitatively or through the use of past performance data. Each constituent system must be assessed for all performance attributes in each epoch.

Representational Outcome: The notional performance of the 19 potential constituent systems was assessed for each of the 91 system-level performance attributes in the five potential epochs. The physical characteristics and baseline performance of each vessel type was drawn primarily from *IHS Jane’s Fighting Ships* (Saunders, 2014). This baseline information was supplemented as necessary from publically available information to assign performance on a 0, 1, 3, 9 discrete interval scale; 0 represented no performance, 1 was minimal performance, 3 was moderate performance, and 9 was performance sufficient to meet the desired portfolio capability. The CSG capability assessment results were reviewed for reasonableness by individuals familiar with naval systems.

Process 6: Design-Epoch-Era Tradespace Evaluation. Figure depicts how the performance capabilities of each constituent system are aggregated in the capability tree to find portfolio Multi-Attribute Utility (MAU) and Multi-Attribute Expense (MAE). Tradespace evaluation using axes of MAU vs MAE has been shown as an effective visualization tool for system and program-level decision making (Wu, 2014). However, unlike in traditional TSE, the points inside a portfolio tradespace do not represent single systems or programs, but rather represent unique combinations of assets determined by the portfolio investment strategy.

Representational Outcome: Lacking the ability to elicit information from each manager in the capability tree, this research developed a series of six aggregation functions to characterize the basic value judgments a manager might make to determine the single attribute performance from the set of constituent systems' performances in a potential portfolio. These aggregation functions assessed performance attribute values as an average, maximum, or a diminishing returns composite value of the constituent systems' performances, for example. Each bottom-level performance attribute of the portfolio was assigned one of the six aggregation functions that best represented the notional program-level manager value statement. Once the bottom-level performance and cost attributes had been calculated, the values were multiplied by the preference weighing of the program-level manager at the node in the next level of the portfolio hierarchy. This process was repeated for each level of the portfolio hierarchy until all branches were aggregated to the portfolio-designer. The portfolio-level preference weightings were then applied to find the ultimate utility and costs of a given potential portfolio.

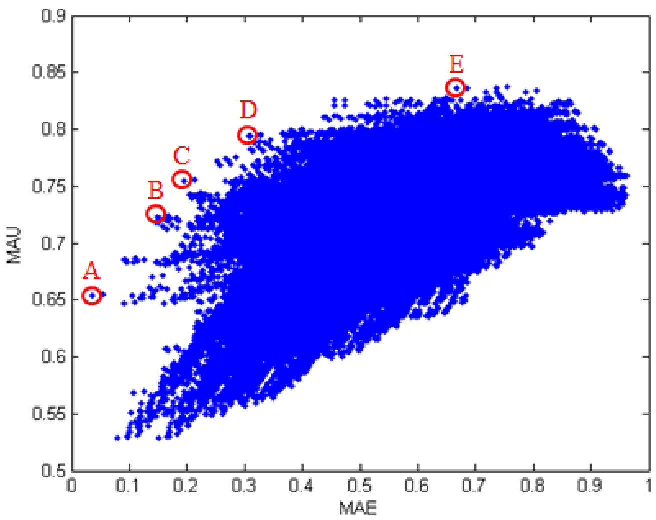
The PLEEAA method enumerated 53,018,336 possible portfolios and identified 524,160 portfolios that met the class constraints. This subset of portfolios was evaluated according to the stakeholder preferences and constituent system performance in each epoch. Table 2 displays the number of valid portfolios that met the MAU and MAE constraints, and the percent of the total potential designs that were found to be feasible (i.e., "yield"). The Small Navy epoch is the most limiting epoch due to its 80% budget and 150% cooperation costs.

Table 2. Single-Epoch tradespace evaluation summary

Epoch	Valid Portfolios	Yield
Baseline	173,581	33.1%
Small Navy	220	0.04%
War on Terror	140,398	26.8%
Major Conflict	477,916	91.2%
Peacekeeping	191,558	36.5%

Process 7: Single Epoch Analysis. The valid portfolios for each epoch may be plotted in a tradespace of MAU vs MAE. By exploring each single-epoch tradespace, a designer may identify the portfolio design options that perform particularly well for the context represented in that epoch and what constituent systems the Pareto efficient portfolios have in common.

Representational Outcome: The tradespace of viable CSG portfolios for the Baseline epoch is provided in Figure 5. The Pareto frontier of the Baseline epoch contains a total of 26 potential portfolio designs. The specifications for five example Pareto optimal portfolios are provided. Figure 6 displays relations in the composition of each promising portfolio. Differences in constituent system investments between the promising portfolios are highlighted in blue, using portfolio A as a reference. This comparison is intended to reveal if the same constituent systems repeatedly appear in numerous promising portfolios. Therefore, two portfolios that have the same types of constituent system, such as portfolios A and C, are identified as having no different systems despite possessing varying numbers of each system type.



#	MAU	MAE	Portfolio Composition
A	0.6536	0.0352	1 Arleigh Burke Flight III 1 Nimitz with Complement 1 Los Angles
B	0.7223	0.1487	1 Arleigh Burke Flight I 1 Arleigh Burke Flight II 1 Arleigh Burke Flight III 1 Nimitz with Complement 1 Los Angles
C	0.7548	0.1953	2 Arleigh Burke Flight III 1 Nimitz with Complement 1 Los Angles
D	0.7942	0.3072	2 Arleigh Burke Flight I 2 Arleigh Burke Flight III 1 Nimitz with Complement 1 Los Angles
E	0.8358	0.6660	2 NGCS Variant 6 2 Arleigh B. Flight II Upgrade 2 Arleigh Burke Flight III 1 Nimitz with Complement 1 Los Angles

Figure 5. Portfolio affordability tradespace (MAU v. MAE) and Pareto efficient portfolios for the Baseline epoch

Potential Constituent Systems

Promising Portfolios	Different Systems	NGCS [1]	NGCS [2]	NGCS [3]	NGCS [4]	NGCS [5]	NGCS [6]	AB I	AB I [Upgrd]	AB II	AB II [Upgrd]	AB IIA	AB IIA [Rstrt]	AB III	Ticonderoga	Zumwalt	Nimitz	Los Angeles	Virginia	Supply
A	0													x			x	x		
B	2							x		x				x			x	x		
C	0													x			x	x		
D	1							x						x			x	x		
E	2						x				x			x			x	x		

x system in current portfolio
reference portfolio
similar to reference portfolio
different than reference portfolio

Figure 6. Constituent system comparison for promising portfolios (referenced to portfolio A)

Process 8: Multi-Epoch Analysis. The performance of the portfolios in each epoch was determined through single-epoch analysis. Various metrics may now be used to assess the portfolio performances across multiple epochs and characterize their robustness to change. The reader should consult Schaffner et al. (2013) for a detailed explanation of multi-epoch analysis.

Representational Outcome: A particularly useful metric to characterize how well a promising portfolio maintains its value across multiple epochs (i.e., passive robust solutions), is the Normalized Pareto Trace (NPT) (Ross et al., 2009). A NPT score is assigned to each promising portfolio and describes the percent of epochs in which that design constitutes a Pareto optimal point. A variant of NPT, the fuzzy NPT (fNPT), reveals the percent of epochs for which a particular design is within a certain fuzzy threshold factor of the Pareto front. The width of this threshold zone is defined by a factor K, where a K of zero indicates 0% fuzziness and is identical to the NPT metric.

Table 3 displays that portfolio A has a NPT value of one. This indicates that portfolio A remains on the Pareto frontier in all epochs considered. From Figure 5 it is apparent that portfolio A also represents the lowest expense and utility of any of the promising portfolio designs. Meanwhile the NPT for portfolio C is 0.6, indicating that in 60% of the epochs the design is Pareto optimal. However, portfolio C reaches a fNPT value of one at a K value of 10%. This means that portfolio C is within 10% of the Pareto frontier in terms of MAU and MAE for all epochs. These two portfolios (A and C) are the most passively robust to the uncertainties in the considered epochs. No other considered portfolio beyond A or C has a fNPT value of one, even at a K value of 20%. This indicates that the other promising portfolios are significantly removed from the Pareto front in at least one epoch. The results from Table 3 may lead a designer to select either portfolio A or C as robust, affordable portfolios with respect to the epochs considered, with each providing a different tradeoff of utility for expense.

Table 3. NPT and fNPT metrics for five CSG portfolio designs over five representative epochs

Portfolio	**NPT**	**5% fNPT**	**10% fNPT**	**20% fNPT**
A	1	1	1	1
B	0.8	0.8	0.8	0.8
C	0.6	0.8	1	1
D	0.8	0.8	0.8	0.8
E	0.4	0.8	0.8	0.8

Process 9: Era Construction. EEA supports the evaluation of portfolio designs over an ordered set of epochs, called an era, to represent a potential lifecycle of the portfolio. Era analysis enables the designer to understand how portfolio designs maintain their value through the uncertainty of a long run potential future. Disturbances and degradation from an earlier epoch in the era may diminish the long term value of a particular portfolio design with respect to another. Time-dependent concerns, such as cumulative carrying costs and time to initial operating capabilities of various assets, can be considered during era analysis. While such time-dependent factors were not considered as part of the initial CSG case study, they are an anticipated area of future research.

Representational Outcome: Eras may be developed through stakeholder elicitation, probabilistic modeling (e.g., Monte Carlo or Markov models), or through a narrative approach to produce likely potential futures. Two eras were created for this case study. A narrative approach was used to select the order and duration of the epochs to represent a potential 30 year operational life for the carrier strike group. Due to time-dependent factors such as technology lock-in (the adoption of UAS, for example) it was necessary to develop an additional six epochs that captured variations in the epoch variables depending upon the previous epochs that occurred in the era: the new variations of the original epochs are notated with roman numerals.

Era 1: Baseline (5 yr), War on Terror (5 yr), Peacekeeping II (10 yr), Baseline II (3 yr), Small Navy II (7 yr)

Era 2: Peacekeeping (5 yr), Small Navy III (5 yr), Major Conflict (5 yr), Peacekeeping III (12 yr), Baseline III (3 yr)

Process 10: Single-Era Analysis. In single era analysis, the performance of portfolio designs is assessed over the sequence of epochs composing the era. Single-Era analysis enables designers to investigate the time-ordered effects of the epochs on the portfolios. This allows for the identification of portfolios that maintain utility and affordability throughout the sequence of potential futures, and of those that may become unaffordable. The concepts of NPT and fNPT may also be applied to an era to quantitatively measure how well a particular portfolio design compares to the Pareto front solutions of each epoch in the era.

Representational Outcome: For the CSG portfolio design study, both the variance of utility and expense of a potential portfolio over the lifecycle of the CSG are of interest to a potential designer. Figure 7 contains two subplots that display the change in MAE and MAU over five epochs for the five promising portfolios from the Baseline I epoch. Tracing the trajectories reveals the emergent affordability, or unaffordability, of the potential CSG portfolios.

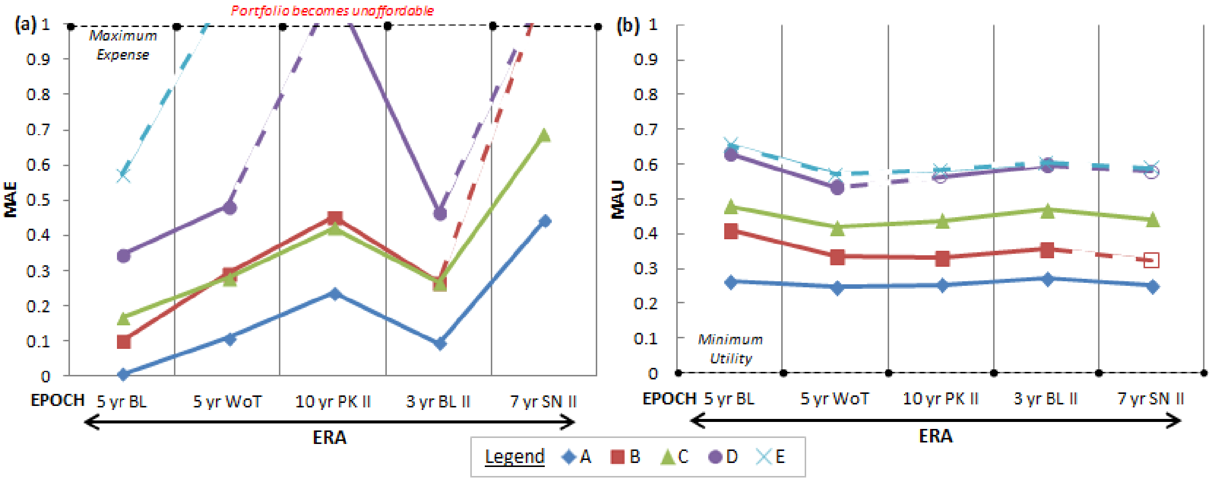


Figure 7. (a) Expense considerations for era 1; (b) Utility considerations for era 1

The purpose of this initial case study was to explore the ability of PLEEAA to support design for affordability. While, the MAE of the portfolios exhibits significant variance over the era in Figure 7(a), there is relatively little variation in the MAU values through all epochs in Figure 7(b). The utility variation is small because, as illustrated in Figure 6, the promising portfolios primarily contain the same constituent system types. As a result, the portfolios exhibit similar utility responses to the uncertainties modeled. Figure 8 displays how the different time-ordering of epochs in era 2 influences the performance of the promising portfolios.

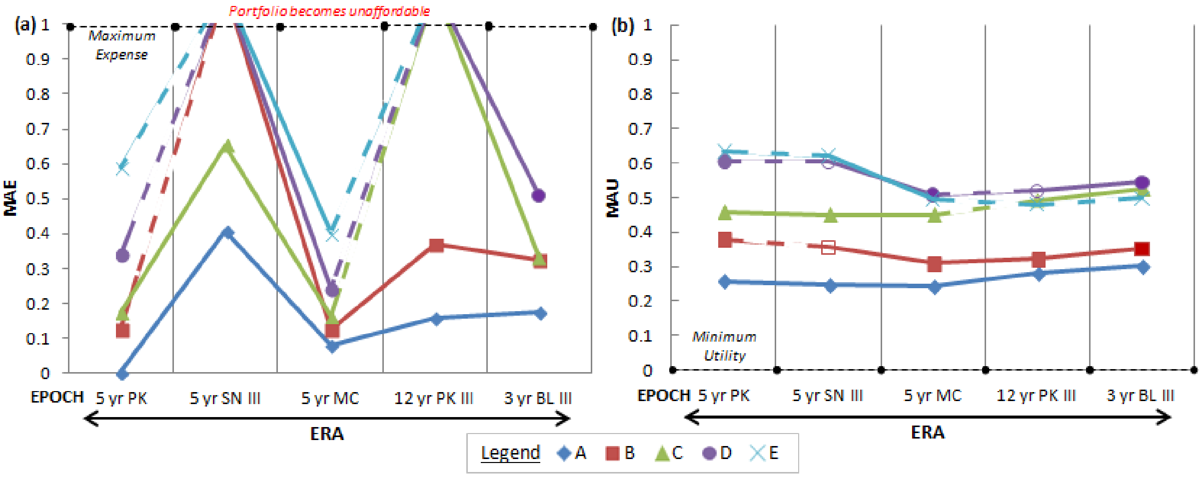


Figure 8. (a) Expense considerations for era 2; (b) Utility considerations for era 2.

Process 11: Multi-Era Analysis. Multi-Era portfolio analysis expands single-era analysis by identifying patterns of affordability (and unaffordability) as well as utility delivery that emerge from the path dependent development of portfolios through multiple contexts. This process enables a designer to develop metrics that characterize the affordability of potential portfolio designs across a variety of potential lifecycles. The reader should consult Schaffner et al. (2013) for a detailed explanation and example of multi-era analysis, and on-going research.

PLEEAA Application to Portfolio Conceptual Design and Analysis

The conceptual design of system of systems and portfolios presents a variety of challenges to traditional toolsets including managerial influence considerations, complementary and substitute systems, and dynamic portfolio composition. The PLEEAA method supports designers to enumerate and consider a greater number of potential portfolio designs than would be possible by current techniques. This is advantageous because it increases the ability of a designer to identify portfolios that display superior performance qualities such as affordability and robustness against exogenous uncertainty.

Tradespace exploration supports decision makers to identify portfolio compositions they may not have been previously considered, to recognize macro-level trends in portfolio affordability, and to conduct micro-level tradeoff studies between portfolios in the area of desired performance. Epoch-Era Analysis provides designers with new abilities to identify the response of potential designs to a variety of anticipated contextual uncertainties, including the impact of simultaneously occurring uncertainties, in the lifecycle development and operation of the portfolio. The insight provided from these studies supports the selection of portfolios that may remain affordable over the entire lifecycle of the program, without the need to alter requirements or design in response to changing contexts.

Conclusion

Higher order systems challenges necessitate specialized and distinct approaches for the design of portfolios of systems, versus the approaches appropriate for the systems themselves. Epoch-Era Analysis has shown promise in previous studies to enable the design of affordable systems that provide adequate utility while remaining under cost thresholds in a variety of potential contexts that may be experienced over the system lifecycle. Modern Portfolio Theory is a well-known finance technique that has been used for decades to select portfolios of investments that maximize utility subject to fixed risk. This research leveraged EEA and elements of MPT to facilitate design for affordability of engineering portfolios with uncertain futures using a portfolio-based hierarchical perspective. The method was demonstrated through the exploration of 524,160 potential carrier strike group portfolio designs across eleven different epochs and two eras. This type of analysis may support decision makers to identify long-term design and acquisition strategies for affordable portfolios that are resilient to the types of contextual uncertainties that have negatively impacted DoD acquisition efforts.

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Biography

Mr. Parker Vascik is a graduate student with the Systems Engineering Advancement Research Initiative (SEAri) at the Massachusetts Institute of Technology and an affiliate of the MIT Strategic Engineering Research Group (SERG). Vascik is earning master's degrees in both Aeronautics & Astronautics and Technology & Policy. His research interests concern the development and application of systems engineering principles to inform decision making on complex socio-technical systems with uncertain futures. He received a B.S. in Aerospace Engineering from the Georgia Institute of Technology and has experience with Rolls-Royce North America, NASA, and Synchrony Industries.

Dr. Adam M. Ross is a research scientist in the Sociotechnical Systems Research Center at the Massachusetts Institute of Technology. Dr. Ross is co-founder and lead research scientist for MIT's Systems Engineering Advancement Research Initiative (SEAri). He has professional experience working with government, industry, and academia. Dr. Ross holds a dual bachelor's degree in Physics and Astrophysics from Harvard University, two master's degrees in Aerospace Engineering and Technology & Policy, as well as a doctoral degree in Engineering Systems from MIT. He has published over 90 papers in the area of space systems design, systems engineering, and tradespace exploration.

Dr. Donna H. Rhodes is a senior lecturer and principal research scientist at the Massachusetts Institute of Technology, and director of the Systems Engineering Advancement Research Initiative (SEAri). Dr. Rhodes conducts research on innovative approaches and methods for architecting complex systems and enterprises, designing for uncertain futures, and evolving anticipatory capacity in enterprises. Previously, she held senior management positions at IBM, Lockheed Martin, and Lucent. Dr. Rhodes is a Past President and Fellow of the International Council on Systems Engineering (INCOSE), and INCOSE Founders Award recipient. She received her Ph.D. in Systems Science from T.J. Watson School of Engineering at Binghamton University.