A Method for Exploring Program and Portfolio Affordability Tradeoffs Under Uncertainty Using Epoch-Era Analysis: A Case Application to Carrier Strike Group Design

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Abstract

The modern warfighter operates in an environment that has dramatically evolved in sophistication and interconnectedness over the past half century. With each passing year, the infusion of ever more complex technologies and integrated systems places increasing burdens on acquisition officers to make decisions regarding potential programs with respect to the joint capability portfolio. Furthermore, significant cost overruns in recent acquisition programs reveal that, despite efforts since 2010 to ensure the affordability of systems, additional work is needed to develop enhanced approaches and methods. This paper discusses research that builds on prior work that explored system design tradespaces for affordability under uncertainty, extending it to the program and portfolio level. Time-varying exogenous factors, such as resource availability, stakeholder needs, or production delays, may influence the potential for value contribution by constituent systems over the lifecycle of a portfolio, and make an initially attractive design less attractive over time. This paper introduces a method to conduct portfolio design for affordability by augmenting 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 with the acquisition of new vessels.

1. Introduction

Enabled by the emerging widespread availability of high speed computing, computational Tradespace Exploration (TSE) has become a valuable tool. TSE empowers system engineers to consider far more potential designs than could be done through prior Analysis of Alternatives methods (Ross & Hastings, 2005). 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) over the lifecycle of the system. EEA enables quantitative support for the design of particular time-contingent system properties such as survivability, flexibility, and affordability (Ross, McManus, Rhodes, & Hastings, 2010).

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*, including advanced TSE techniques. To this end, EEA was adapted for affordability analysis in naval acquisitions by Schaffner, Wu, Ross, & Rhodes (2013) through the introduction of aggregate cost and schedule considerations. As system interconnectedness and interdependence continues to increase, especially in Navy and DoD operations involving numerous assets, conceptual design techniques that consider only the acquisition and operation of individual systems are not fully sufficient. Of additional value in this regard is expanding the scope of such techniques to support acquisition decisions at the multi-system level; this necessitates consideration of two related concepts: *systems 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 so as to achieve mutually desired, oftentimes emergent, capabilities (Maier, 1998). A portfolio is a construct which describes a collection of assets, acquisition programs, and research programs that are jointly invested in to exploit qualities of the set, regardless of whether the assets are operationalized independently or participate in a SoS. The Carrier Strike Group (CSG) case study conveniently illustrates the difference between SoS and portfolio design. The CSG portfolio design problem seeks to ascertain what acquisition strategies result in an affordable set of available assets that may be assembled into any number of CSG SoS to meet a variety of possible desired performance attributes. The SoS design problem, on the other hand, would occur downstream of portfolio design where a designer seeks to select available assets from the portfolio, apply concept of operations (CONOPS) to dictate SoS interactions, and meet specific desired capabilities.

SoS and portfolio design considerations represent unique challenges for tradespace analysis, and especially for affordability analysis under uncertainty. Because engineering portfolios may include assets that are SoS themselves, and because there is typically a high degree of interaction and interdependencies in the costs, risks, and capabilities of the assets, traditional portfolio assessment techniques must be modified to address these complexities that violate prior assumptions. SoS-based design approaches enable consideration of these unique qualities of engineering portfolios and shall inform the development of the method presented in this research.

This paper discusses recent efforts to adapt a resource-centric approach to EEA developed by Schaffner, Ross, and Rhodes (2014) for use in 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 CSG may be assembled. The method is leveraged to provide design insight into CSG lifecycle affordability. This insight is achieved by identifying the utility and costs of portfolio designs in potential future contexts that embody a variety of uncertainty factors, such as unit availability, budget constraints, capability requirements, strategic threats, and technology development. The eleven processes of the proposed method are described as applied to the CSG portfolio, and they illustrate the method's potential value for naval acquisition and operations. Furthermore, a discussion of the potential for broad applicability of the method to other DoD capability portfolios is proffered, specifically with respect to the Joint Capabilities Integration and Development System (JCIDS).

1.1. Motivation

Between 1997 and 2011 there were 74 Nunn-McCurdy program unit cost breeches in 47 of 134 major DoD acquisition efforts (U.S. Government Accountability Office (GAO) , 2011). According to an audit by the GAO, many of these breeches corresponded to *context* changes in the environment surrounding the acquisition programs. These context changes included affordability measurement statute modifications, presidential administrations turnover, unit order size reduction, schedule changes, and requirements changes. These cost breeches occurred in over one third of major DoD acquisition programs and indicate the need for conceptual design methodologies that consider potential changes in context in order to achieve consistent lifecycle program affordability.

In light of these breeches, and supported by the DoD emphasis of an "affordability mandate" in BBP 1.0, 2.0, and now 3.0 (Carter, 2010; Kendall, 2012; Kendall, 2014), design for affordability literature and practice grew rapidly. This provides the foundation for extending EEA to the portfolio-level. First, the concept and meaning of the term *affordability* was explored and defined by many organizations including INCOSE and the NDIA, as well as by the DoD (Schaffner, et al., 2013). Second, metrics were developed to assess the contextual and dynamic attributes of affordable systems (Bobinis, et al., 2013), and a variety of tools were produced to support affordability tradeoffs between potential systems. Third, EEA was employed to reveal system affordability across a variety of uncertain futures and to provide insight into changing contexts, such as those which caused many of the recent Nunn-McCurdy breeches (Wu, Ross, & Rhodes, 2014).

These advances, however, address only a part of the challenge in achieving affordability for the DoD since they do not explicitly consider the higher order complexities inherent to multi-system acquisition and operations (Wu, 2014). As early as 2010, DoD decision makers recognized that design for affordability at the system level did not necessarily translate to the affordability of the overall capability portfolio. Remarks by General Peter Chiarelli indicate an understanding of this concept and call for a portfolio-level conceptual design paradigm (Association of the United States Army, 2010, p. 1):

> *If you look at any one of these systems as an individual system, you can sell just about anything. But, when you look at [an] entire portfolio you can start to see where we have duplication in different systems or maybe we're overinvesting in one and underinvesting in another.*

A variety of portfolio management techniques have been developed to begin to fill this design and acquisition capability gap. The *Systems Engineering Guide for System-of-Systems* (2008) provides guidelines for the engineering of SoS in DoD acquisitions. Komoroski, Housel, Hom, and Mun (2006) applied a variant of real options analysis to identify long-term SoS acquisition strategies for information technology. The Computational Exploratory Model by Mane and DeLaurentis (2011) was developed to assess development networks of SoS architectures. Initial efforts to inform the acquisition and integration of systems in a SoS through MPT were also made by Davendralingam, Mane, and DeLaurentis (2012). Epoch-Era Analysis complements these previous efforts by adding the ability to assess the influence of changing contexts on the affordability of potential portfolios.

2. Extending EEA for Affordability from "System-Level" to "Portfolio-Level"

To clarify the terminology used in this paper and link it to trends in the SoS literature, a set of terms is introduced to describe three "tiers" of design abstraction. Table I presents an example of the design scope for each tier of design abstraction as applied to the CSG case.

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). 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 independent or semi-independent constituent elements (typically systems themselves). However, like system-level analysis, the designer of a program is typically assumed to have a moderate to high degree of design authority. Two primary types of programs have been identified, and they are distinguished by the attributes of the constituent systems.

I) *Type I programs* are composed of homogenous constituent systems. Type I program design is readily conducted through traditional EEA where the most promising single system solution is also expected to produce the greatest program benefit. Initial research into Type I programs was conducted by Wu (2014).

II) *Type II programs* are composed of heterogeneous constituent systems which often complete similar missions and are evaluated by a common set of value metrics. Because Type II programs concern either semi-independent or fully-independent constituent systems, as opposed to the closely managed homogenous systems in Type I programs, the design problem involves SoS challenges.

Portfolio-Level: A portfolio is a collection of selected assets that may be either new or legacy programs as defined above, which are simultaneously invested in to collectively provide a set of 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, but can create a portfolio with attractive procurement, management, and capability features based upon the possible assets and their likely applications. Design at the portfolio-level must not only consider traditional financial portfolio investment techniques that identify emergent properties from a set of independent assets, but also must consider SoS techniques that consider value arising from the potential interaction of the assets when operationalized.

Table I. Design abstraction tiers as applied to a carrier strike group.

	SYSTEM	PROGRAM *Type I*	PROGRAM *Type II*	PORTFOLIO
Basic Unit	Arleigh Burke-class destroyer	Arleigh Burke-class destroyer fleet	Carrier strike group guided missile support	Carrier strike group
Design Goal	Meet required capability criteria for assigned mission	Provide multi-mission offensive and defensive capabilities	Provide multi-mission guided missile support to a potential CSG	Provide military dominance in assigned sphere of influence
Sub-Units	Destroyer components: - GE LM 2500 Engines - Superstructure - Weaponry - Crew life support - Etc.	- DDG-51 - DDG-52 - … - DDG-112	- Arleigh Burke-class - Zumwalt-class - Ticonderoga-class - Virginia-class - Los Angles-class	- Nimitz-class carrier - Cruisers - Destroyers - Attack submarines - Aircraft complement - Etc.

In prior research, Wu (2014) proposed a methodology for program and portfolio-level affordability analysis utilizing a *bottom-up* "survival of the fittest" approach. Wu's approach leveraged EEA to identify promising individual systems for affordability; such system-level analysis is an extensively explored capability of EEA. At the next tier of design abstraction, the program level, new program-level performance attributes were applied to a set of programs seeded from the "promising" systems identified in system-level design. It was then ascertained which combination of these systems most promisingly fulfilled the program-level goals. This "wrapping" approach was a logical first step towards program and portfolio design with EEA. However, the method may prematurely discard potentially valuable designs that do not appear attractive in lower levels of design abstraction, but produce a favorable overall portfolio.

The concern for premature abandonment of potential assets is supported by Walton (2002). Walton's work applied portfolio theory to tradespace analysis for a space science mission and 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, Walton found that designs for portfolio-level minimum uncertainty included sub-par, system-level solutions that interacted to exhibit emergent benefits and the highest portfolio-level utility.

Recognizing the limitations of both the bottom-up and top-down (traditional requirements-driven design) approaches to portfolio design for affordability, Wu suggested a two pronged method to leverage the strengths of each approach may lead to higher-utility portfolios. TSE is inherently a bottom-up process where constituent systems are first designed for desired system level attributes, and then linked together through multiple levels of larger subsystems to result in portfolio capabilities. MPT is an inherently top-down approach where designers identify desired portfolio-level attributes (big picture) and an algorithm then seeks to compile a set of investments (systems) which satisfy those attributes in aggregate (Amenc & Sourd, 2005). This paper intends to leverage both of these techniques by applying elements of MPT and TSE to EEA. Synthesized bottom-up and top-down models have found traction in land use portfolio planning and energy portfolio management (Castella, Kam, Quang, Verburg, & Hoanh, 2007; Wing, 2006).

2.1. Overview of an EEA-Based Approach for Design for Affordability

Acquisition program planning under 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 in which they exist over the system lifecycle. Epoch-Era Analysis is an effective mechanism to evaluate acquisition strategies 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 describe a potential progression of contexts over the lifecycle of the system.

EEA consists of several distinct, but related analysis techniques. In *single-epoch analysis*, potential portfolios are evaluated in individual epochs to determine how close to the Pareto front the portfolio lies. 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 ordered epochs are strung together into an era, changes in the value of proposed portfolios over time becomes apparent, and portfolios which may become unaffordable are identifiable. Figure 1 illustrates how *single-era analysis* may reveal lifecycle deficiencies in initially promising portfolio designs.

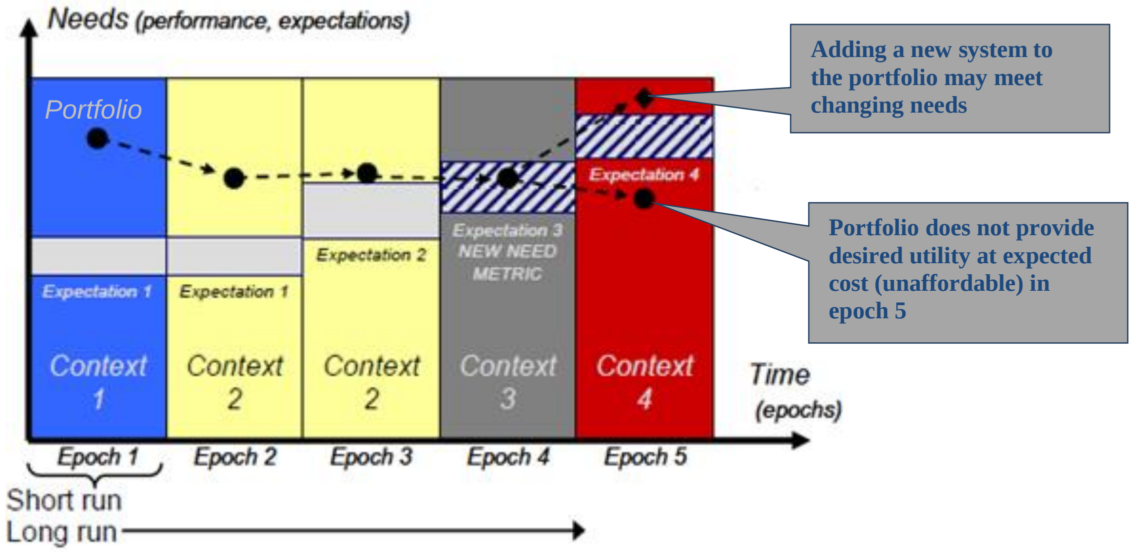


Figure 1. Epoch-Era Analysis reveals the performance (including affordability) of a system through a sequence of varying contexts illustrating potential lifecycle value of the system (Ross & Rhodes, 2008).

In prior research, Schaffner et al. (2014) developed a composite method for affordability based upon the Responsive Systems Comparison (RSC) method, and applied their approach to the acquisition of a Next Generation Combat Ship (NGCS) for the Navy. RSC is a variant of EEA which leverages TSE as a powerful tool to conduct analysis. Complex system design, and particularly SoS design, involves multiple dimensions of relevant benefits, expenses, and boundary conditions which do not lend themselves to optimization and are often too complex for intuitive decision making. TSE applies the capabilities of modern computing to enumerate a large variety of design alternatives to support a decision maker to holistically investigate subtle tradeoffs and previously unconsidered designs. As a result, RSC may lead a designer to select an acquisition program with superior lifecycle results than those determined by a numerical optimizer operating under simple tradeoffs and rules of thumb (Wu et al., 2014). Building on this prior research, this paper describes the extension of the method to the program and portfolio levels.

2.2. Overview of Modern Portfolio Theory in Systems Engineering

Modern Portfolio Theory has ubiquitous impact on financial investment strategies. MPT provides a methodology to identify an efficient frontier of portfolio investments based upon the elicited values and preferences of the investor(s) and the asset performance forecasts. Such an efficient frontier is composed of potential portfolios of investments which maximize the return on investment while minimizing the risk. To achieve this end, MPT relies on the concept that groups of investments with negative trending covariance exhibit a portfolio risk which is less than the average of the risks of each constituent investment (Amenc & Sourd, 2005).

Numerous derivatives have extended the capabilities of MPT. Post-Modern Portfolio Theory (PMPT) allows for the consideration of non-normally distributed risks (a more realistic assumption) and provides for the minimization of "downside risk" (negative outcomes) rather than mean variance (Swisher & Kasten, 2005). Walton (2002) employed TSE to allow for formal trade-offs between value and uncertainty (risk) in an effort to reveal "synergistic combinations of architectures". Furthermore, Walton's work introduced semi-variance as a method to treat upside and downside risks independently in portfolio optimization. The authors have elected to utilize MPT in this initial application to EEA due to its greater simplicity, and the availability of literature documenting application to fields beyond finance.

The fusion of aspects of portfolio theory with TSE is not a novel concept. Davendralingam et al. (2012, p. 63) introduced a modification to a model of SoS acquisition originally developed by Lane, Dahmann , Rebovich, and Lowry (2010) as a mechanism to support portfolio design and "maintain compliance with the 'top-down integration, bottoms-up implementation' paradigm" of traditional SoS design. Davendralingam et al.'s approach relied upon an ongoing, iterative circuit of design, implementation, and feedback to mitigate dynamic contextual uncertainties. The method in this paper utilizes EEA to consider the potential uncertainties of the internal and external environment at the outset, and select a portfolio which is resilient against changes in context.

2.3. Generalization of MPT and Combination with EEA

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 SoS which violate assumptions necessary for MPT. Ricci and Ross (2012) conducted a review of the similarities and differences of MPT and EEA. Their work yielded Table II which describes key differences between financial and SoS portfolios.

Table II. List of salient differences between financial and SoS portfolios (Ricci & Ross, 2012).

Financial Portfolios	SoS Portfolios
Often assume normally distributed asset returns	Performance models use various distributions
Linear aggregation of asset return	Non-linear relationships dictate asset aggregate performance
Covariance can express correlation of assets	Covariance is not sufficient to describe correlation
Various types of assets are often generally available	Assets may be limited based on economics, technology, politics
Availability of assets remains fairly constant	Assets may change availability over time
No portfolio diversification cost	Diversification costs
Low carrying costs	Possibly large carrying costs
Small switching costs	Possibly large switching costs

Ricci and Ross propose a variety of modifications to MPT which address asset availability, diversification costs, carrying costs, and switching costs. However, the disconnect between SoS and financial portfolios over non-normal distributions and non-linear relationships of constituent systems to portfolio value is yet to be addressed.

In MPT, the distribution of return (utility) is assumed to be a normal distribution around the expected value. This is an effort of MPT to characterize asset response to potential changes in future context. The assumption of a normal distribution may not be appropriate for engineering portfolios where, especially for novel systems, there is not a large set of historical data upon which constituent system performance simulations may be grounded. EEA proves a convenient mechanism to address this challenge. Multi-Epoch and era-level analyses reveal changes in utility through possible changes in context and expectations, while also identifying path-dependent uncertainty. EEA may therefore be used to determine promising portfolios that maintain acceptable value across these potential futures, rather than relying on value predictions from the aggregation of utility distributions. In a sense, when EEA and MPT are combined, assumptions about the distribution of risk of constituent systems no longer need to be made, but rather the impact of various uncertainty factors may be readily simulated and examined in the ultimate design choices.

When considering an engineering portfolio, the utility (and expense) of the overall portfolio may not simply be the aggregated, linear-sum of the stand-alone utilities of the constituent elements. Rather, engineering portfolio utility may be greater or less depending upon additional operational relationships among the constituent elements. For example, while a Ticonderoga-class cruiser provides a great deal of anti-ship missile defense value, two cruisers do not necessarily provide a potential CSG with twice the value. The anti-missile systems, radar systems, and concept of operations (CONOPS) used by the cruisers are identical (and therefore susceptible to the same vulnerabilities) and would not provide a CSG with twice the value of a single cruiser. Therefore the presence of both systems should not increase the acquisition portfolio value for these capabilities by the linear sum of both systems' utility. Conversely, the anticipated Air and Missile Defense Radar (AMDR) on Flight III Arleigh Burke destroyers is expected to provide enhanced value beyond the linear aggregation of the individual ship capacities when two more ships operate in conjunction. While MPT does not consider such investment interactions, the development of SoS utility from the capabilities of constituent systems is an active field of research. Therefore, this paper adopts two possible constructs based on SoS research as initial attempts to address this challenge for portfolio design: the *capability tree*, and *combination coefficients*.

3. Introduction of the Method for Portfolio Affordability Analysis

Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) is proposed as a new method for portfolio affordability analysis. The key innovative feature of the method is the fusion of elements from Modern Portfolio Theory with the capabilities of Epoch-Era Analysis. Figure 2 displays a graphical representation of how this is achieved.

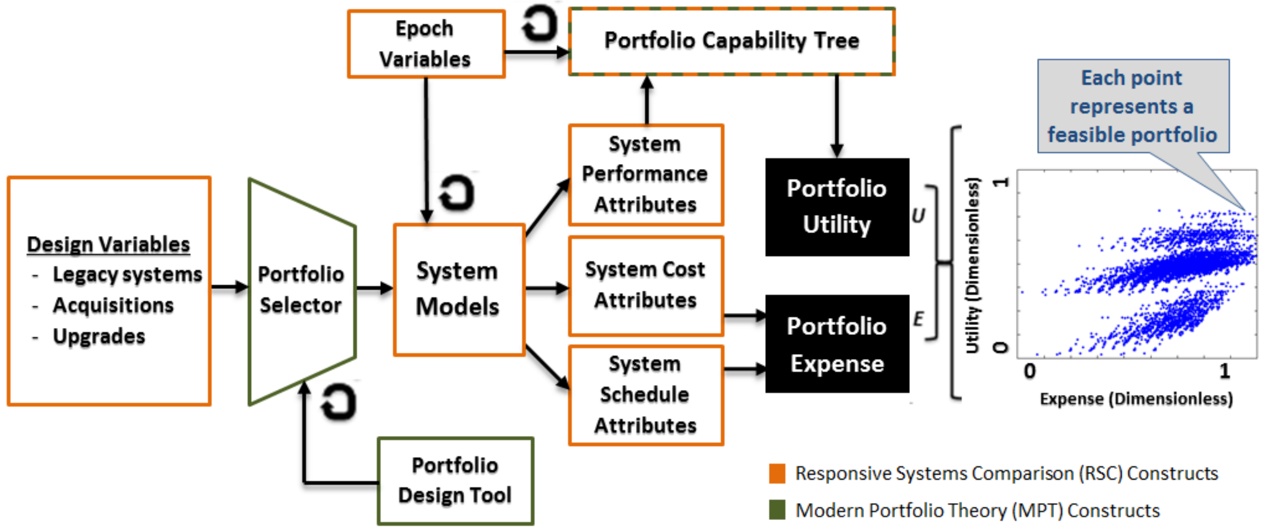


Figure 2. Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) process model for affordability analysis.

Multi-Attribute Tradespace Exploration (MATE) is a method that has been used extensively in system-level design. When used with EEA, MATE may design for a variety of "ilities," including affordability. As shown in RSC, MATE combined with EEA may be used to consider dynamic uncertainty of contexts and needs. 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.

3.1. Portfolio Design Tool and Portfolio Selector

A fundamental element of MPT is "asset allocation," or the identification of potential asset classes which 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.

The asset allocation decisions in the portfolio design tool represent the most significant lever a portfolio designer has to influence the outcome of the PLEEAA method. If a portfolio designer wishes to constrain the analysis to reflect current institutional inertia or design paradigms, they may develop highly specific classes and class constraints which force the portfolio selector to only consider designs similar to existing portfolios. However, if the designer wishes to explore potentially novel approaches and unconsidered emergent qualities of constituent systems, they may choose to set few to no class constraints on the analysis. This would enumerate a far greater portion of the potential portfolios design space, but possibly at significant computational cost.

A second role of the portfolio design tool and class constraints is to reduce the computational complexity of the portfolio design problem, as shown in the case example.

3.2. Portfolio Capability Tree

A key challenge of any tradespace-based portfolio analysis is linking constituent system performance attributes with portfolio-level capabilities. This research uses the concept of a *capability tree*, a capability-based value mapping, to both percolate portfolio designer needs down through the portfolio levels to the constituent system managers, and then to amalgamate system-level performance attributes back up the capability tree and define a 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 seek to link portfolio asset options to the overall portfolio utility for the same purpose.

The process to develop the capability tree begins with value-elicitation. A portfolio designer decomposes the strategic objectives of the portfolio-level stakeholders into a set of desired capabilities, or performance attributes. Performance attributes become a measure of how well a potential portfolio meets the needs of the portfolio designer.

Each performance attribute of the portfolio is communicated to a unique program-level manager who is the decision maker for constituent programs contributing to that portfolio performance attribute. Similar to before, the program-level manager decomposes their values into a set of program-level performance attributes which are communicated to either another program-level manager, or to the constituent systems of the portfolio.

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 utility measurement of a program must be effectively communicated at the interface of the two managers, referred to as a "node". The effective communication of utility between individuals is a non-trivial task, and in general, may benefit from multi-party utility negotiations such as those under research by Fitzgerald and Ross (2015). The capability tree model, as described here, is an imposed constructed value model and is illustrated in Figure 3 where nodes are represented by collate symbols.

The "nesting" process utilized to decompose portfolio-level strategic objectives into performance attributes, and communicate these values to constituent programs or systems, creates a two-dimensional root or tree structure of desired performance attributes at various levels of the portfolio hierarchy. The multi-document symbol in Figure 3 represents a program-level manager who utilizes their own value and performance models to determine the utility of the constituent systems or programs in their subtree.

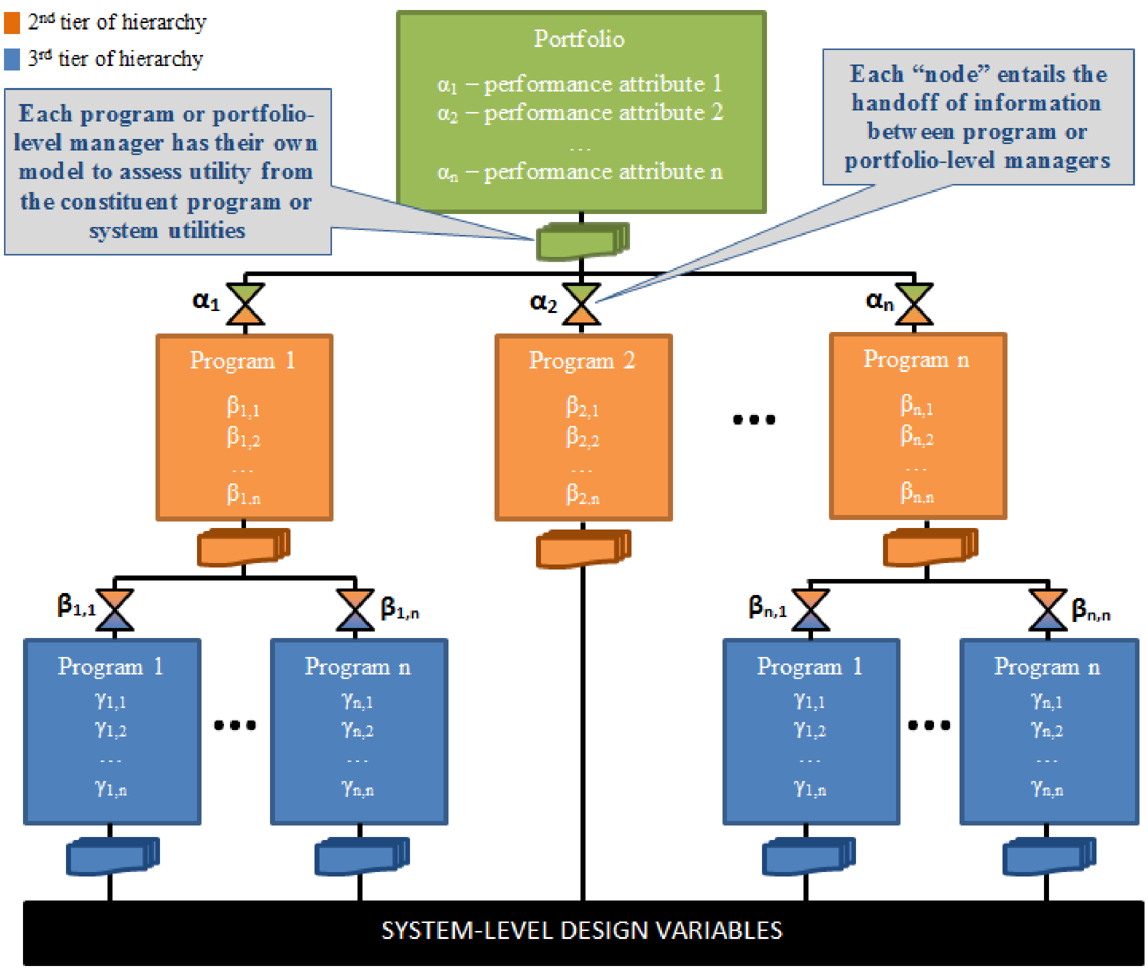


Figure 3. PLEEAA "capability tree" portfolio design architecture.

Through the capability tree, desired portfolio strategic objectives flow down to lower-level program managers as performance attributes. The capability trees are 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 may also substantially increase the analysis complexity. All "branches" of the tree do not need to have the same number of levels. Some capabilities will naturally terminate in system-level attributes after the first 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.

In the command hierarchy of military institutions, utility handoffs may be straightforward due to the subordinate decision making (chain of command) architecture. For example, the structure of the Joint Capabilities Integration Development System (JCIDS) represents the information hierarchy that the capability tree seeks to leverage for portfolio affordability analysis. JCIDS manages the DoD's joint capability portfolio and conducts capability gap assessments, among other capability requirement development and approval functions, by identifying *joint capability areas* (similar to the capability tree portfolio-level performance capabilities) and engaging decision makers in a 4-tier hierarchy which moves information from individual subject matter experts up to four star decision makers (Chairman of the Joint Chiefs of Staff, Feb 2015). In a very real sense, the PLEEAA method adopts the portfolio management structure of the JCIDS process established by Chairman of the Joint Chiefs of Staff (Jan 2015) and integrates MPT and EEA tradespace exploration techniques to produce more robust, data-driven portfolio analyses.

3.3. Complementary and Substitute Systems

A fundamental challenge unique to engineering portfolios versus financial portfolios is that portfolio-level capability may not simply be an aggregate sum of the constituent asset capabilities. As discussed previously, while a portfolio is a non-operational construct that describes the acquisition and inherent values of a set of assets, engineering portfolios must consider emergent value from asset interaction in a SoS. The concept of complementary and substitute systems in SoS has been an area of intense academic focus. To provide a few definitions:

1) Complementary systems are two or more constituent systems that experience a change in value delivery towards existing performance attributes, or gain capability in new performance attributes, when simultaneously present in a SoS (in this case, a portfolio). Such changes in value usually result from an adjustment in the CONOPS of the systems. The sign and magnitude of the performance change is variable. For example, the missile strike capability of a submarine may be significantly increased when combined with the advanced radar and fire control capabilities of a missile cruiser. However, the same submarine may experience a reduction in stealth capability as it must be within a certain range of the cruiser and transmit targeting information.

2) Substitute systems are those that provide an overlapping performance attribute capability in an operating scenario (i.e. CONOPS) of interest. A guided missile cruiser and guided missile destroyer may perhaps be considered substitute systems in terms of anti-ballistic missile capabilities. However, they would not likely be substitutes for littoral operations as their capabilities and vulnerabilities differ.

The PLEEAA capability tree architecture provides a unique mechanism to identify and assess substitute systems. Since all potential systems are simultaneously evaluated by each bottom-level portfolio hierarchy manager, substitute systems that provide similar capability are likely to be identified. The manager's value model may then appropriately determine the node's aggregate utility resulting from the interacting substitute systems.

The identification of complementary systems is not as straight forward, but is still enabled by the capability tree architecture. Again, because bottom-level portfolio hierarchy managers ideally have visibility of the relevant potential constituent systems of the portfolio that contribute to the performance attribute of interest, they will likely be able to identify system pairings which complement each other's value delivery. The bottom-level managers, unlike the portfolio designer or higher-level program managers, will reasonably have the expertise to understand the potential interactions between systems. In other words, the capability tree framework releases portfolio-level designers from trying to make technical evaluations on the numerous constituent systems in the portfolio, but rather allows each manager in the capability tree to only consider system or program interactions and values at their node. If a bottom-level portfolio manager is unable to identify system interactions, then emergent complementary value may not be properly considered in the portfolio design.

On an additional note, both complementary and substitute systems are likely to represent opportunities for cost savings through joint development or production programs. While this information is unlikely to be offered by the constituent system operators during value elicitation, the bottom-level managers will likely recognize such potential. Therefore, the capability tree framework may allow for the adjustment of both utility and costs with respect to complementary and substitute system interactions.

While the capability tree framework may help discern the influence of complementary and substitute systems, the approach outlined above would require 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 also adopts a second approach to manage complementary and substitute systems in lower fidelity analyses.

In her work to apply tradespace exploration to SoS, Chattopadhyay (2009) introduced the concept of "level of attribute combination complexity." Chattopadhyay identified three levels of combination complexity which express general, first-order estimates of performance attribute interaction from different constituent systems in the portfolio. "Low-level combination" characterizes performance attributes which exist independent of one another. An example of low-level combination may be an E-2 Hawkeye early warning capability and a Littoral Combat Ship (LCS) green-water minesweeping capability. "Medium-level combination" describes attributes of systems which contribute to the delivery of the same portfolio performance attribute, but are characterized by a sharing of value deliver, such as through a handoff of responsibility. The handoff of targeting information from a Ticonderoga cruiser to a Virginia-class submarine may be envisioned as medium-level combination for the cruise missile strike performance attribute. Finally, "high-level combination" are system attributes which interact to simultaneously provide a portfolio performance attribute, such as the anti-submarine warfare capabilities of a Virginia-class submarine and an Arleigh-Burke destroyer. A given system may contribute to performance attributes at one or all of these levels of combination complexity when considering their interactions with other systems.

PLEEAA elicits bottom-level portfolio hierarchy managers to characterize the combination complexity for each performance attribute in their area of responsibility for each of the potential constituent systems. Various models may be used to represent the impact of the level of combination on the resulting utility and cost of the portfolio. For the CSG case study, in general, low-level combination attributes are not adjusted, medium-level combination attributes utilize alternative models for utility calculation, and high-level combination attributes receive appropriate utility and cost multipliers.

3.4. Overview of PLEEAA

PLEEAA is a variant of the RSC method for affordability analysis developed by Schaffner et al. (2013). The Gather-Evaluate-Analyze structure of the RSC method was maintained and 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.

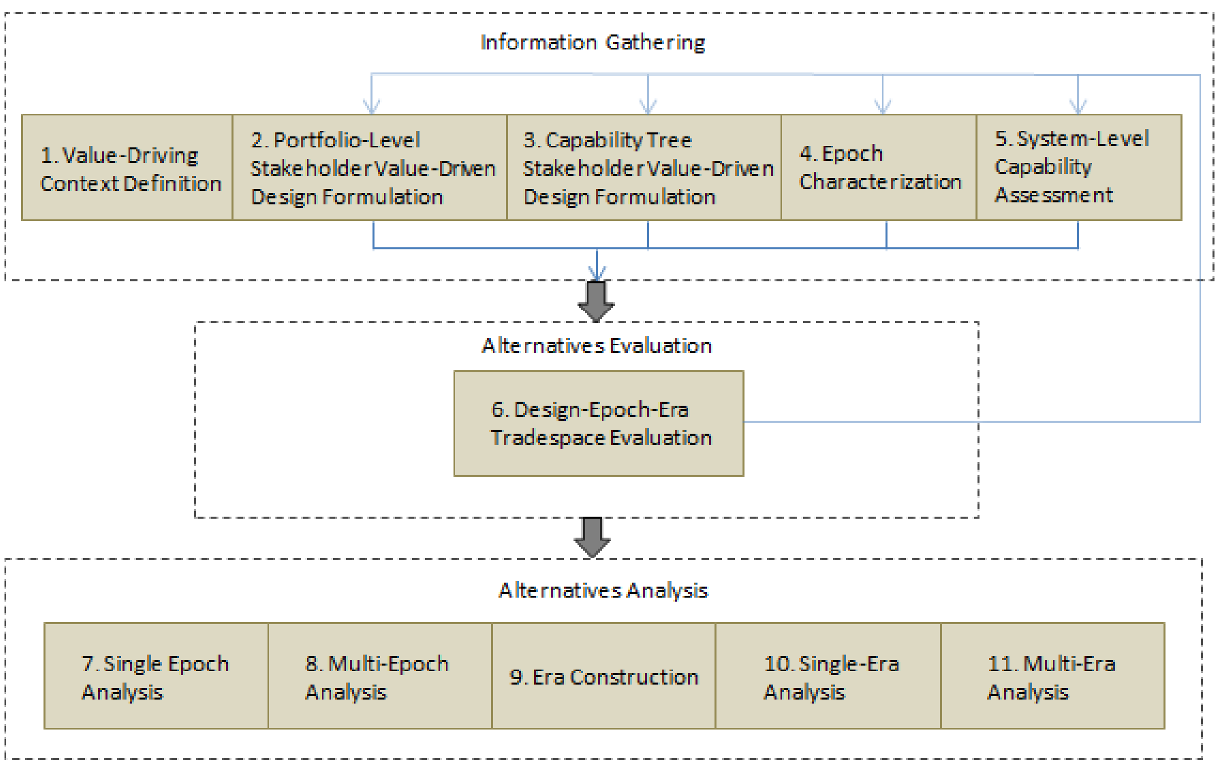


Figure 4. A graphical overview of the modified Gather-Evaluate-Analyze structure for PLEEAA.

The basic steps of PLEEAA are represented as an 11-process method shown in Figure 4. Processes 1 through 5 involve value elicitation of multiple-levels of stakeholders in the portfolio to define the problem scope, assess stakeholder needs, identify contextual variables, and assess combination complexity information for potential systems. Process 6 conducts the composite EEA/MPT analysis to produce a tradespace of potential portfolio designs for the considered epoch. Before proceeding to the following processes, feedback is provided to the designers and stakeholders to allow for adjustments in the provided information, as necessary. This feedback loop is a key element of TSE as stakeholder values may change as portfolio options and tradeoffs are made clear. Finally, processes 7 through 11 support designers at the portfolio-level to compare the dynamic properties of potential portfolios in light of their anticipated performance in a variety of point futures (epochs), as well as possible lifecycle narratives (eras). These processes are described and applied to the CSG study in section 4 of this paper.

4. Demonstration Case: Carrier Strike Group Design for Affordability

According to a 2006 RAND study, the cost growth rates for new naval units such as “amphibious ships, surface combatants, attack submarines, and nuclear aircraft carriers have ranged from 7 to 11 percent,” an inflationary rate which significantly outstrips development costs in other sectors (Arena, Blickstein, Younossi, & Grammich, 2006). In the decade since this report, the severe cost overruns in the Littoral Combat Ship (LCS) and Zumwalt class destroyer (DDG1000) programs have likely exacerbated this figure. In light of this matter, it appears appropriate to apply PLEEAA to an application of large ship acquisitions in order to display the potential of this method to assist decision problems in the following ways:

- (i) As the LCS and DDG1000 programs are scaled back (or eliminated) and replaced with alternative systems, portfolio-level affordability analysis may aid the identification of resulting capability gaps in the Navy’s strategic portfolio.
- (ii) The use of a PLEEAA may facilitate the definition of acquisition program requirements which limit capability creep, such as what was seen in the LCS development.
- (iii) Portfolio-level affordability analysis will give decision makers insight into the value tradeoff of investing in high capability, high costs systems, versus low capability, low cost systems for future naval group operations.
- (iv) EEA, when applied to a ship acquisition portfolio, will allow designers to foresee the affordability of the proposed capability portfolio in multiple potential future scenarios.

Considering these potential benefits to the naval acquisition process, the design of a portfolio of systems, from which a CSG(s) may be developed, presents itself as an appropriate case study to demonstrate PLEEAA. Beyond the relevance of the analysis to the DoD’s goals of an affordable Navy and the emergence of new tactics and asymmetric threats for exiting CSGs, the complexity the CSG design problem is conveniently reduced through a series of realistic assumptions. The simplifying assumptions adopted include:

1. A CSG is a *directed SoS* as defined by Maier (1998) in which a central authority (the combatant commander (CCDR) and operational commander) have decision authority over the constitute systems (Chief of Naval Operations, 2010). A directed SoS is ideal for the initial application of this method as the additional complexities inherent to incomplete managerial influence or decentralized control are avoided (Shah, 2013).
2. The baseline composition and basic mission capabilities of as CSGs are well-defined by Chief of Naval Operations (2010) enabling effective bounding of the potential portfolio asset set for the purposes of this case study. Furthermore, a CSG is intended to function autonomously for many of its operations. This further simplifies the scoping of the portfolio boundary conditions and interfaces.
3. The hierarchy of the Navy designates specific decision making authority to specific individuals. This structure, including the Navy’s use of subject matter experts, is directly paralleled by the capability tree structure of PLEEAA. Therefore, in the analysis each node of the capability tree may be mapped to a specific decision maker in the CSG command structure.

The following sections briefly describe each process in PLEEAA. A *representational outcome* is included, which provides a first pass, high-level application of PLEEAA to CSG portfolio design, subject to the assumptions highlighted above. 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.

4.1. Process 1: Value-Driving Context Definition

The first process in PLEEAA begins by identifying the basic problem statement and design space for the proposed portfolio. The portfolio-level stakeholders are identified 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 predicted.

Representational Outcome: According to the Chief of Naval Operations (2010), the primary portfolio-level stakeholders influencing the design of a CSG are the combatant commander (CCDR) and operational commander of the naval group. The CSG value proposition is outlined therein 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." An initial set of 12 potential constituent systems is provided in the work instruction. Seven more systems were added to capture the NGCS work conducted in prior research and the new Zumwalt-class destroyer. For this analysis, the portfolio designer is assumed to have total control over the acquisition of new systems for the CSG portfolio (subject to the defined constraints).

4.2. Process 2: Portfolio-Level Stakeholder Value-Driven Design Formulation

In process two, the portfolio designer elicits a variety of information from the portfolio-level stakeholders to establish the root (top level) of the capability tree and clarify the constraints of the portfolio design and composition.

A) Performance Attributes: A set of overarching capabilities which the portfolio must be able to fulfil to meet the strategic objectives. These capabilities, or performance attributes, are assigned weights based on elicited information to reflect the stakeholder preferences. A utility function is developed.
B) Expense Attributes: Portfolio resource statements are translated into specific costs measured in the portfolio. Acceptable expense thresholds are identified, and expense functions are created.
C) Portfolio Investment Strategy Constraints: 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 value to any single system.

Representational Outcome: Simplified interpretations of notional, portfolio-level performance and expense attributes for a CSG portfolio are shown in Table III. For this initial case study, the performance and expense attributes yield 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 sufficient first order estimation for the demonstration purposes of this case study.

Table III. Portfolio-level performance and expense attributes for a CSG.

Performance Att.	**Notional portfolio strategic objective**
Electronic Warfare Capability	Suppress enemy EM spectrum capabilities to detect friendly assets while providing constant functionality despite enemy EM countermeasures
Defensive Capability	Maintain asset functionality against enemy attack and countermeasures
Offensive Capability	Provide offensive capabilities both within and beyond the battlespace
Power Projection	Project psychological power in the sphere of influence of the CSG to support peacekeeping missions, deter attack, and increase the prestige of the U.S.
Logistics	Replenish the consumables of the CSG anywhere in the world at appropriate intervals in combat and non-combat situations. The CSG shall be capable of operation for a reasonable period of time without re-supply
Expense Attribute	**Notional portfolio strategic objective**
Acquisition Cost	The cost of producing new constituent system
Influence Cost	The cost incurred to leverage a constituent system to participate in the CSG
Operation Cost	The annual cost of a constituent system
Schedule Cost	The perceived cost to portfolio designers of constituent system late entry into the portfolio

4.3. 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. As a reminder, the manager at each node controls, or has expertise in, a performance capability identified in the higher level of the portfolio. The portfolio designer elicits a variety of information from each program manager of the capability tree 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. For while the representation of the CSG has been simplified, the corresponding capability tree developed 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 entire capability tree has not been included in this paper; however, Figure 5 displays the tree with all but the system-level performance attributes included. It should be noted that some branches terminate after only the portfolio-level attributes, while other branches decompose capabilities through three nodes before reaching system-level attributes.

Levels of capability tree hierarchy
Portfolio Level Capability Attributes
2nd Level SoS Capability Attributes
3rd Level SoS Capability Attributes
# of System Level Performance Attributes

Portfolio Level	2nd Level	3rd Level	#
CSG Electronic Warfare Capability	Early Warning		6
	Weapon system detection		6
	Electromagnetic System		5
CSG Defensive Capability	Battlespace Defense Capability	Sea superiority	5
		Air Superiority	5
		Undersea Superiority	5
		Combat Search and Rescue	2
	Naval Asset Defense Capability	Anti-Ship Missile Defense	5
		Anti-Ship Kinetic Weapon	5
		Sea Mine Defense	5
		Torpedo Defense	5
		Crew Defense	4
CSG Offensive Capability	Naval Gun Fire Support		5
	Missile Strike Capability	Ballistic Missile Interception	5
		Cruise Missile Strike	5
	Torpedo Capability		5
	Sea Basing Capability		3
	Special Forces Insertion		4
Power Projection			2
CSG Logistics			4

Branch of capability tree

Figure 5. CSG case study capability tree outline (read tree from left to right)

4.4. Process 4: Epoch Characterization

All stakeholders related to the portfolio (portfolio decision makers, program managers, system operators, external stakeholders, etc.) are engaged to identify possible key future contexts that might impact success, and to characterize the uncertainty of each context. 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. Any anticipated changes in stakeholder preferences (performance attribute weightings) are identified.

Representational Outcome: Seven epoch variables were identified from five major categories of uncertainty (technology levels, maintenance events, policy environment, SoS management abilities, and CSG threats). Table IV displays the range of uncertainty represented by each epoch variable as well as units of measurement. The technology epoch variables most directly influence constituent system performance. The maintenance, policy and SoS management epoch variables most directly influence the cost functions. The threats epoch variables change the stakeholder preferences for portfolio attribute performance.

Table IV. Contextual uncertainties of CSG captured in epoch variables.

EV Category	Epoch Variable	[Range]	Units
EV – Technology	Advanced Energy Weapons (AEW)	[0, 5, 50]	MW
EV – Technology	Unmanned Aerial Systems (UAS)	[2, 10, 50]	Berths
EV – Maintenance	Overhaul Event Costs	[0, 0.5e9, 2e9]	Billions $
EV – Policy	Budget	[80, 100, 150]	%
EV – SoS management	Cooperation Costs	[80, 100, 150]	%
EV – Threats	Enemy Threat	[Low, Med, High]	Level
EV – Threats	Asymmetric Threat	[Low, Med, High]	Level

For the initial case study presented in this paper, the technological epoch variables were excluded to simplify the analysis and focus the results on affordability considerations of the variance in portfolio cost attributes.

The five remaining epoch variables were enumerated independently and combined to produce a total of 243 potential epochs. For the sake of simplicity, five possible epochs that represent recognizable potential futures were extracted from this set in a "narrative" sampling approach. These five epochs and their epoch variable levels are provided in Table V.

Table V. Epoch construction from epoch variables for five selected epochs.

Epoch Names	*Epoch Variables*				
	Overhaul	**Budget**	**Cooperation**	**Enemy**	**Asymmetric**
Baseline (BL)	0	100	100	Low	Med
Small Navy (SN)	0	80	150	Low	Low
War on Terror (WoT)	0	100	80	Low	High
Major Conflict (MC)	0	150	80	High	Med
Peacekeeping (PK)	0.5e9	100	100	Med	Med

4.5. 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 performance models to computationally assess the potential constituent systems' performance. In other cases however, such models may not exist and the bottom-level managers, or an appropriate subject matter expert, shall be engaged to assess system performance qualitatively. 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. Publically available information was utilized to assign performance on a 0, 1, 3, 9 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.

4.6. Process 6: Design-Epoch-Era Tradespace Evaluation

A key high level summary visualization is a tradespace with axes of Multi-Attribute Utility (MAU) vs Multi-Attribute Expense (MAE) as demonstrated by 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. The process flow of PLEEAA depicted in Figure 2 highlights the process utilized to design portfolios, find portfolio MAU and MAE, evaluate the validity of the result, and create the data necessary for depicting a tradespace of viable alternatives.

Representational Outcome: Without the ability to elicit performance attribute aggregation models from each of the program-level managers, this research developed a series of six functions to evaluate bottom-level portfolio manager utility and cost attributes from the constituent systems in a portfolio. Each performance and cost attribute of the portfolio was assigned one of the six functions depending upon which one best represented the notional program-level manager value. Once the bottom-level performance and cost attributes had been calculated, the value was 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 the portfolio. Table VI provides information on the approach and result for utility evaluation at each level of the capability tree.

Table VI. Approach to derive portfolio-level utility from system performance attributes through the capability tree.

	Portfolio Designer	2nd Level Program Manger	3rd Level Program Manager	System Performance Attributes
Approach	Applied linear-weight sum aggregation to the utility from each 2nd level program manager	Applied linear-weight sum aggregation to the utility from each 3rd level program manager	Applied one of six models which best assess 3rd level program manager utility from the constituent systems	Each system was evaluated on 0,1,3,9 scale for each performance attribute
Result	Portfolio utility on a 0 to 1 scale	2nd level program utility on a 0 to 1 scale	3rd level program utility on a 0 to 1 scale	System performance attribute values

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

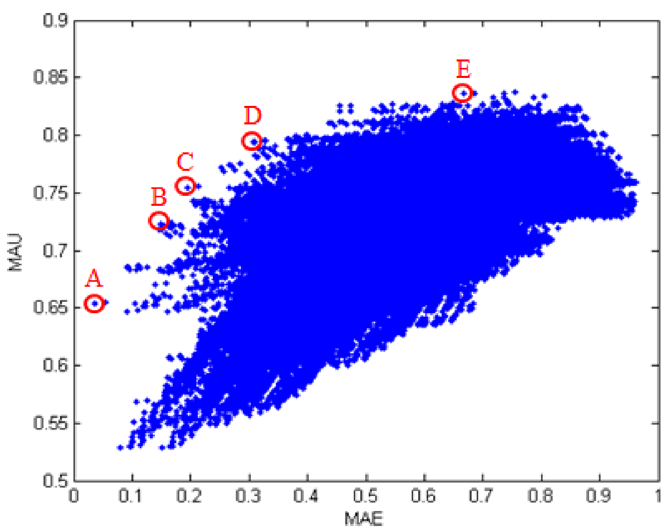
Table VII. Single-Epoch tradespace evaluation summary.

Epoch	Valid Portfolios	Yield
Baseline	156,750	29.9%
Small Navy	420	0.08%
War on Terror	156,750	29.9%
Major Conflict	492,400	93.9%
Peacekeeping	156,750	29.9%

4.7. 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 can identify which portfolio design options for the CSG perform particularly well for the context represented in that epoch, and what constituent systems Pareto efficient portfolios have in common.

Representational Outcome: The tradespace of viable CSG portfolios for the Baseline epoch is provided in Figure 6. The Pareto frontier of the Baseline epoch contains a total of 26 potential portfolio designs. The specifications for five example Pareto optimal portfolios have been provided. Figure 7 visually displays the composition of the promising portfolios and highlights constituent system investments. The constituent system types which differ between the promising portfolios were identified with portfolio A as a reference. This portfolio comparison is intended to reveal to what degree the same constituent systems appear in various promising portfolios. Two portfolios which 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 6. Portfolio affordability tradespace (MAU v. MAE) and Pareto efficient portfolios for the Baseline epoch.

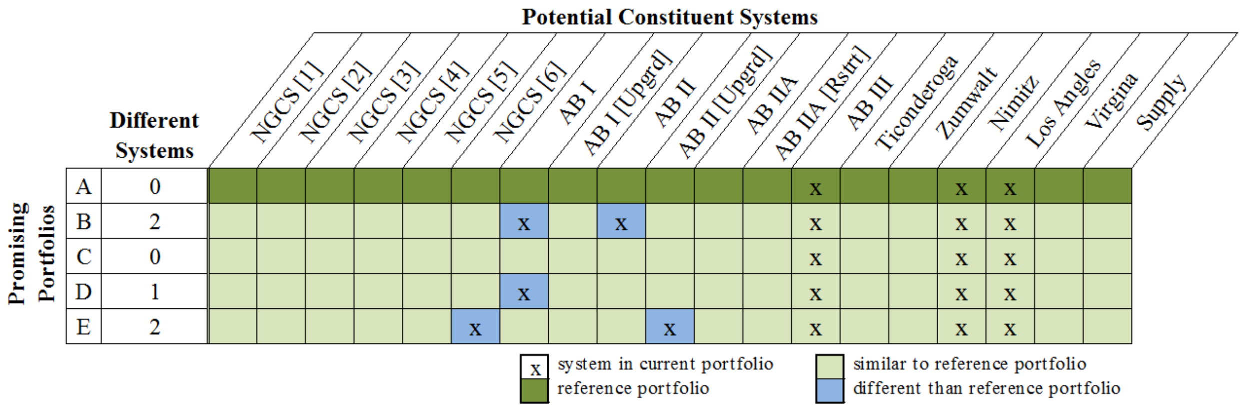


Figure 7. Constituent system comparison for promising portfolios with portfolio A as the reference portfolio.

4.8. Process 8: Multi-Epoch Analysis

A fundamental technique within EEA is the comparison of potential portfolios across multiple epochs. Following single-epoch portfolio analysis, a general understanding of performance of the SoS in each epoch has been established. By comparing the performance of each portfolio across multiple epochs, various metrics can be utilized to assess the design's robustness against change and uncertainty, or how well a single portfolio can maintain its value across multiple epochs. The reader should consult Schaffner et al. (2013) for a detailed explanation of multi-epoch analysis.

Representational Outcome: A particularly useful concept to assess the performance of a promising portfolio design across multiple epochs, or to discover passive robust solutions, is the concept of Normalized Pareto Trace (NPT) (Ross, McManus, Rhodes, Hastings, & Long, 2009). A NPT score is assigned to each portfolio design of interest 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 threshold factor of the Pareto front. The width of this threshold zone is defined by a K factor, where a K factor of zero indicates 0% fuzziness and is identical to the NPT metric. Figure 8 illustrates the concept of fNPT, and Table VIII displays the NPT and fNPT measures for the five portfolios identified in Figure 6.

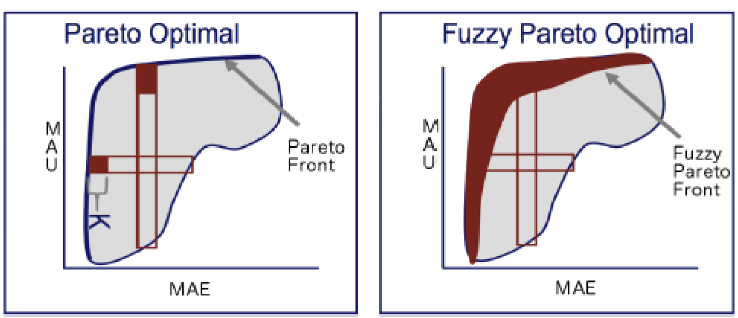


Figure 8. Illustration of the fNPT metric, where K is the threshold width applied below the Pareto frontier.

Table VIII. NPT and fNPT metrics for five promising CSG portfolio designs over the 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

Table VIII 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 6 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.

4.9. Process 9: Era Construction

Another useful technique in EEA involves the concept of evaluating 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 could 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.

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

Era 2: Peacekeeping (5 yr), Major Conflict (7 yr), Peacekeeping (10 yr), Small Navy (5 yr), Baseline (3 yr)

4.10. Process 10: Single-Era Analysis

In single era analysis, the performance of portfolio designs is assessed over a sequence of epochs as described in process 9. Single-Era analysis enables designers to understand the time-ordered effects of the epochs on the portfolios. This allows for the identification of portfolios which maintain utility and affordability throughout the sequence of potential futures, and of those which 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. Therefore, Figure 9 contains two subplots which display the change in MAU and MAE over the five epochs for the five Pareto efficient portfolios in the Baseline epoch. Tracing the trajectories reveals the emergent affordability, or unaffordability, of the potential CSG portfolios.

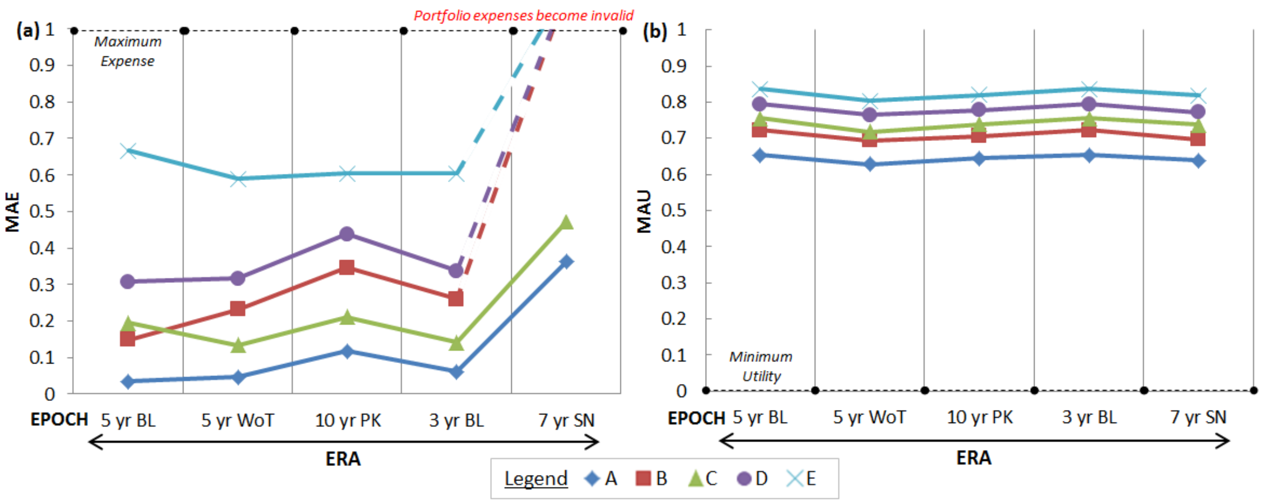


Figure 9. (a) Expense considerations for era 1; (b) Utility considerations for era 1.

The purpose of this initial case study was to explore the ability of PLEEAA to support design for affordability. The case study was therefore constructed to focus on exogenous factors anticipated to impact expense attributes. As a result, the MAE of the portfolios exhibits significant variance over the era in Figure 9(a). However, there is relatively little variation in the MAU values between the selected portfolios through all epochs in Figure 9(b). The utility variation is small because the technology epoch variables, which most significantly influence constituent system performance, were not included in this initial study. Additionally, the class constraints of this analysis required all portfolios to have an aircraft carrier, a submarine, and at least one multi-mission capable surface combatant. The class constraints therefore provided a relatively high minimum utility of all valid portfolios which further reduces apparent variation. Finally, as illustrated in Figure 7, the promising portfolios primarily contained multiple units of the same constituent systems. As a result, the portfolios exhibit similar utility responses to the uncertainties modeled. Future research will include epoch variables which strongly impact capability performance attributes in order to more fully represent the design problem.

*4.11. 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 of multi-era analysis.

4.12. Discussion of the "Affordable" CSG Design through PLEEAA

There are hundreds, if not thousands of factors that influence the lifecycle design of a CSG portfolio. While it may not be possible to ever consider each of them, modern day computing capabilities and systems engineering methodologies enable a designer to consider far more of these influence factors during conceptual design than was traditionally possible. PLEEAA provided a method to consider 91 distinct CSG system-level performance attributes and relate their value back up to the overall portfolio utility. The performance attributes and expense attributes, along with the preferences of the relevant stakeholders, were defined in PLEEAA for five epochs to characterize contextual uncertainty of potential future states.

PLEEAA supported the identification of CSG designs which appear on the Pareto frontier of each epoch through single-epoch analyses. Furthermore, utilizing the metrics of NPT and fNPT in multi-epoch analysis, PLEEAA identified five promising portfolios which exhibit acceptable performance and affordability across a majority of the epochs considered. From Table VIII it can be seen that portfolio A remains Pareto optimal through all epochs. Portfolio C, which may have been overlooked in traditional analysis as it does not appear Pareto optimal in two of the epochs, is the only other design which is Pareto dominant in all epochs when a 10% fuzziness factor is applied. Therefore, portfolio C represents a passive robust solution that remains affordable against uncertainty, but is displaced in some cases from the Pareto frontier. Portfolios A and C are composed of identical types of constituent systems, simply with different numbers of these systems. This may indicate to a portfolio designer that the constituent systems in these portfolios provide promising value to potential future CSGs while maintaining affordability under potential uncertainty.

Finally, though single-era analysis PLEEAA discerned which initially promising portfolio designs were likely to remain affordable, while maintaining their utility, over the lifecycle of the CSG. Figure 9 illustrates that while all portfolios maintain sufficient utility delivery, portfolios B, D and E become unaffordable in the Small Navy epoch. Upon investigation, these portfolios were found to exceed the operational costs allowable under the context of hypothetical Navy downsizing, while portfolios A and C remained affordable. Single-Era analysis of portfolios provides a mechanism to identify challenging lifecycle circumstances and robust solutions during conceptual design.

5. Discussion of PLEEAA Application to Portfolio Conceptual Design and Analysis

The conceptual design of systems of systems and portfolios presents a variety of challenges to traditional toolsets, including influence considerations, complexity of combination factors, and dynamically changing portfolio composition. However, with the prevalence of major acquisition Nunn-McCurdy breeches in recent years, the ability to evaluate the affordability of portfolios with respect to lifecycle uncertainty is desired to support acquisition decision makers. The PLEEAA method enables 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 which 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

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

studies between portfolios in the area of desired performance. Epoch-Era Analysis provides acquisitions officers with new abilities to identify how potential designs may respond 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 will support the selection of portfolios which may remain affordable over the entire lifecycle of the program, without the need to alter requirements or design in response to changing contexts. In implementation, the authors envision a network of system designers, each using tradespace exploration to design their own systems, connected by a SoS and interacting through the PLEEAA method to ensure that needed capabilities are provided in the portfolio at an acceptable cost with a desired level of uncertainty robustness.

6. Conclusion

The differences between capability portfolios of assets and individual systems necessitate specialized and distinct approaches for design and acquisition planning. 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 through a variety of potential contexts that may be experienced over the lifecycle of the system. Modern Portfolio Theory is a well-known financial tool that has been used for decades to select portfolios of investments which maximize utility subject to fixed uncertainty. This research leveraged EEA with elements of MPT to facilitate design for affordability of systems of systems with uncertain futures using a portfolio-based hierarchical perspective. The proposed method was used to explore 524,160 potential carrier strike group portfolio designs across five different epochs and two eras. This type of analysis may help decision makers to identify long-term acquisition strategies for affordable portfolios that are resilient against the types of contextual uncertainties that have negatively impacted recent DoD acquisition efforts.

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