26th annual INCOSE international symposium

Edinburgh, UK

July 18 - 21, 2016

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

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# Presentation Outline

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## Motivation

- Influence of Uncertainty on Lifecycle Value Delivery

## Research Approach

- Strategies for Considering Uncertainty
  - Epoch-Era Analysis (EEA)
  - Modern Portfolio Theory (MPT)
- Joint EEA and MPT Design Method for Portfolios

## Case Application

- Carrier Strike Group (CSG) Portfolio

## Conclusion

# THE CHALLENGE
# OF DESIGN UNDER UNCERTAINTY

# Design for Value Sustainment

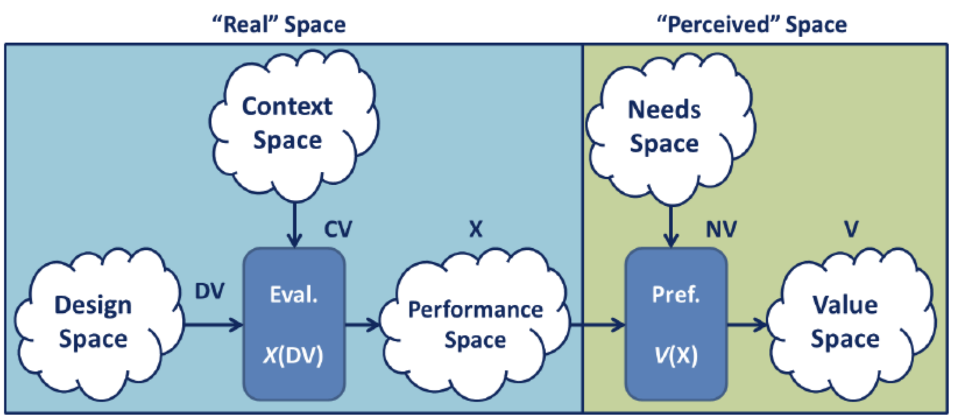
**Many systems exist in a global environment that will inevitably experience dramatic, dynamic shifts in context**

Exogenous uncertainties exist in the acquisition and operational environment

- Emerging technologies (e.g., UAS maturation)
- Political transition (e.g., low carbon fuels mandate)
- Economic shifts (e.g., global recession)
- Resource availability (e.g., rare-earths crisis)

Stakeholder needs may vary with the decision context

- Change of stakeholder *preferences*
- Change of mission *objectives*




(Beesemyer, 2012)

**Design for value sustainment seeks to maximize portfolio value across a variety of foreseeable contexts and needs**

# Design for Affordability

- 74 US Nunn-McCurdy cost breaches between 1997 and 2011
- Numerous breaches corresponded to context changes in the environment of the acquisition programs(GAO, 2011)
- A variety of system-design methodologies have been developed in response to the Better Buying Power (BBP) mandates(Carter, 2010)

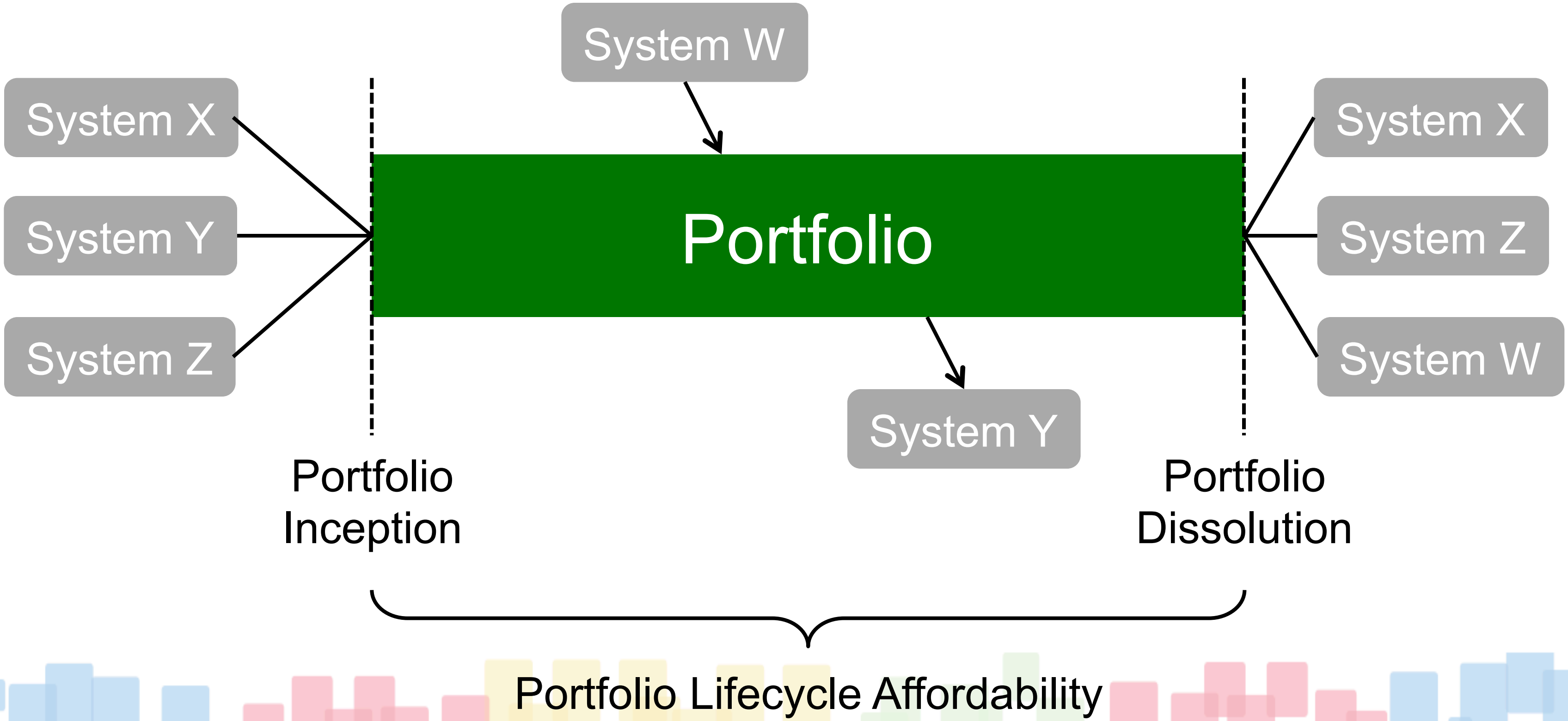

http://www.navsource.org/archives

http://www.ainonline.com

**Can aspects of MPT and EEA be combined to create sustained lifecycle *affordability* for engineering portfolios despite changing contexts?**

# Design for Affordability

Affordability may be defined as "the property of becoming or remaining feasible relative to resource needs and resource constraints over time" (Wu, Ross, Rhodes, 2014)



# RESEARCH APPROACH

# Design Abstraction Terminology

Acquisition and development efforts face different challenges and opportunities contingent on the scope of the design abstraction

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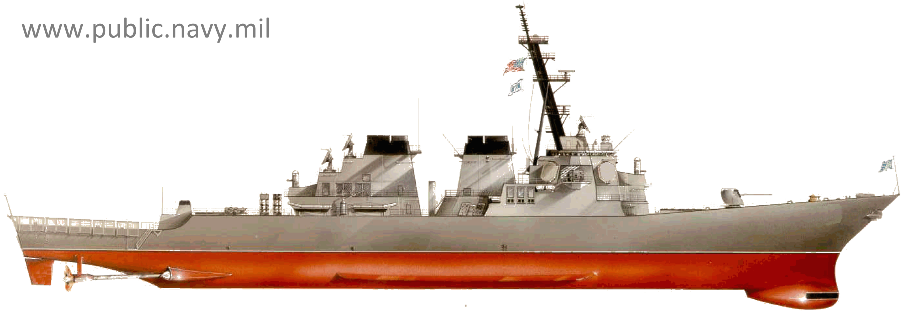


System-Level: a singular major architectural element

Program-Level: multiple elements fulfilling common capability requirements

Portfolio-Level: multiple elements that collectively fulfill a set of joint capability requirements

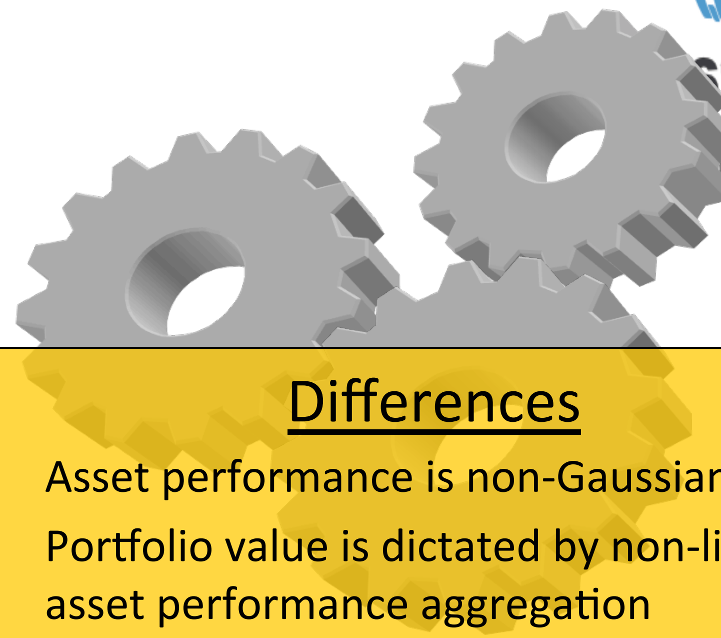
# Portfolio-Level Design

**System-level design methods do not effectively support the creation of specific portfolio-level properties**

- Multi-system acquisition of portfolios and operation of SoS present higher order complexities not addressed by system-level design techniques
- SoS engineering has developed approaches to consider the interactions of constituent systems and determine "satisficing" solutions(Keating et al. 2003)
- Some methods have also been adapted for portfolio design
  - Portfolio Theory application for SoS decision making(Davendralingam et. al, 2011)
  - Real options analysis for IT SoS acquisition strategies(Komoroski et. al, 2006)
  - Tradespace-based affordability analysis for complex systems(Wu et.al, 2014)

# Modern Portfolio Theory (MPT) for Engineering Portfolios





## Consistencies

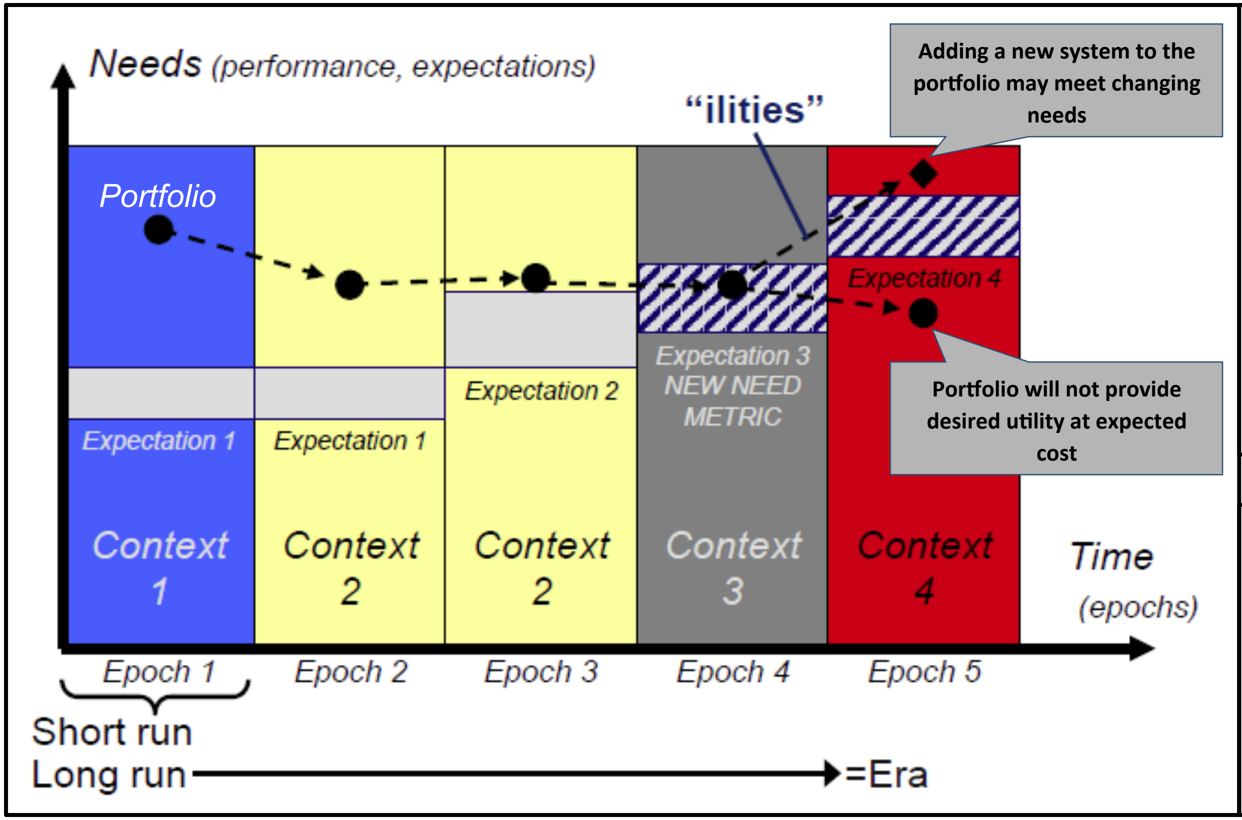
- Value elicitation from stakeholders
- Modeling of asset value
- Founded in utility theory
- Identifies "efficient frontier" of potential alternatives

## Differences

- Asset performance is non-Gaussian
- Portfolio value is dictated by non-linear asset performance aggregation
- Covariance is insufficient to describe asset correlation
- Asset availability is dynamic
- Costs may accompany diversification

**Select elements of Modern Portfolio Theory can improve the design and acquisition of engineering systems portfolios**

# Epoch-Era Analysis




**Epoch**
A time period of static contexts and stakeholder expectations, like a snapshot of a potential future

**Era**
An ordered sequence of epochs with finite time durations; a potential progression of contexts over the portfolio lifecycle

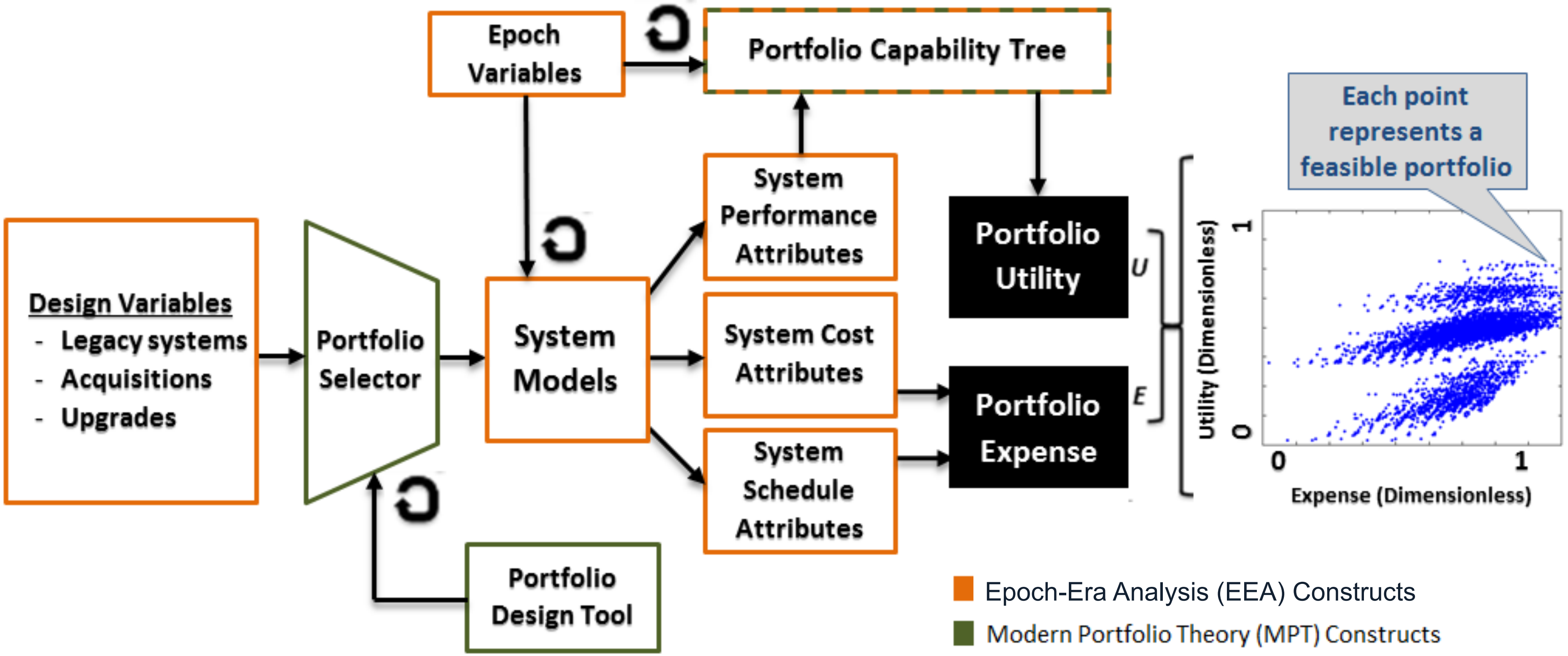
**Legend**
- Portfolio
- Portfolio Trajectory
- Expectations

(Ross & Rhodes, 2008)

**EEA is an analytic method useful to assess potential portfolio performance over the dynamic environment in which it operates**

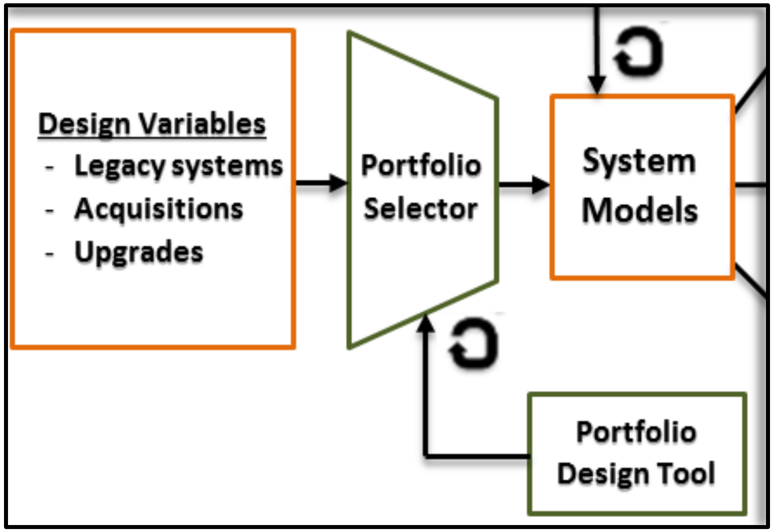
# JOINT EEA AND MPT METHOD TO SUPPORT DESIGN FOR AFFORDABILITY

# Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA)




**Fuses elements of MPT with EEA through the framework of multi-attribute tradespace exploration**

# Portfolio Enumeration




Portfolio Design Tool

- Conducts asset allocation
- Applies portfolio class constraints
- Enumerates all possible portfolios

Portfolio Selector

- Compiles a specific portfolio for modeling

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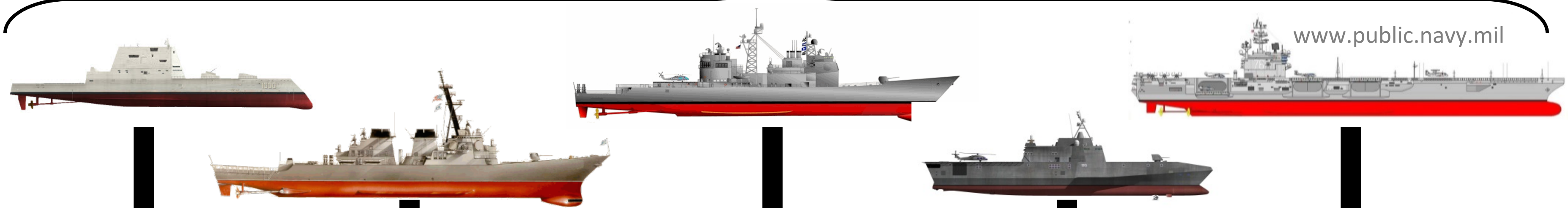
An engineering portfolio may be represented by three primary design variables

- Legacy Systems – existing hardware available to the portfolio
- Acquisitions – new assets produced for the portfolio
- Upgrades – change options available for legacy systems

# Portfolio Design Tool



Fundamental to MPT, asset allocation identifies potential classes of assets which may constitute portfolio elements



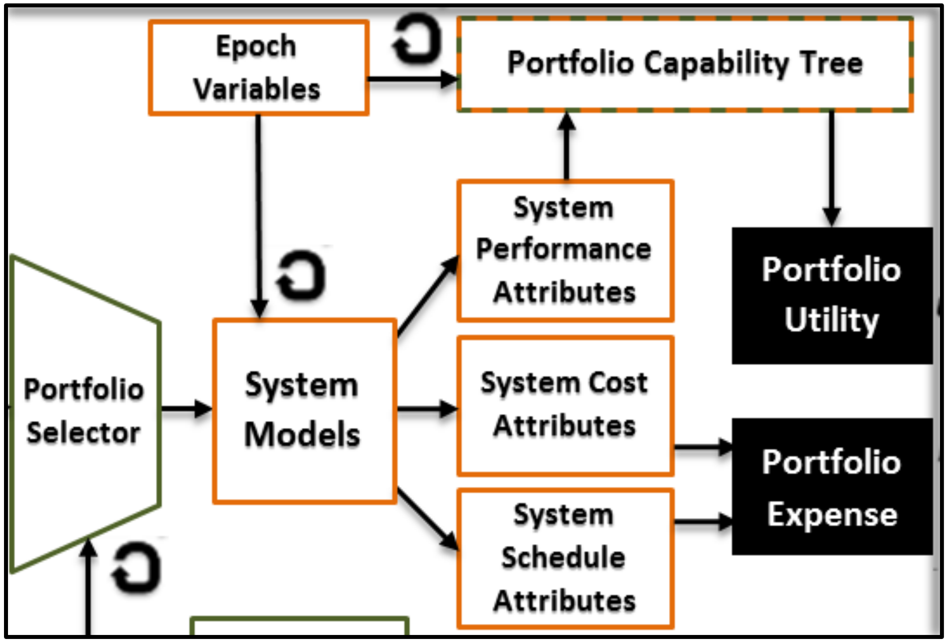

| 0 to 3 | 0 to 5 | 0 to 1 | 0 to 5 | 1 |
|---|---|---|---|---|

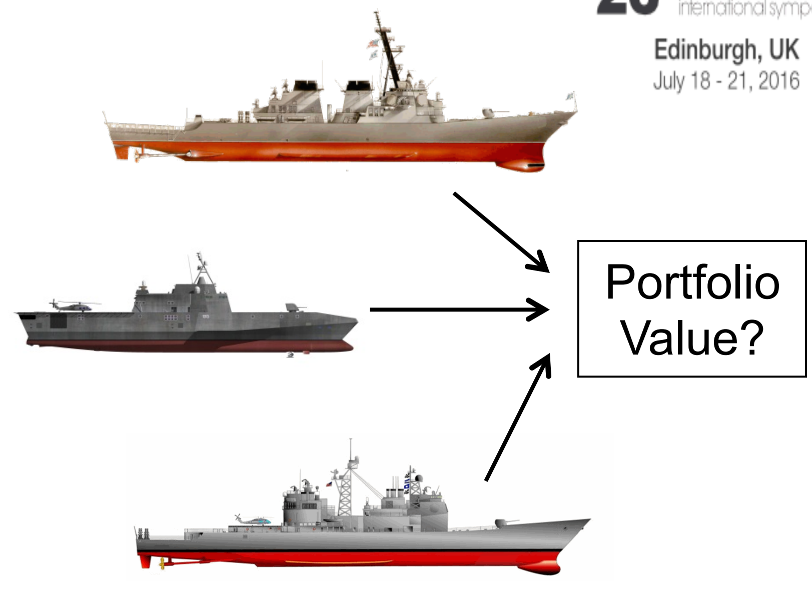
At least 2

Class constraints set specific rules for each asset class (similar to finance investment thresholds)

- Min/Max # of assets
- Min/Max cost of asset

# Constituent System Modeling

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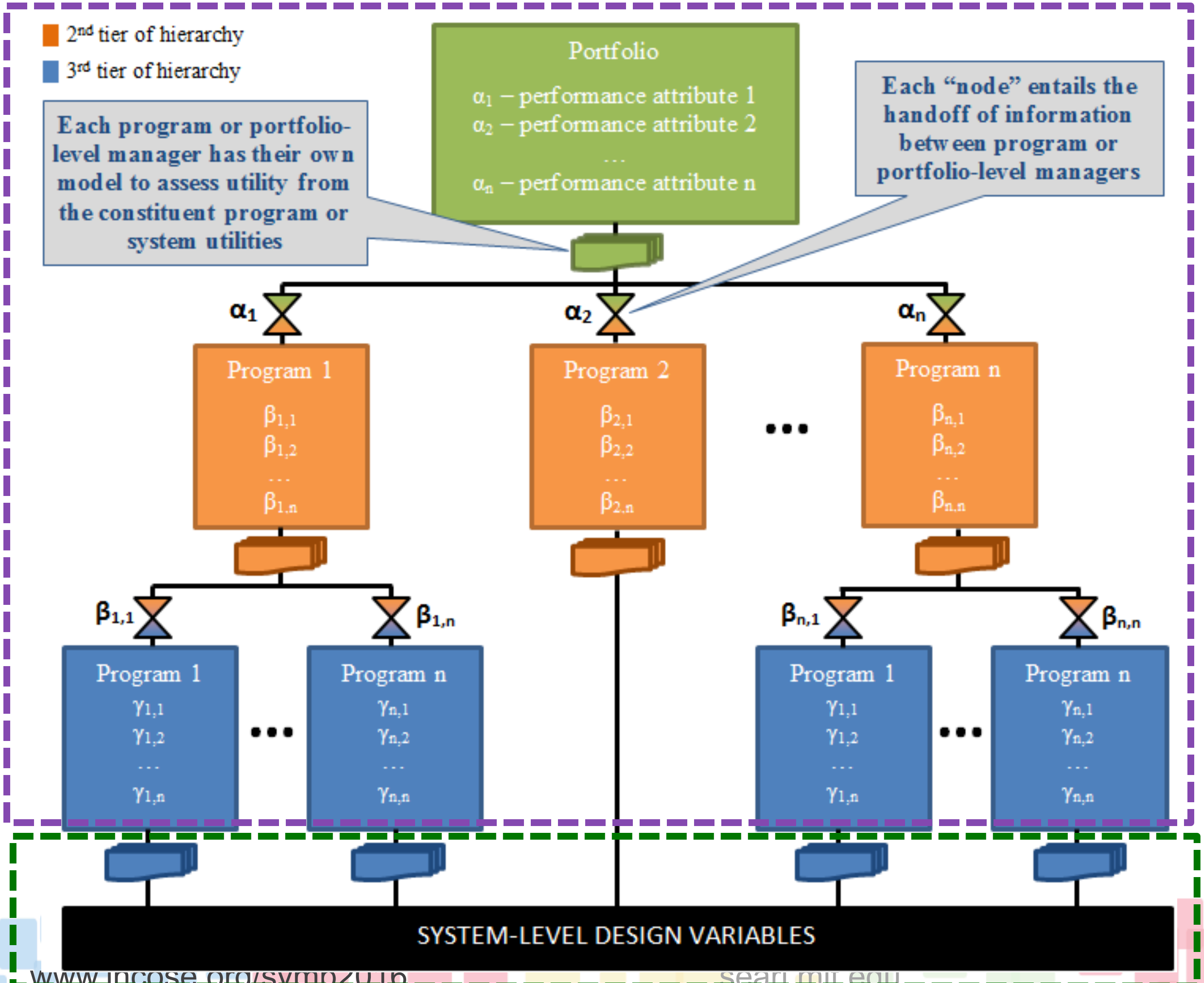
- System-level cost attributes are directly aggregated to portfolio expense
- The capability tree is a capability-based value mapping to aggregate system performance to determine portfolio utility

# Portfolio Capability Tree

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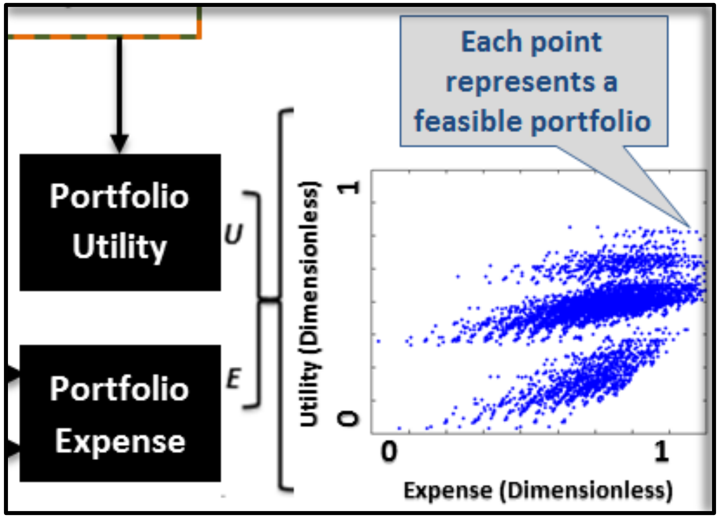
Value Model

Supports top-down transfer of needs and bottom-up aggregation of performance

Enables the consideration of complementary and substitute system impacts

Evaluation Model

# Multi-Attribute Tradespace Exploration with Epoch-Era Analysis




Tradespace of Portfolios

- Utility and Expense axes
- Multi-attribute utility theory used to describe value of portfolio performance
- Hundreds of thousands of portfolios may be visualized

EEA provides several techniques to analyze the promising portfolio designs and conduct design tradeoffs with respect to value sustainment

- Single-Epoch Analysis: identification of "promising" portfolios in isolated epochs
- Multi-Epoch Analysis: exploration of the influence of contextual uncertainty on a set of promising portfolios
- Single-Era Analysis: identification of time-dependency of promising portfolio value delivery through multiple epochs
- Multi-Era Analysis: exploration of path-dependency of promising portfolio value delivery

# CASE APPLICATION:
# CARRIER STRIKE GROUP (CSG)

# Portfolio-Level Context Definition and Design Formulation

**Identify the basic problem statement and design space for the proposed portfolio**

## VALUE PROPOSITION

"responsive, flexible capability for sustained maritime power projection and combat survivability to shape the operation environment, respond to crisis, and protect the US and allied interest in any threat environment" – Chief of Naval Operations (2010)

## PERFORMANCE ATTRIBUTES

1. Electronic warfare capability
2. Defensive capability
3. Offensive capability
4. Power projection
5. Logistics

Primary portfolio stakeholders

- Combatant commander (CCDR)
- Operational commander

## EXPENSE ATTRIBUTES

1. Acquisition cost
2. Influence cost
3. Operations cost
4. Schedule cost

## Potential Constituent Systems

| *Legacy Systems* | *Legacy Systems* | *Acquisitions* | *Upgrades* |
|---|---|---|---|
| Arleigh Burke Flight I | Nimitz with Complement | Next Generation Combat Ship (NGCS) – 6 variants | Arleigh Burke Flight I upgrade |
| Arleigh Burke Flight II | Los Angles | Arleigh Burke Flight IIA Restart | Arleigh Burke Flight II upgrade |
| Arleigh Burke Flight IIA | Virginia | Arleigh Burke Flight III | |
| Ticonderoga | Supply Class | Zumwalt | |

# CSG Capability Tree Formulation

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

*Branch* of capability tree:

| Portfolio Level | 2nd Level | 3rd Level | # of System Level Performance Attributes |
|---|---|---|---|
| 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 |

# CSG Epoch Characterization

**Seven epoch variables identified yielding a total of 2187 distinct epochs**

| EV Category | Epoch Variable | [Range] | Units |
|---|---|---|---|
| EV – Technology | Advanced Energy Weapons (AEW) | [0, 5, 40] | MW |
| EV – Technology | Unmanned Aerial Systems (UAS) | [0, 2, 5] | 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 |

**Five epochs initially selected for demonstration through the Carrier Strike Group case study**

| *Epoch Names* | *Epoch Variables* | | | | | | |
|---|---|---|---|---|---|---|---|
| | AEW | UAS | Overhaul | Budget | Cooperation | Enemy | Asymmetric |
| Baseline | 0 | 0 | 0 | 100 | 100 | Low | Med |
| Small Navy | 0 | 2 | 0 | 80 | 150 | Low | Low |
| War on Terror | 5 | 5 | 0 | 100 | 80 | Low | High |
| Major Conflict | 40 | 5 | 0 | 150 | 80 | High | Med |
| Peacekeeping | 5 | 0 | 0.5e9 | 100 | 100 | Med | Med |

# Design-Epoch-Era Tradespace Evaluation



- Based upon the 19 potential constituent systems
  - 53,108,336 unique portfolios were enumerated
  - 524,160 portfolios were evaluated
  - Between 220 and 477,916 portfolios were affordable, depending upon the epoch

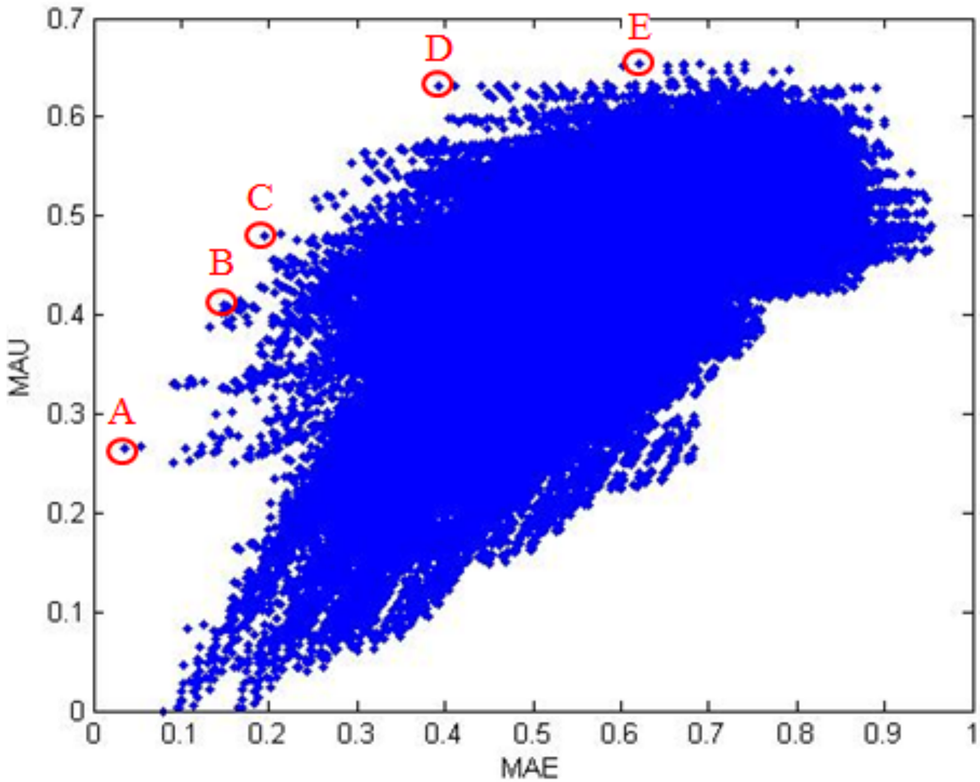
| Epoch | Valid Portfolios | Yield |
|---|---|---|
| Baseline | 173,581 | 33.1% |
| Small Navy | 220 | 0.04% |
| War on Terror | 140,398 | 26.8% |
| Major Conflict | 477,916 | 91.2% |
| Peacekeeping | 191,558 | 36.5% |

Severely limiting epoch due to a 20% budget cut and 50% rise in cooperation costs

**The PLEEAA method enables a designer to consider far more alternatives, each in numerous potential future scenarios**

# Single-Epoch Analysis

Tradespace Exploration is conducted independently in each epoch




| # | MAU | MAE | Portfolio Composition |
|---|---|---|---|
| A | 0.2651 | 0.0352 | 1 Arleigh Burke Flight III<br>1 Nimitz with Complement<br>1 Los Angles |
| B | 0.4109 | 0.1487 | 1 Arleigh Burke Flight I<br>1 Arleigh Burke Flight II<br>1 Arleigh Burke Flight III<br>1 Nimitz with Complement<br>1 Los Angles |
| C | 0.4800 | 0.1953 | 2 Arleigh Burke Flight III<br>1 Nimitz with Complement<br>1 Los Angles |
| D | 0.6305 | 0.3920 | 2 Arleigh B. Flight II Upgrade<br>2 Arleigh Burke Flight III<br>1 Nimitz with Complement<br>1 Los Angles |
| E | 0.6532 | 0.6206 | 2 NGCS Variant 6<br>2 Arleigh B. Flight II Upgrade<br>2 Arleigh Burke Flight III<br>1 Nimitz with Complement<br>1 Virginia |

**Promising portfolios are identified on the efficient frontier of each epoch**

# Multi-Epoch Analysis

**Promising portfolio designs are simultaneously explored in multiple epochs**

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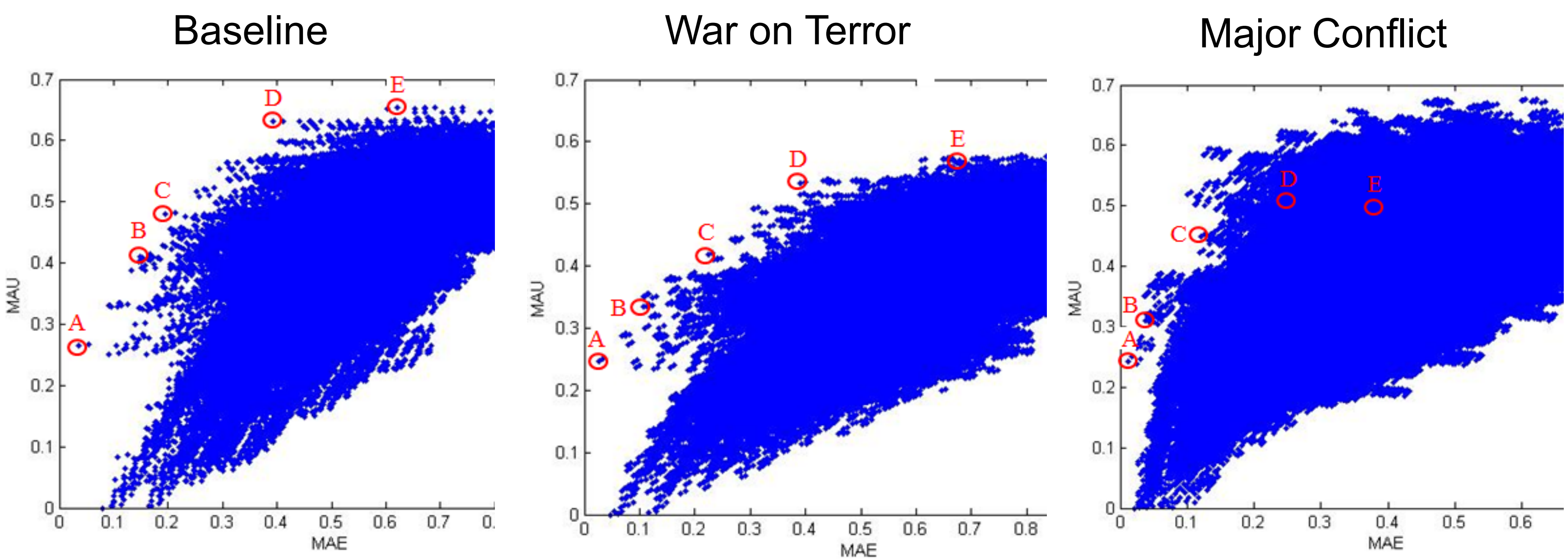


**Multi-Epoch analysis illustrates the influence of contextual uncertainty on the utility of potential Carrier Strike Group portfolios**

# Multi-Epoch Analysis

Promising portfolio designs are simultaneously explored in multiple epochs

Small Navy Epoch

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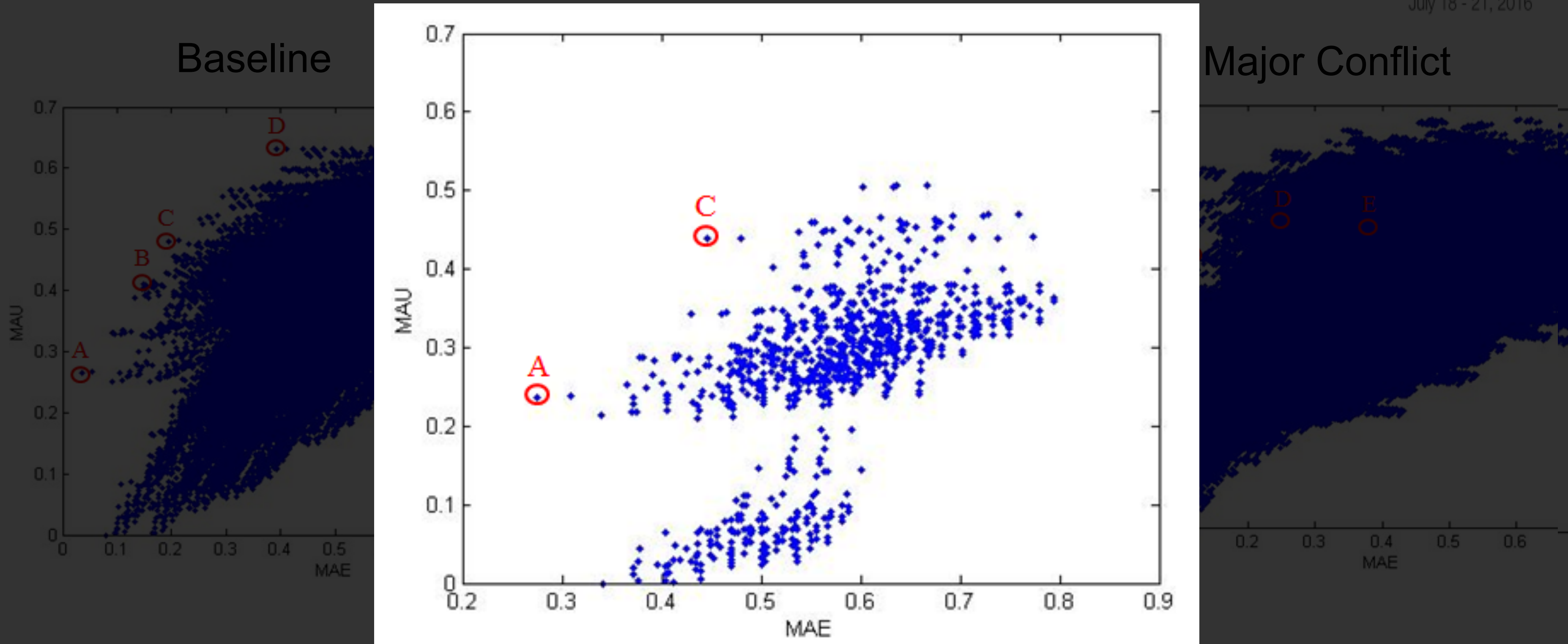
Baseline

Major Conflict




**Multi-Epoch analysis illustrates the influence of contextual uncertainty on the utility of potential Carrier Strike Group portfolios**

# CSG Era Construction



- An era is an ordered sequence of epochs
- Evaluating portfolio designs over an era illustrates the potential lifecycle value robustness of the portfolio
- Two eras were constructed from the five epochs through a narrative approach

**ERA 1**
Baseline (5yr) → War on Terror (5yr) → Peacekeeping (10yr) → Baseline (3yr) → Small Navy (7yr)

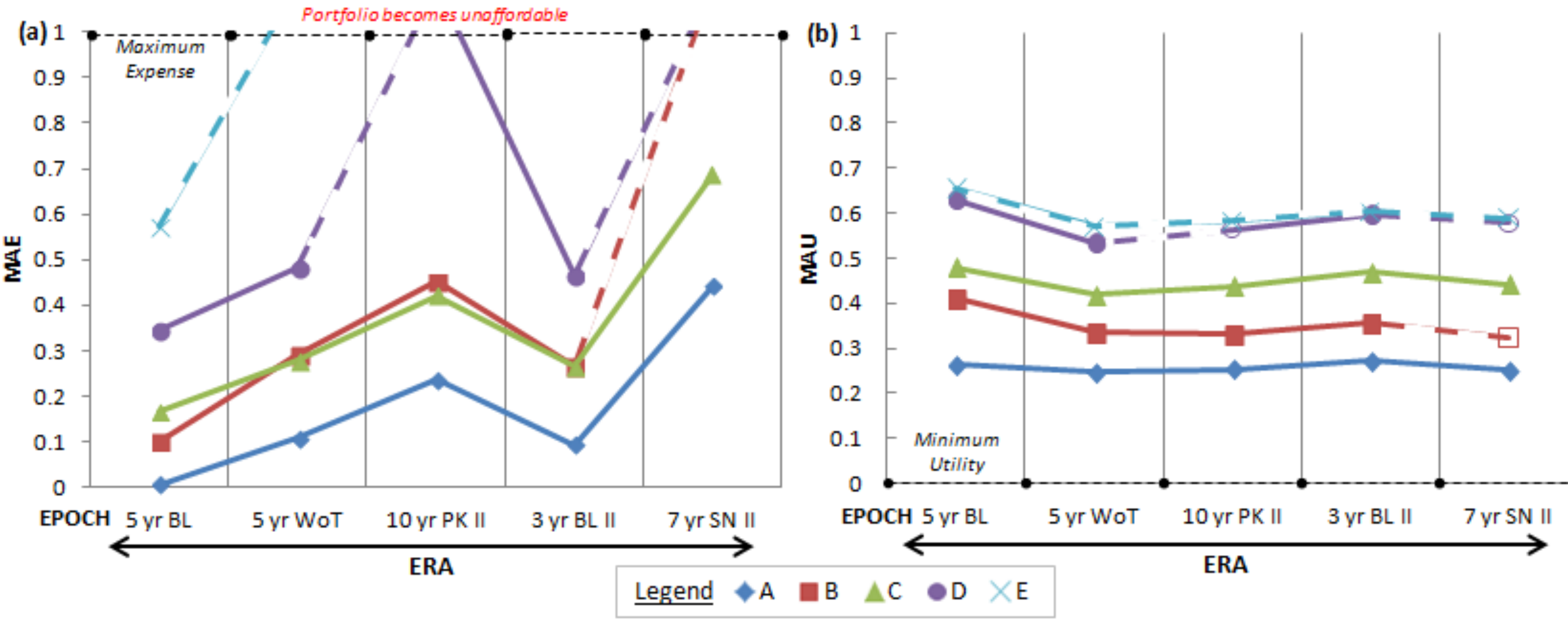
TIME →

**ERA 2**
Peacekeep. (5yr) → Small Navy (5yr) → Major Conflict (5yr) → Peacekeep. (12yr) → Baseline (3yr)

# Single-Era Analysis

**Promising portfolio designs independently explored in the constructed eras**

Baseline (5yr) → War on Terror (5yr) → Peacekeeping (10yr) → Baseline (3yr) → Small Navy (7yr)




**Single-Era Analysis enables exploration of the time-dependent affordability of promising CSG portfolios in one potential future**

# Conclusion

**Can aspects of MPT and EEA be combined to create sustained lifecycle *affordability* for engineering portfolios despite changing contexts?**

- The PLEEAA method supports portfolio design for affordability during conceptual design
  - Considers new contexts before they arrive
  - Assesses lifecycle value sustainment of potential portfolios
- The case study displays how designers and acquisitions officers may explore promising CSG portfolio value in numerous potential futures
- The initial PLEEAA method accepts the following limitations:
  - Constituent system performance, costs and degradation uncertainties are not modeled
  - All performance attributes exhibit utility independence
  - Few portfolio stakeholders exist, or they may be represented in aggregate (Arrow, 1963)
  - The portfolio operates under *directed* management (Maier, 1998)

# Questions?

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# Support Slides

# Multi-Attribute Tradespace Exploration

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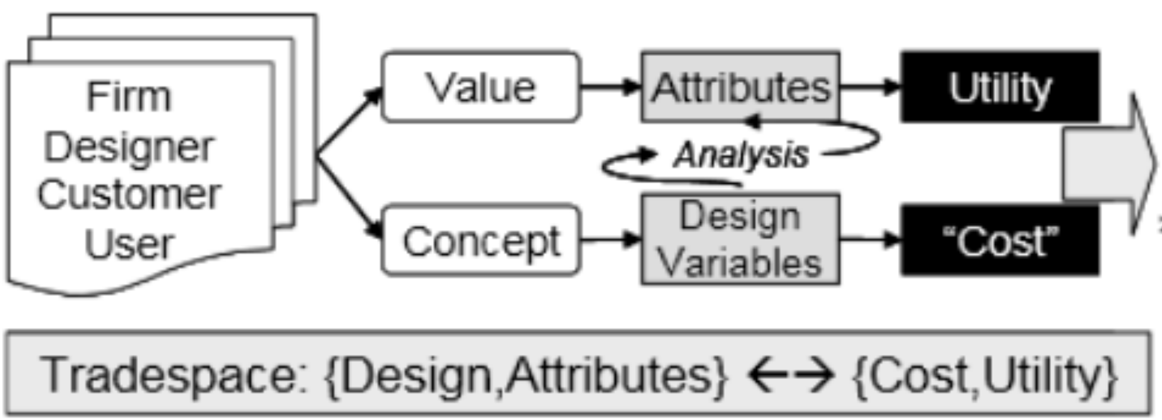
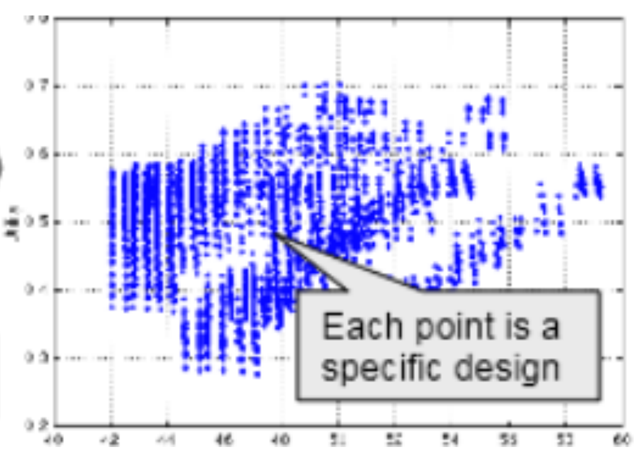
- Engineering portfolio design has traditionally revolved around Analysis of Alternatives studies concerning a few promising point designs
- Multi-Attribute Tradespace Exploration (MATE) enables designers to consider a far greater set of alternatives for affordability (Wu et.al, 2014)



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# System, Program and Portfolio

Acquisition and development efforts face different challenges and opportunities contingent on the scope of the design abstraction

System-Level: Design that is inclusive of a singular major architectural element that is semi-independent from the remainder of the architecture

Program-Level: Design that requires joint consideration of multiple independent or semi-independent constituent elements such that each element fulfills a common set of capability requirements subject to identical stakeholder value metrics

Portfolio-Level: Design that seeks to create a collection of heterogeneous assets, both from legacy and new sources, that can collectively provide a set of emergent capabilities through the aggregate performance of each constituent system

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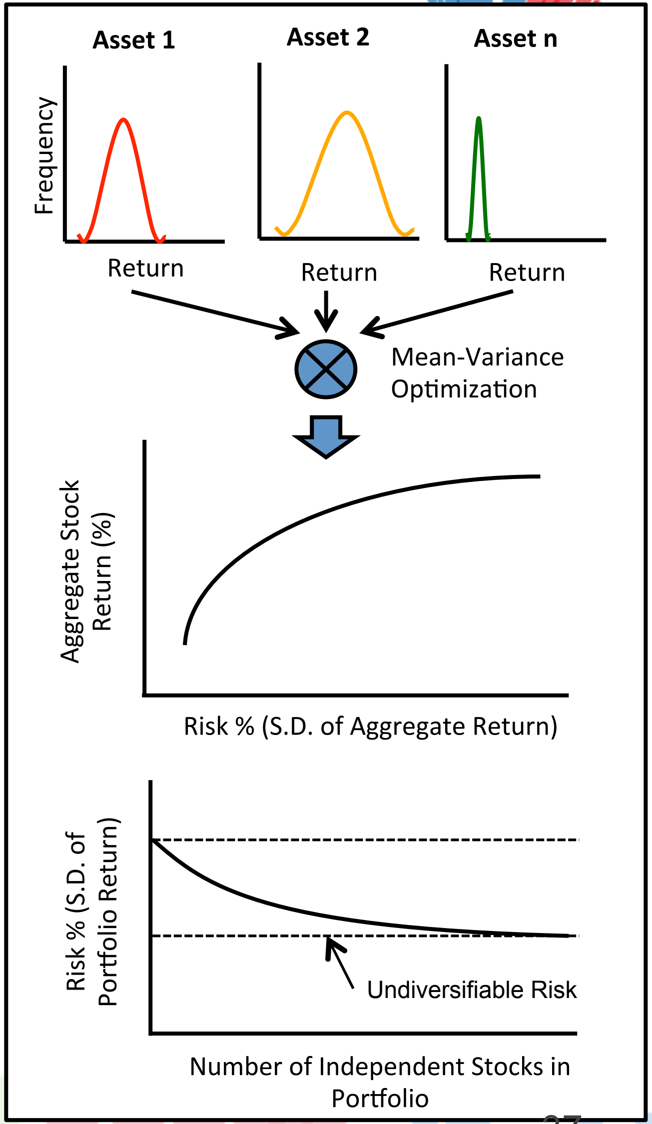
# Modern Portfolio Theory

- Utilized by financial institutions and operations research since the 1950's
- Constructs groupings of investments that maximize return (utility) subject to an acceptable threshold of risk (cost)
- Result in an "efficient frontier" of potential investment sets
- Relies upon negative trending covariance in diversified assets to reduce aggregate risk, or mean-variance optimization
- A variety of MPT derivatives exist that introduce non-normally distributed risks and semi-variance among assets



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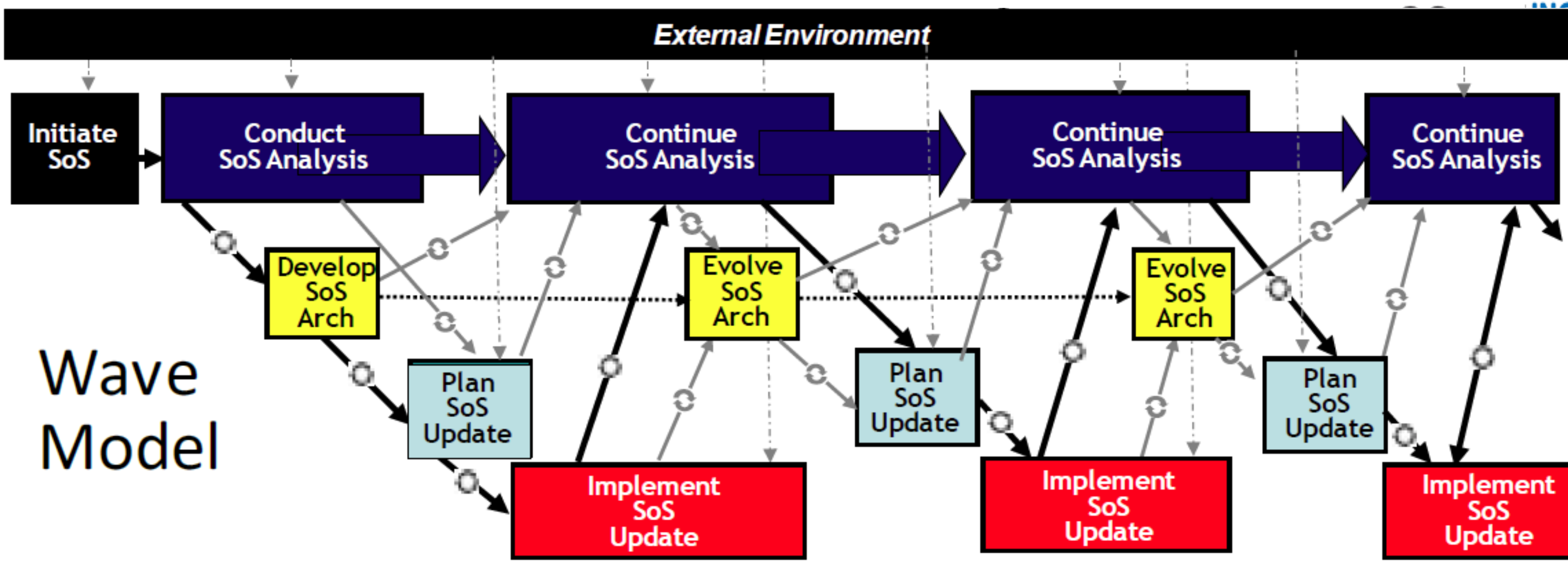
# Wave Model of SoS Design




Wave Model

(Baldwin, Dahmann , Rebovich, Lane, & Lowry, 2011)

- “Time-sequenced”, or adaptive approach to SoS construction
- Iterates to identify and respond to uncertainty/changes in context
- Risks requirement creep, spiraling design and rising costs

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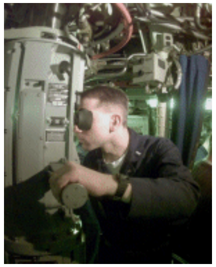
# Constituent Systems Considered

| Potential Constituent System | Legacy Variants | New Variants | Upgrade Variants | Selected for Case Study |
|---|---|---|---|---|
| Next Generation Combat Ship (NGCS) | 0 | 6 | 0 | 6 new variants |
| Arleigh Burke Class Destroyer | 3 | 2 | 2 | All 7 variants |
| Ticonderoga Class Cruiser | 2 | 0 | 0 | 1 legacy variant |
| Zumwalt Class Destroyer | 0 | 1 | 0 | 1 new variant |
| Nimitz Class Aircraft Carrier | 1 | 0 | 0 | 1 legacy variant |
| Los Angles Class Submarine | 1 | 0 | 0 | 1 legacy variant |
| Virginia Class Submarine | 1 | 0 | 0 | 1 legacy variant |
| Supply Class fast combat support ship | 1 | 0 | 0 | 1 legacy variant |
| F/A-18 Aircraft | 4 | 0 | 0 | None |
| F/A-35 Aircraft | 2 | 0 | 0 | None |
| E-2 Aircraft | 2 | 0 | 0 | None |
| EA-6B Aircraft | 1 | 0 | 0 | None |
| EA-186 Aircraft | 1 | 0 | 0 | None |
| SH-60 Helicopter | 5 | 0 | 0 | None |
| C-2A Helicopter | 1 | 0 | 0 | None |

# Complementary and Substitute Systems

Return




http://www.navsource.org/archives


http://www.navy.mil/navydata

<u>Complementary Systems</u>

- Value delivery enhanced in at least one performance attribute
- Gain new capability in a performance attribute
- Often results from a change to the system's CONOPS

<u>Substitute Systems</u>

- Simultaneous, overlapping value delivery in a performance attribute
- Often dependent upon the CONOPS
- Systems may be substitute in one performance attribute, but not necessarily in others

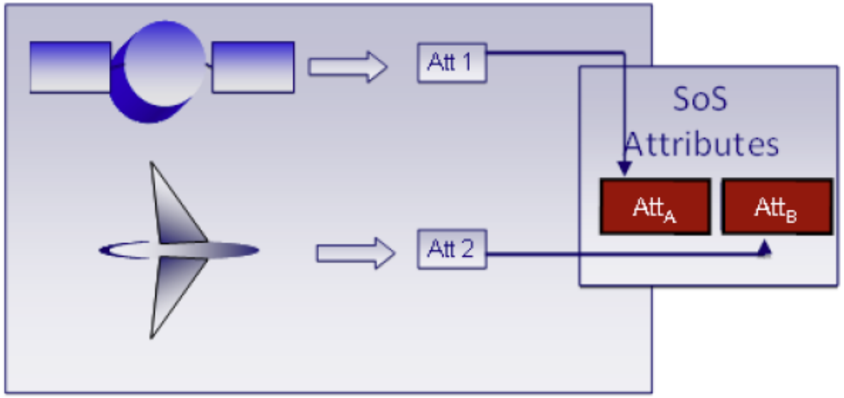
**PLEEAA, provides two mechanisms to address complementary and substitute systems through the capability tree architecture**

**1. SME matching with potential interaction opportunities**

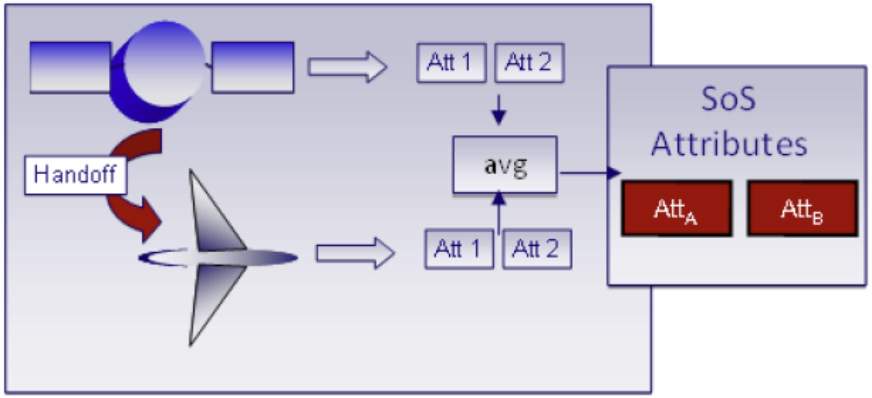
**2. Level of Combination Complexity adjustment factors (Chattopadhyay, 2009)**

# Performance Aggregation Approaches for Constituent Systems

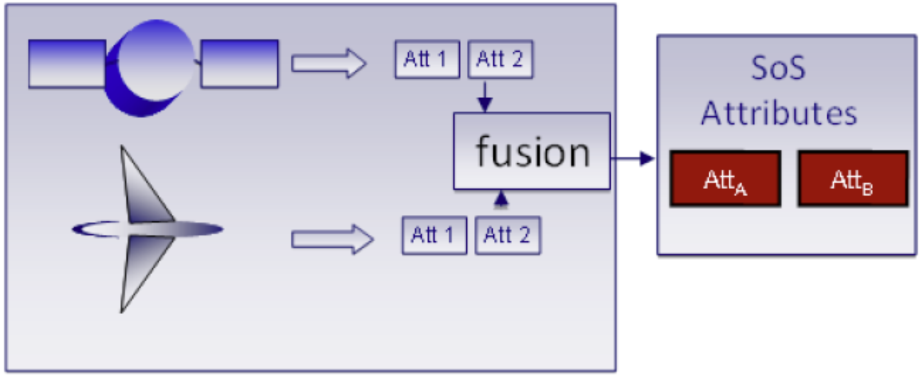
Return




‘Low’ Level Combination



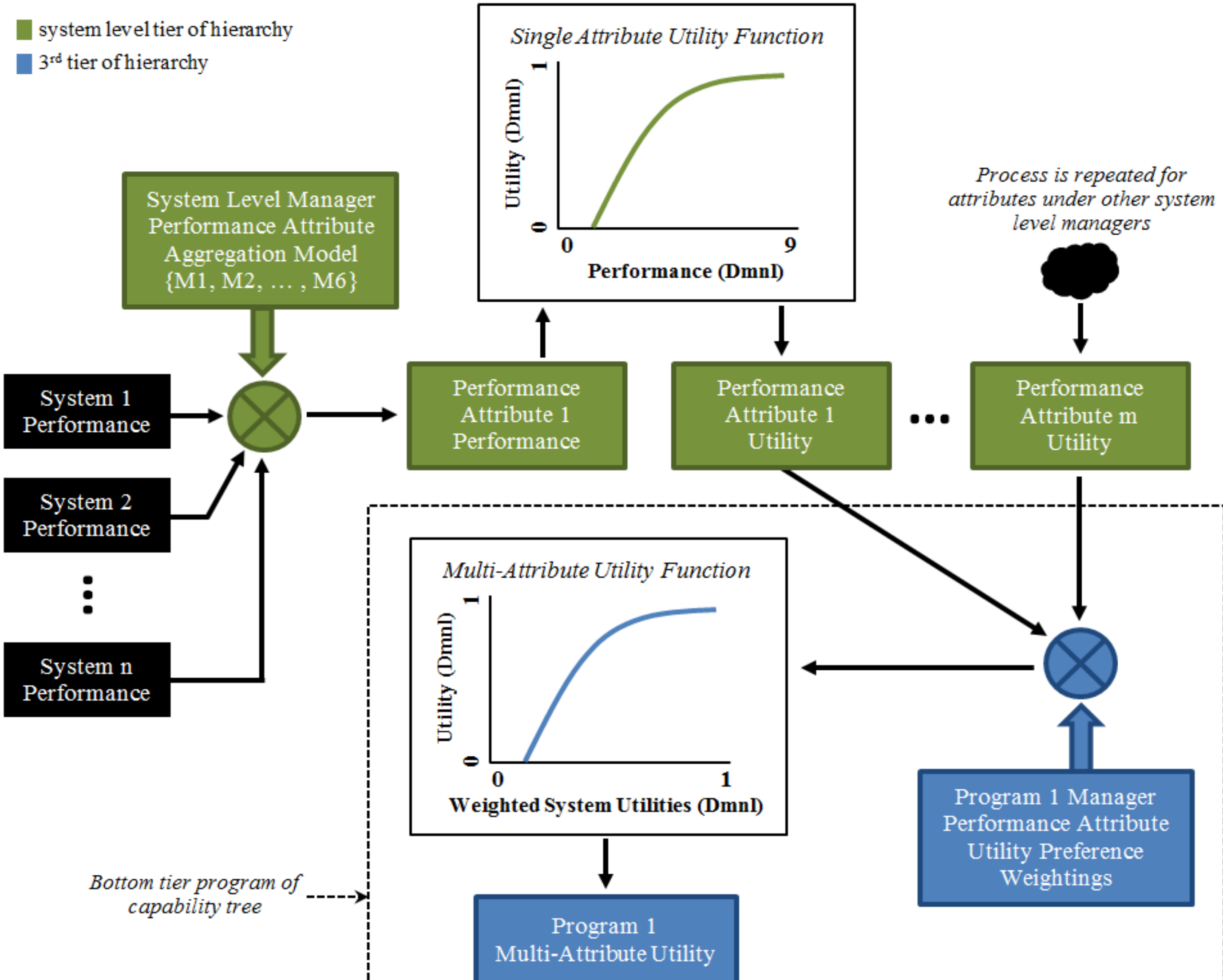

‘Medium’ Level Combination




‘High’ Level Combination

(Chattopadhyay, 2009)

# Performance Aggregation and Utility Development



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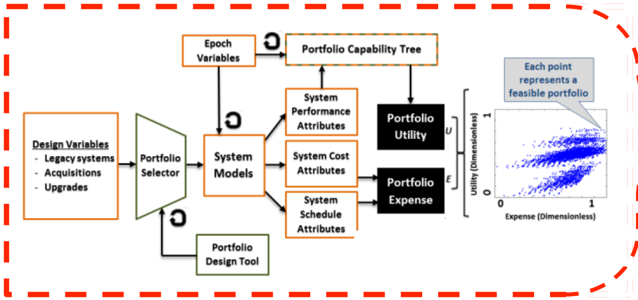
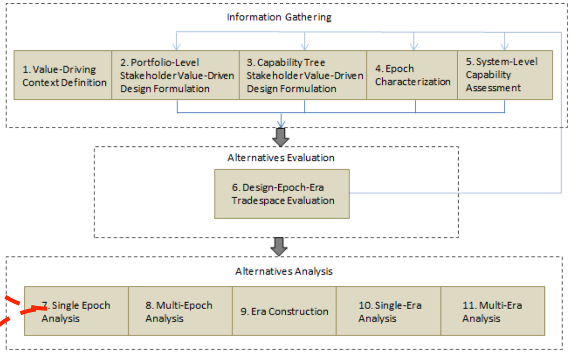
# Performance and Cost Aggregation Models for Constituent Systems

| Model | Description of Approach |
|---|---|
| **M1** | A summation of the average performance of each major system class: $\sum[\sum[(v_{NGCS} * \varphi), (v_{AB,Tico} * \varphi), (v_{ABIII,Zmwlt} * \varphi)]/3, (\bar{v}_{LA,VA} * \varphi), (v_{Nimitz} * \varphi), (v_{supply} * \varphi)]$<br>$v$ is the performance capability of the system for the attribute in consideration<br>$\bar{v}$ represents the average performance capability of systems in that category<br>$\varphi$ is a multiple unit function which adjusts performance if more than one unit of a system type is present: $\varphi = \sum_{i=1}^{n} \frac{1}{i}$ where n is the number of units of a system type |
| **M2** | The mean of all non-zero constituent system performance capabilities: $(\sum_{i=1}^{s}(v_i * \varphi > 0))/s$<br>$s$ is the number of different potential systems (19 for the CSG case study) |
| **M3** | The maximum performance from any constituent system performance ranking: $\bigvee_{i=1}^{s}(v_i * \varphi)$ |
| **M4** | A summation of the constituent system performance capabilities, weighted by the relative contribution of the constituent system to the highest preferred program manager attribute: $\sum_{i=1}^{s}\left(v_i * \varphi * \frac{x_i}{x_P}\right)$<br>$x$ is the system performance capability for the most desired program manager attribute<br>$x_P$ is the portfolio performance capability for the most desired program manager attribute |
| **M5** | The mean of all constituent system performance capabilities: $(\sum_{i=1}^{s}(v_i * \varphi))/s$ |
| **M6** | The summation of all constituent system performance capabilities: $\sum_{i=1}^{s}(v_i * \varphi)$ |

# Responsive Systems Comparison Augmentation with PLEEAA




(Schaffner et al. 2013)

# Promising Portfolio Constituent System Investment Comparisons

Return

| 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 | Virgina | 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 | | |

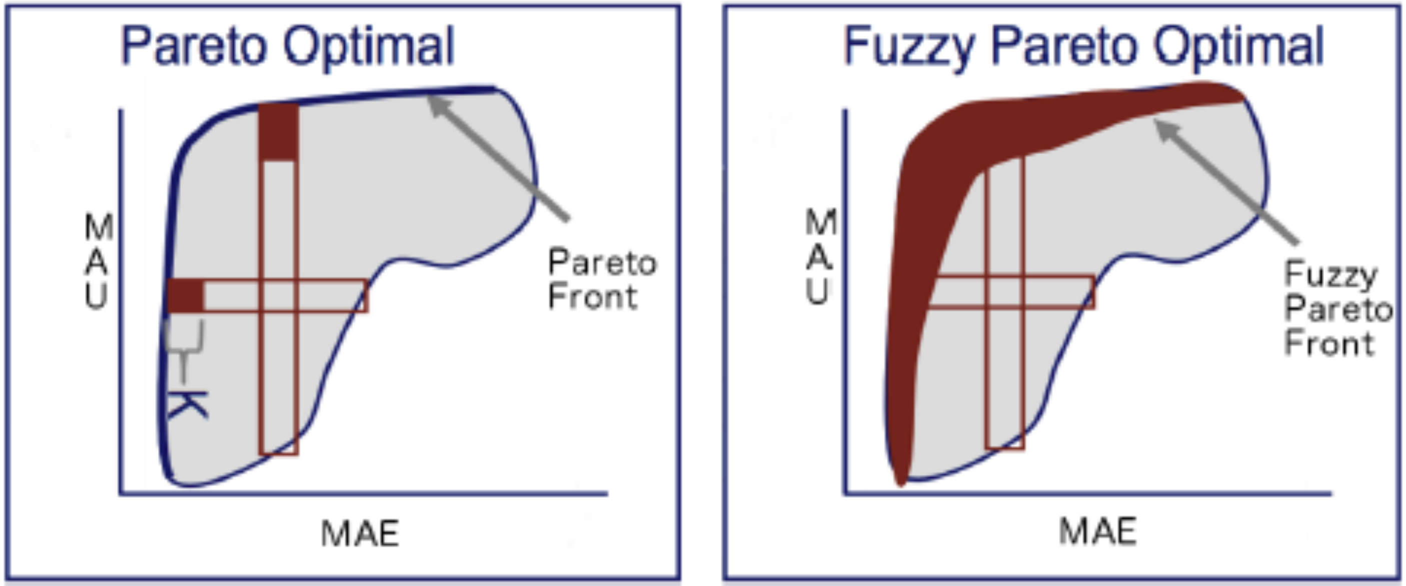
Potential Constituent Systems

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

- Portfolios A and C are contain the identical constituent systems, albeit varying numbers of each system
- Well performing portfolios with similar composition may identify complementary constituent system interaction or latent value robustness

Return

# Fuzzy Normalized Pareto Trace




- Describes the percent of epochs for which a design is within a certain threshold of the efficient front
- Width of threshold defined by a constant, K

**Useful concept to assess portfolio performance across multiple epochs and reveal *passive robust solutions***

Return

# Fuzzy Normalized Pareto Trace

| 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 |

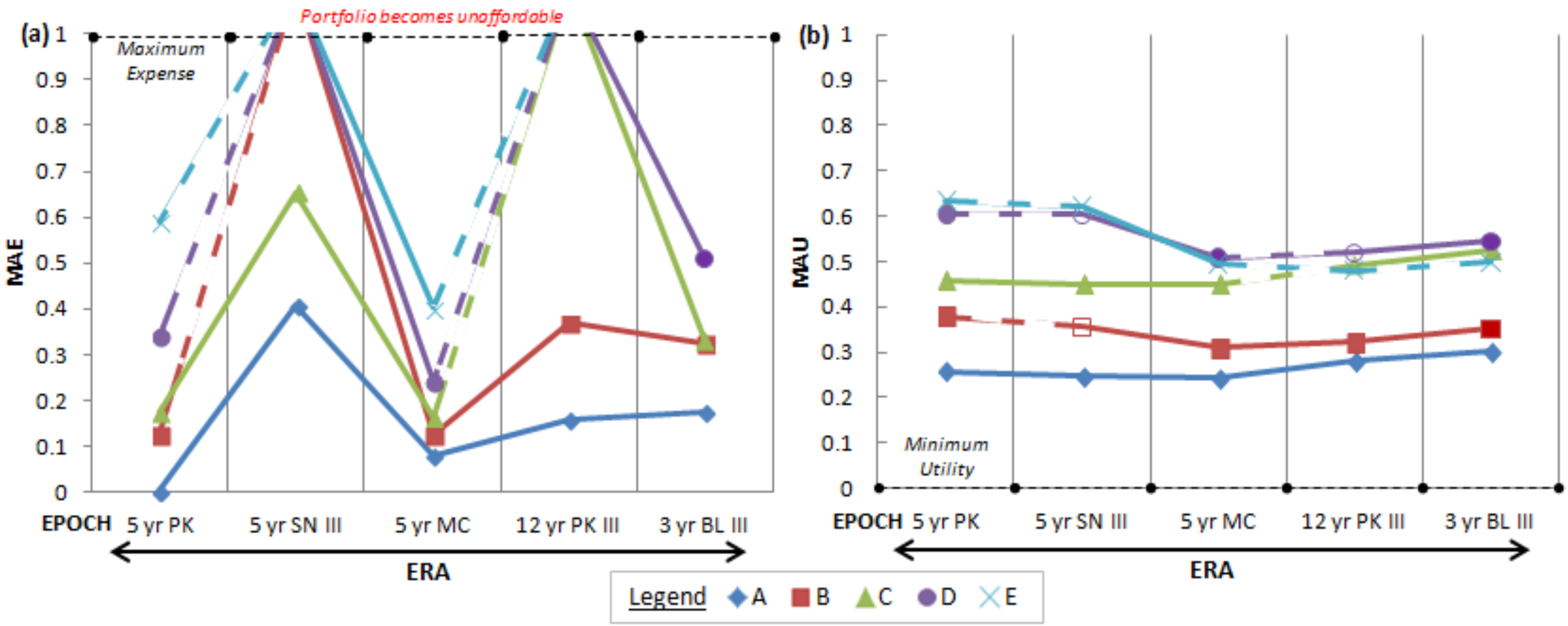
- Portfolio A is on efficient front in all epochs considered
- While Portfolio C is only on the efficient front in 60% of the epochs, it lays within 10% of the Pareto front for all five epochs
- Not other portfolios are within 20% of the efficient front for all epochs indicating significantly increased cost or reduced performance

Return

# Single-Era Analysis

**Promising portfolio designs independently explored in the constructed eras**

Baseline (5yr) → War on Terror (5yr) → Peacekeeping (10yr) → Baseline (3yr) → Small Navy (7yr)




**Single-Era Analysis enables exploration of the time-dependent affordability of promising CSG portfolios in one potential future**

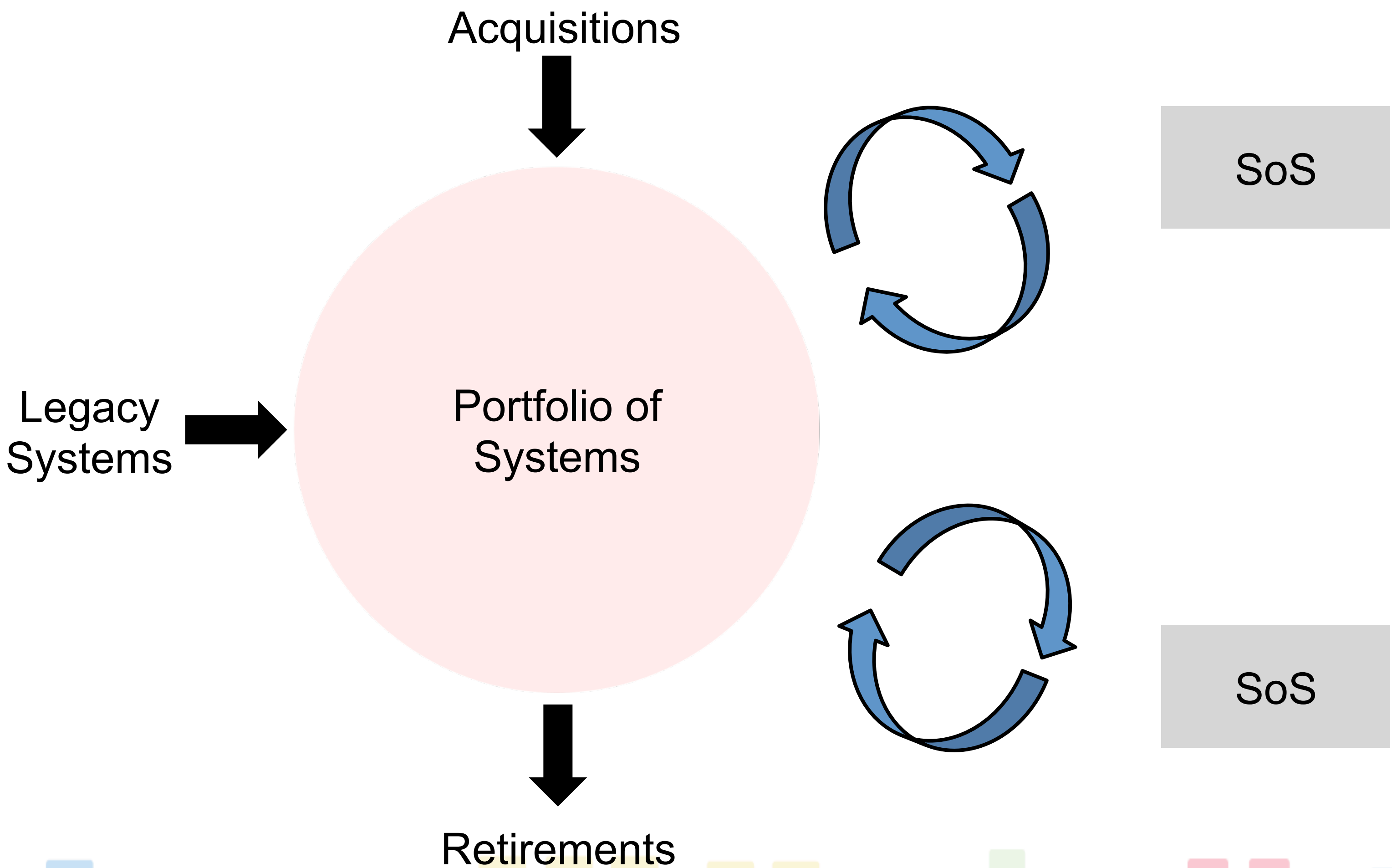
# SoS Relation to Portfolios

26th annual INCOSE international symposium
Edinburgh, UK
July 18 - 21, 2016

- A System of Systems 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 that 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

# SoS Relation to Portfolios



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# Value-Centric Design Methodologies

26th annual INCOSE international symposium
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- A Value-Centric Design Methodology, as opposed to a requirements or cost-related design approach, link together physics and cost-based system models with a valuation model to provide system selection criteria based on *derived* system value (Ross et al., 2010a)

- Value-Centric Design Methodologies include
  - Net Present Value
  - Cost-Benefit Analysis
  - Multi-Attribute Utility Theory
  - Cumulative Prospect Theory
  - Value Functions
  - Analytic Hierarchy Process
  - Technique for Order Preference by Similarity to Ideal Solution

Return

# Value-Centric Design Methodologies

- Ross et al. 2010a presents a framework for assessing how well the conditions and assumptions of an analysis meet the needs and limitations of the various VCDM techniques

- MAUT was deemed the most appropriate VCDM for engineering portfolio design
  - Value is an aggregation of a set of benefits relative to their net cost; it is difficult to monetize
  - Value is derived from multiple benefits and costs, not simply profits
  - Mutual Utility Independence versus Mutual Additive Independence (preferential independence) enables consideration of substitution and complementary affects among attributes

Return



# Multi-Attribute Utility Theory (MAUT)

Governing Equation:

$$K * U(\hat{X}) + 1 = \prod_{i=1}^{n} (K * k_i * U(X_i) + 1)$$

Normalization Constant:

$$K = -1 + \prod_{i=1}^{n} (K * k_i + 1)$$

If the performance attribute swing weights sum to one (i.e. preferential independence of attributes), K = 0

Additive Utility Function:

$$U(\hat{X}) = \sum_{i=1}^{n} k_i * U(X_i)$$

Return

# Future Work

26th annual INCOSE international symposium
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- The work conducted in this research represent initial efforts to extend EEA to the portfolio-level of design
- Numerous opportunities exist to improve the PLEEAA method and expand the set of problems to which it may be applied:
  - Stochastic/probabilistic modeling for system-inherent uncertainty
  - Dynamic entry and exit of systems from portfolios (technology infusion)
  - Usage of multiplicative utility equation to consider utility dependent attributes
  - Enhanced collaboration costs and “likelihood of participation” factors (Shah, 2013)
  - Design for “graceful degradation” capability
  - Co-design features to identify system-level design requirements to complement portfolio
  - Expanded schedule cost factors
- A regime of validation tests also need to be conducted