26th annual INCOSE international symposium

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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

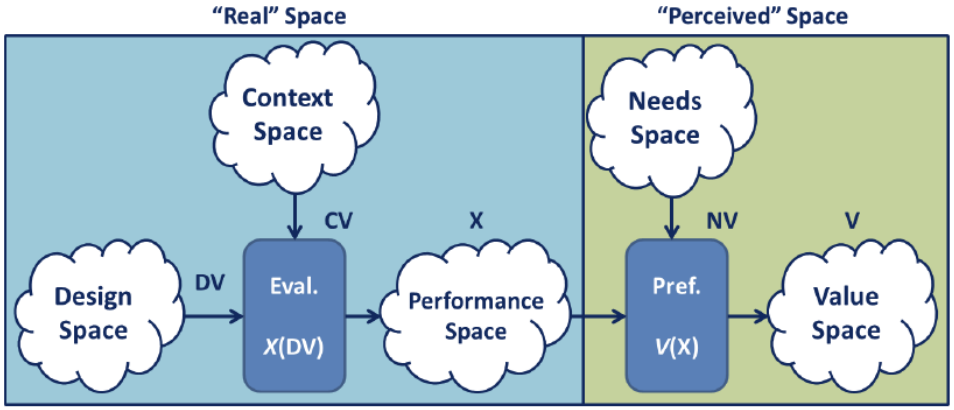
Many systems exist in a global environment that will inevitably experience dramatic, dynamic shifts in context

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)

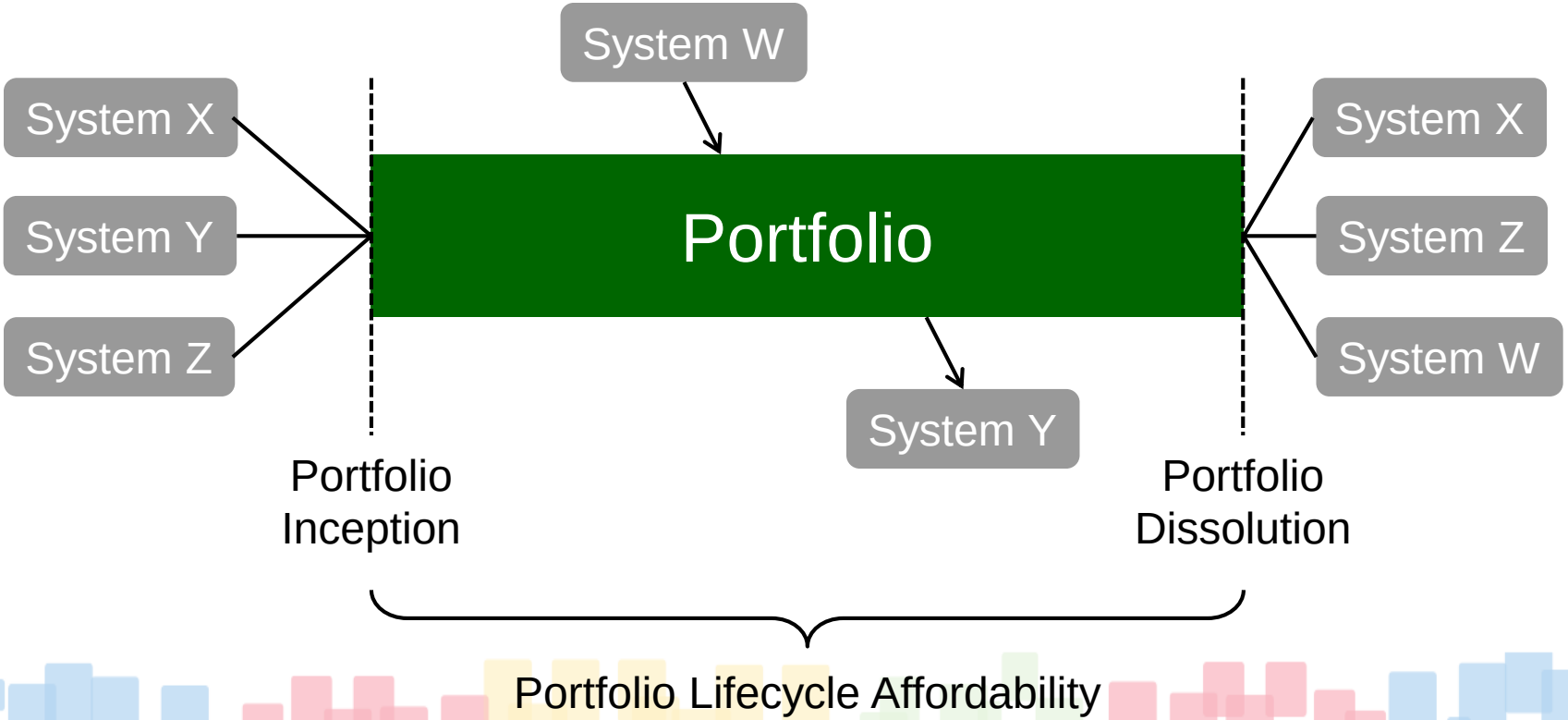
http://www.navsource.org/archives

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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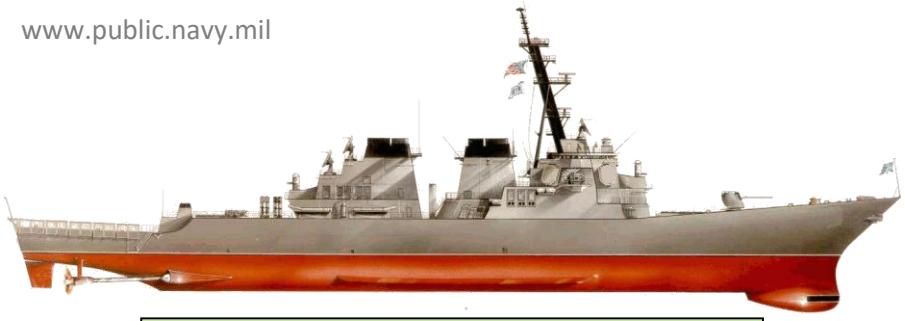


System-Level: a singular major architectural element

Program-Level: multiple elements fulfilling common capability requirements

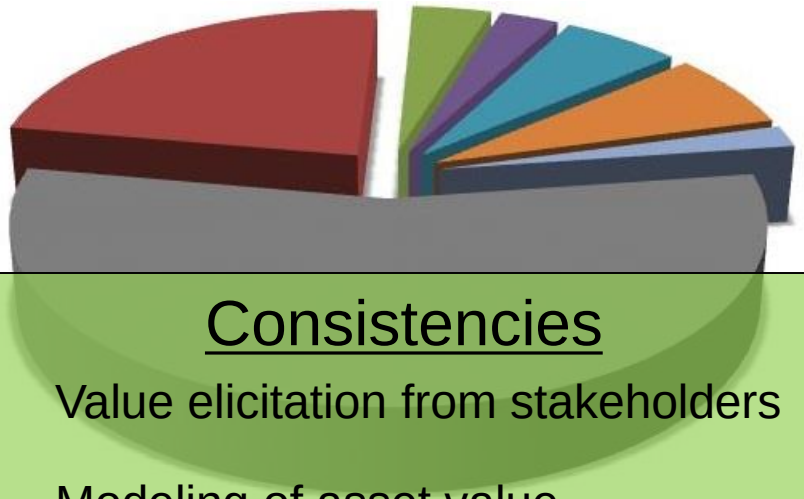
Portfolio-Level: multiple elements that collectively fulfill a set of joint capability requirements

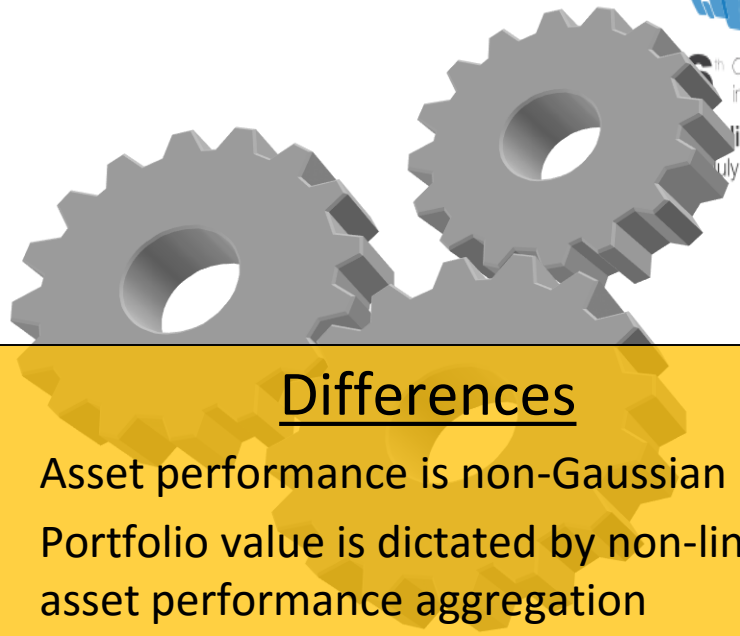
Portfolio-Level Design

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

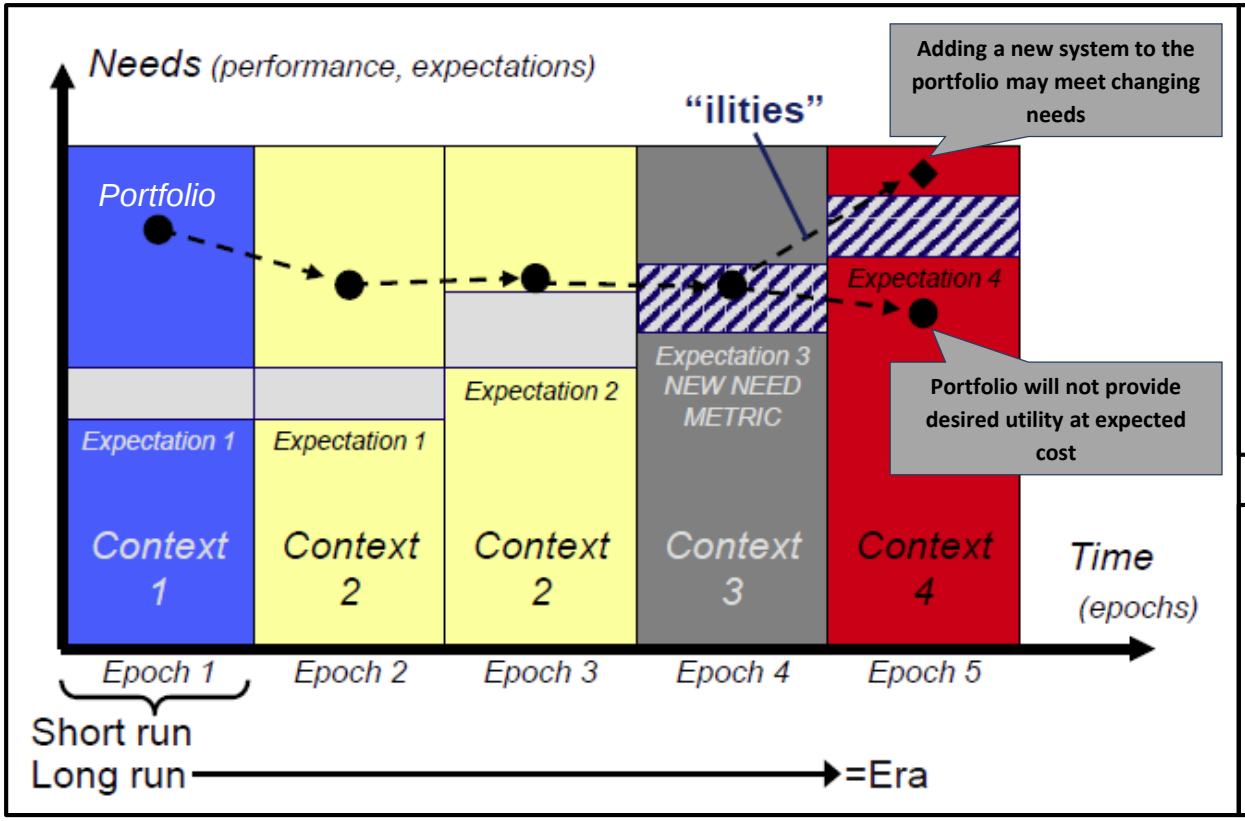
- Value elicitation from stakeholders
- Modeling of asset value
- Founded in utility theory
- Identifies “efficient frontier” of potential alternatives

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

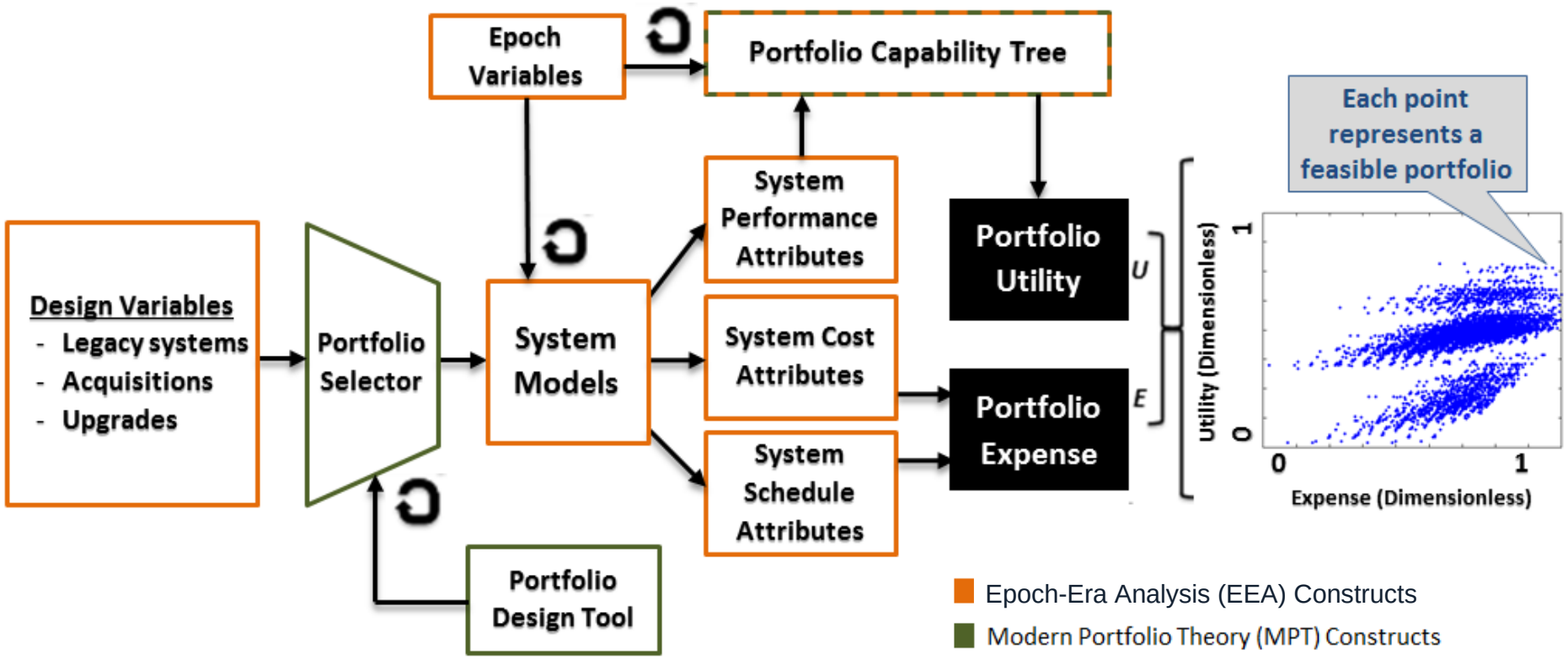
- **Portfolio**
- **Portfolio Trajectory**
- **Expectations**

(Ross & Rhodes, 2008)

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

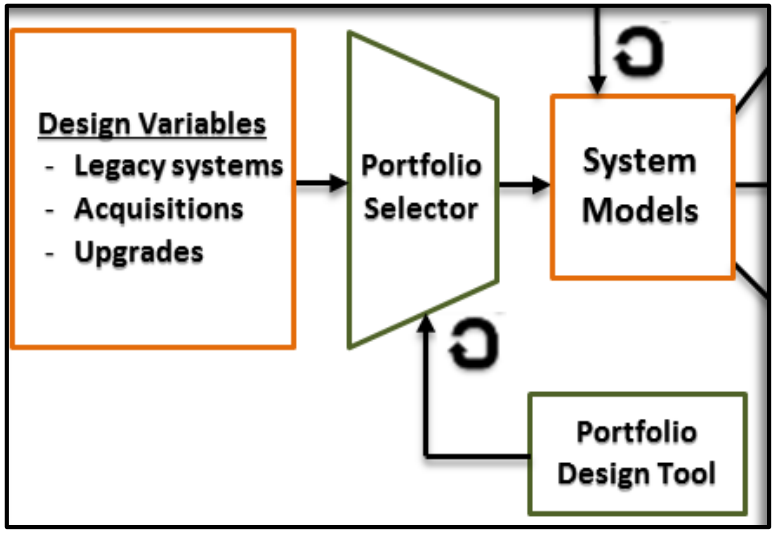
JOINT EEA AND MPT METHOD TO SUPPORT DESIGN FOR AFFORDABILITY

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

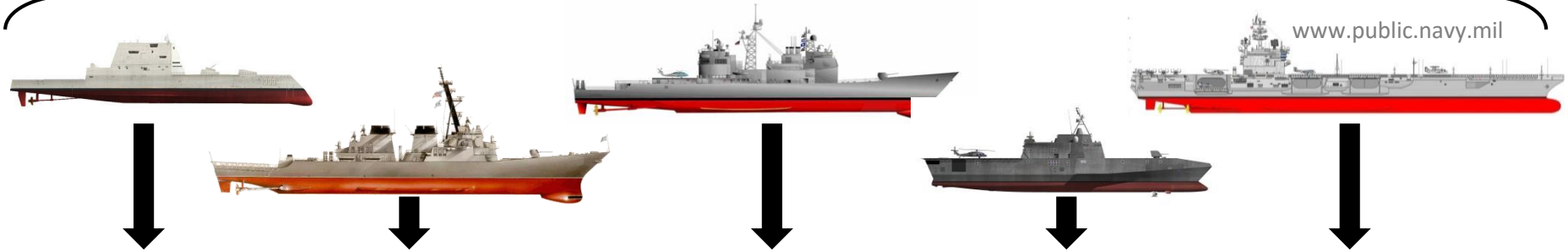
- Compiles a specific portfolio for modeling

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



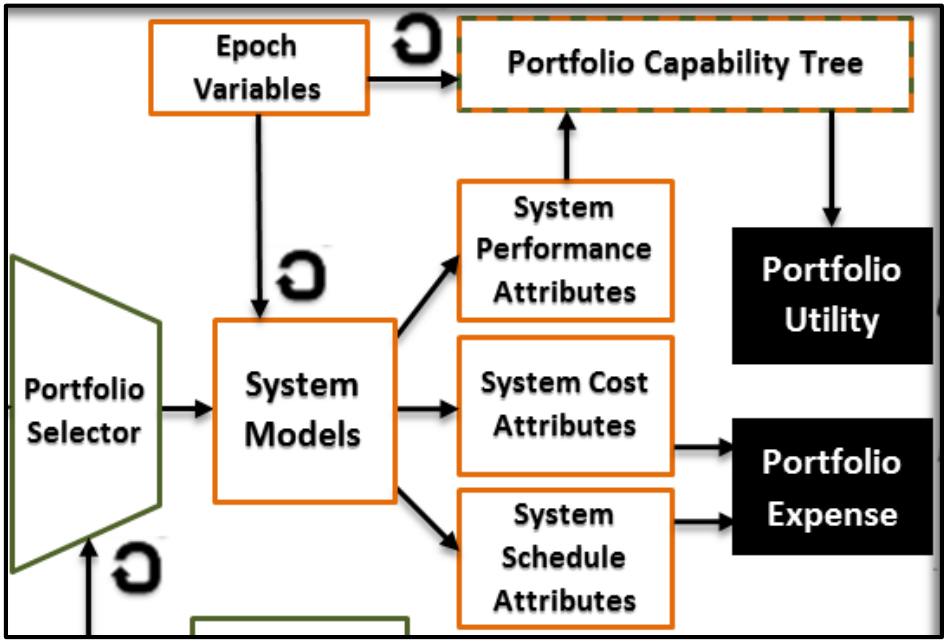
0 to 3 | 0 to 5 | 0 to 1 | 0 to 5 | 1

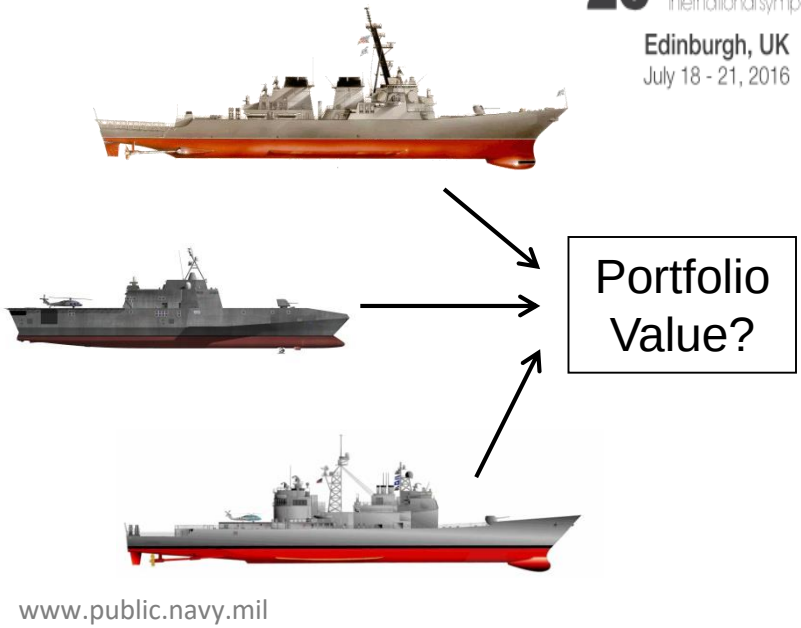
At least 2

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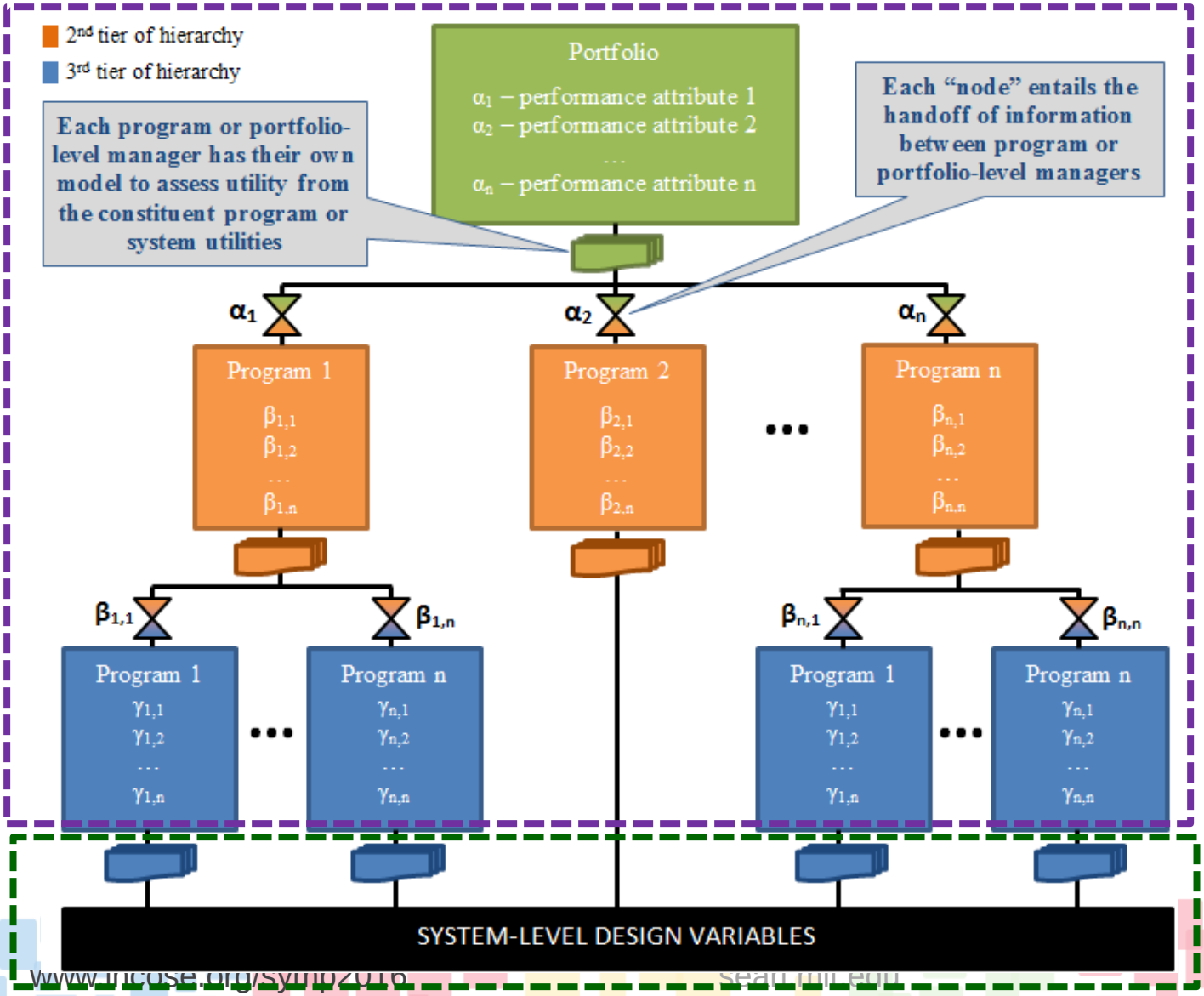
- System-level cost attributes are directly aggregated to portfolio expense
- The capability tree is a capability-based value mapping to aggregate system performance to determine portfolio utility

Portfolio Capability Tree



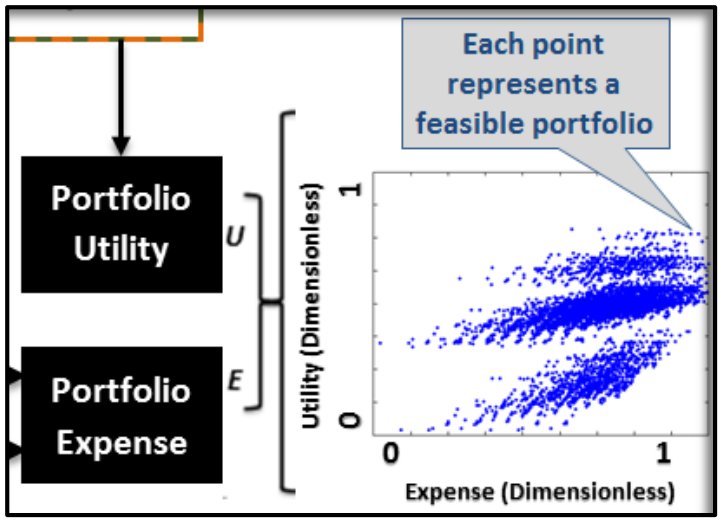
Value Model

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

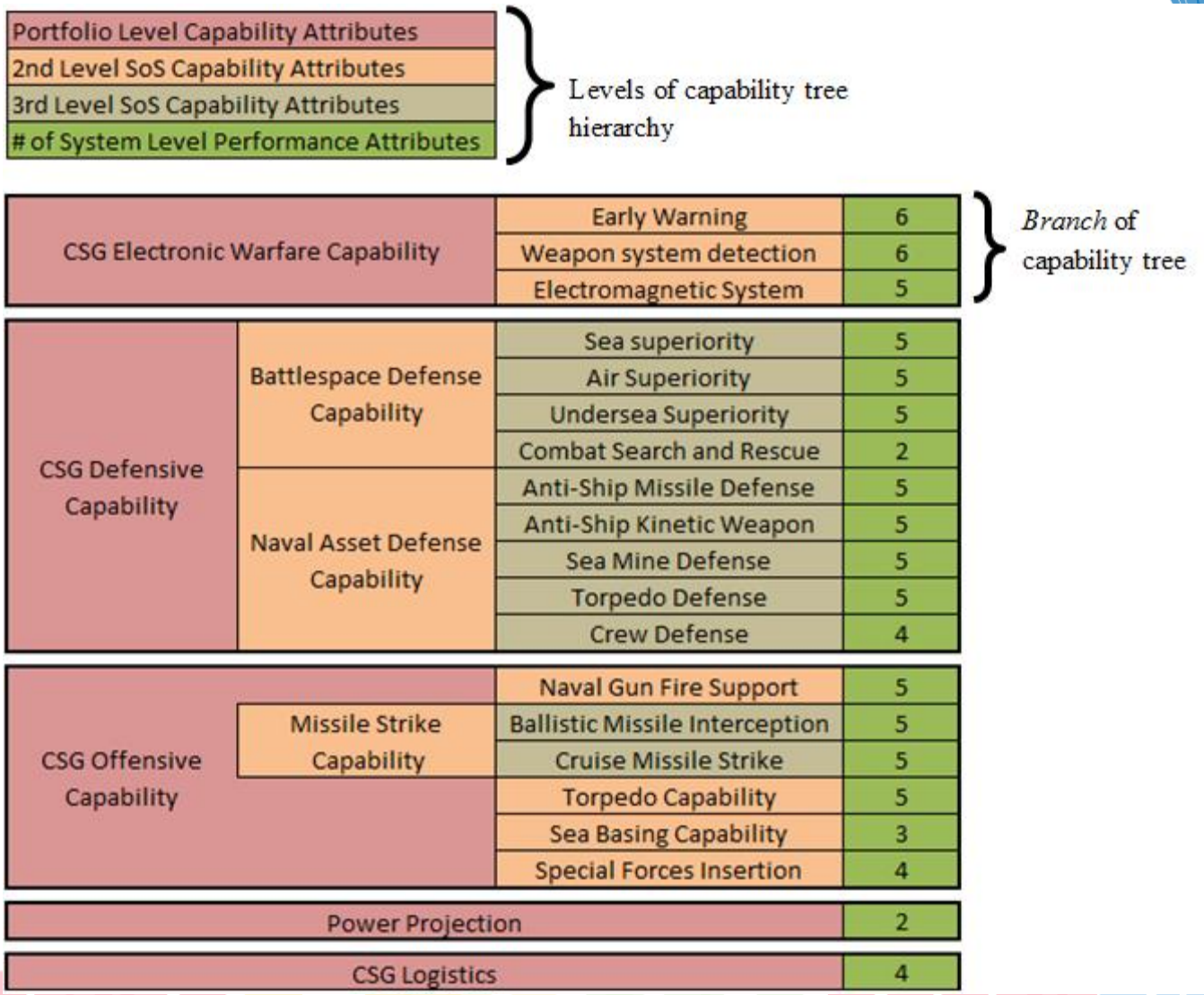
EXPENSE ATTRIBUTES

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



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

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- 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

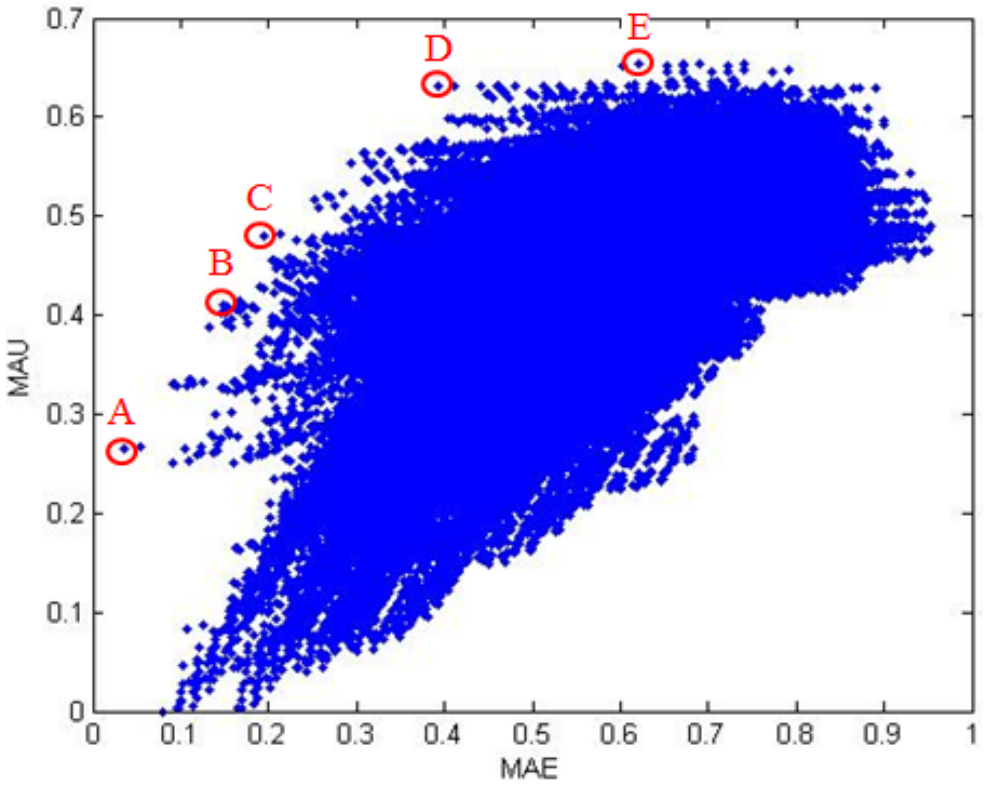
Epoch	Valid Portfolios	Yield
Baseline	173,581	33.1%
Small Navy	220	0.04%
War on Terror	140,398	26.8%
Major Conflict	477,916	91.2%
Peacekeeping	191,558	36.5%

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



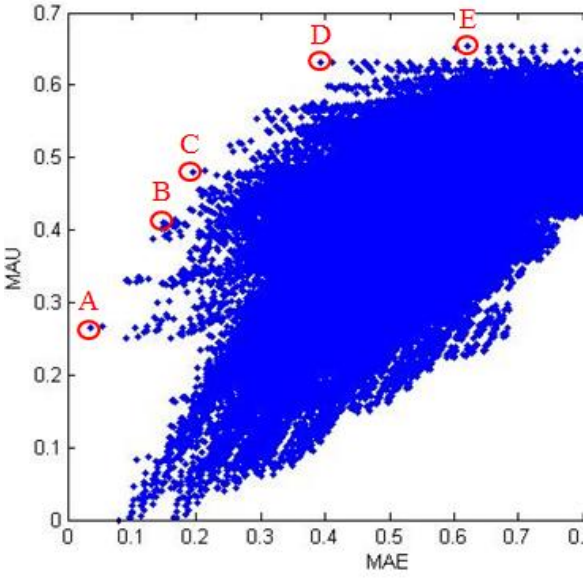
#	MAU	MAE	Portfolio Composition
A	0.2651	0.0352	1 Arleigh Burke Flight III 1 Nimitz with Complement 1 Los Angles
B	0.4109	0.1487	1 Arleigh Burke Flight I 1 Arleigh Burke Flight II 1 Arleigh Burke Flight III 1 Nimitz with Complement 1 Los Angles
C	0.4800	0.1953	2 Arleigh Burke Flight III 1 Nimitz with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

Promising portfolios are identified on the efficient frontier of each epoch

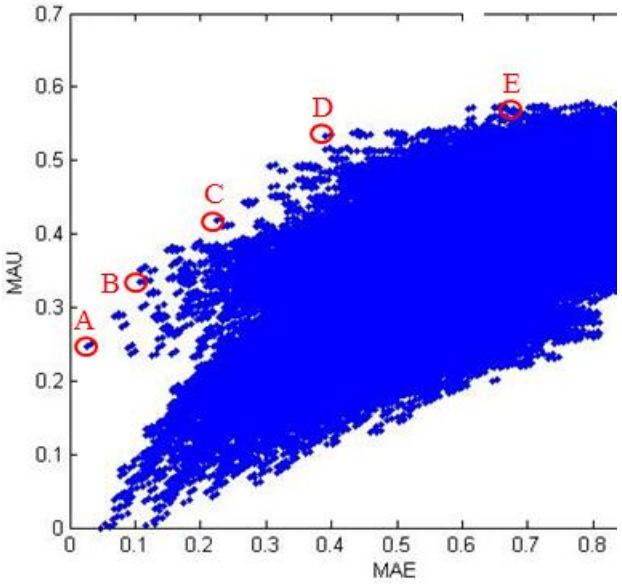
Multi-Epoch Analysis

Promising portfolio designs are simultaneously explored in multiple epochs

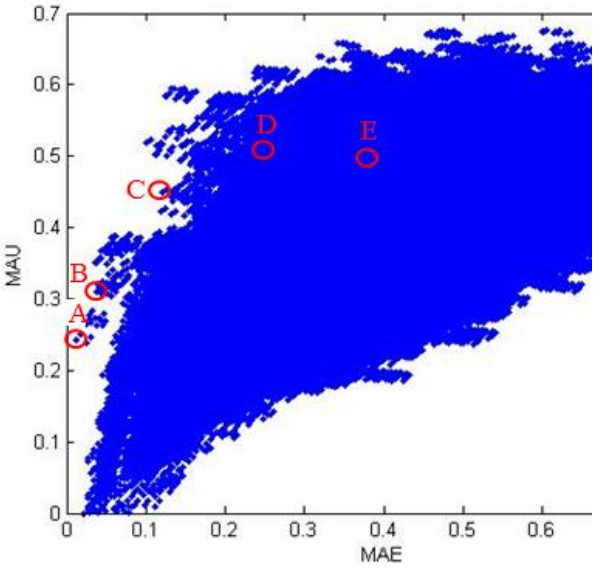
Baseline



War on Terror



Major Conflict



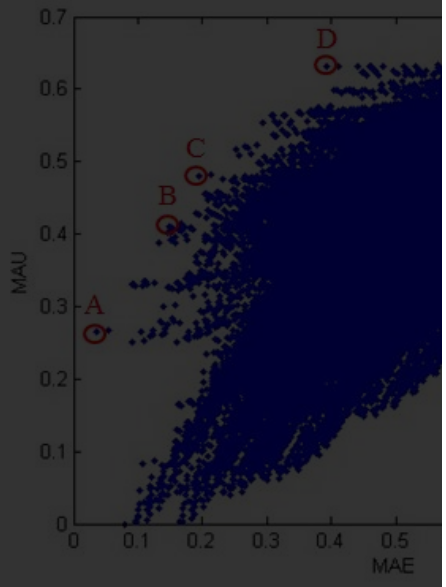
Multi-Epoch analysis illustrates the influence of contextual uncertainty on the utility of potential Carrier Strike Group portfolios

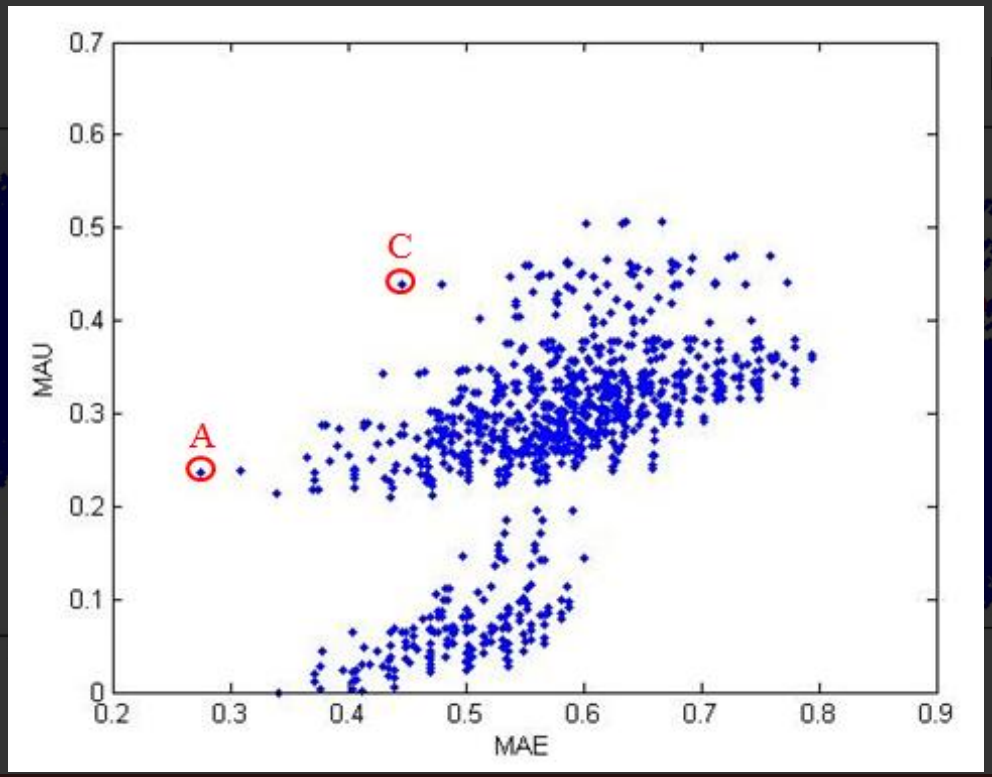
Multi-Epoch Analysis

Promising portfolio designs are simultaneously explored in multiple epochs

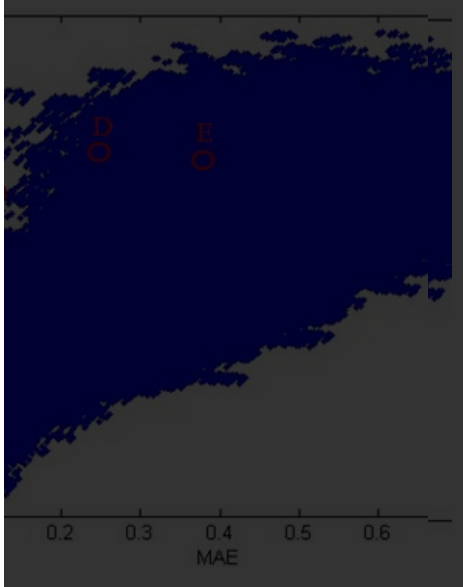
Small Navy Epoch

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)

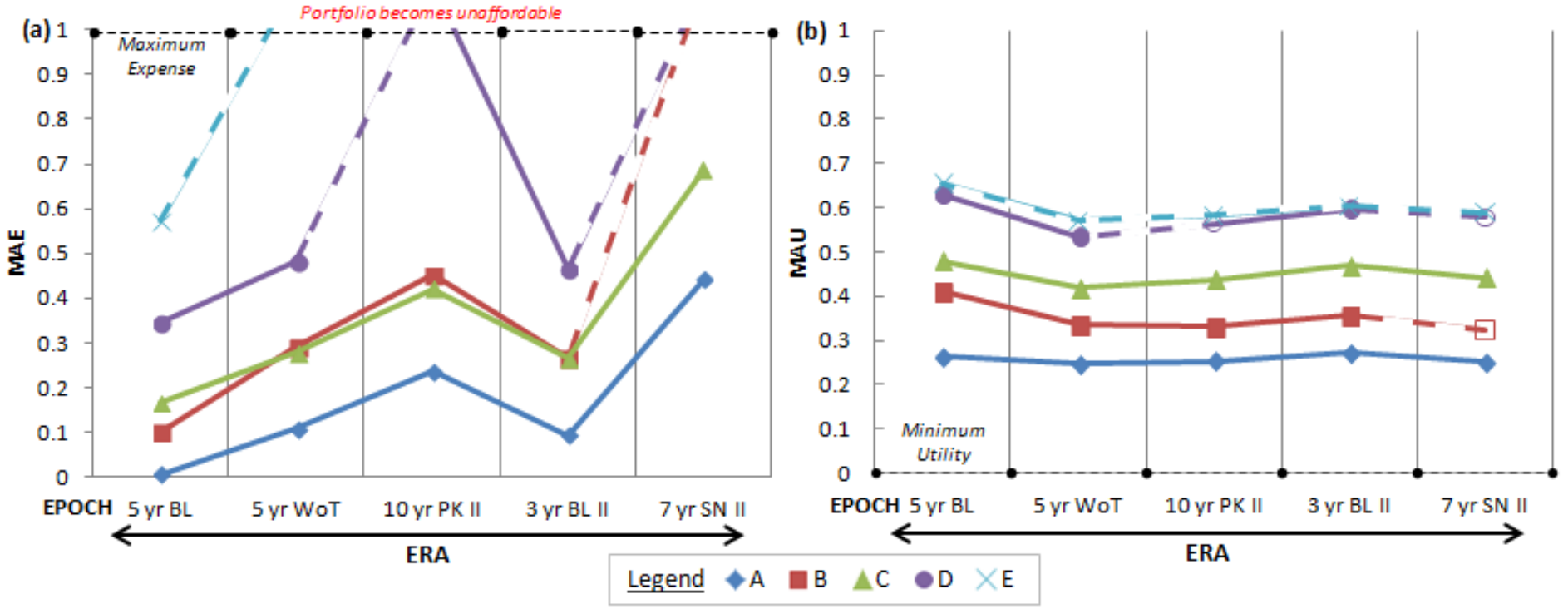
TIME

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?

References

Amenc, N., & Sourd, V. L. (2005). *Portfolio theory and performance analysis*. John Wiley & Sons.

Arrow, K. J., Social Choice and Individual Values, 2nd ed., Yale University Press, New Haven, CT, 1963.

Baldwin, K., Dahmann , J., Rebovich, G., Lane, J., & Lowry, R. (April 2011). An Implementers' View of Systems Engineering for Systems of Systems. IEEE International Systems Conference. Montreal, Canada: IEEE.

Carter, A. B. (2010). Better Buying Power: Guidance for obtaining greater efficiency and productivity in defense spending [Memorandum]. Washington, DC: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD [AT&L]).

Chattopadhyay, D. (2009). *A Method for Tradespace Exploration of Systems of Systems*. Cambridge, MA: Massachusetts Institute of Technology.

Chief of Naval Operations. (2010). *OPNAV Instruction 3501.316B*. Washington, DC: Department of the Navy.

Davendralingam, N., Mane, M., & DeLaurentis, D. (2012). Capability and Development Risk Management in System-of-Systems Architectures: A Portfolio Approach to Decision-Making. Ninth Annual Acquisition Research Symposium. Monterey, CA: Naval Postgraduate School Acquisition Research Program.

Keating, C., Rogers, R., Unal, R., Dryer, D., Sousa-Poza, A., Safford, R., Peterson, W., & Rabadi, G. (2003). System of Systems Engineering. Engineering Management Journal. Vol. 15, No. 3, 36-45.

Komoroski, C. L., Housel, T., Hom, S., & Mun, J. (2006). A methodology for improving the shipyard planning process: using KVA analysis, risk simulation and strategic real options/Acquisition Management. Monterey, CA: Naval Postgraduate School.

Lane, J., Dahmann , J., Rebovich, G., & Lowry, R. (2010). Key System of Systems Engineering Artifacts to Guide Engineering Activities. NDIA SE Conference. San Diego, CA. Retrieved from http://www.dtic.mil/ndia/2010systemengr/WednesdayTrack3_10806Lane.pdf

Maier, M. W. (1998). *Architecting principles for systems-of-systems*. Systems Engineering, 257-284.

References

Mane, M., & DeLaurentis, D. A. (2011). Capability and development time tradeoff analysis in system-of-systems. Eighth Annual Acquisition Research Symposium. Monterey, CA: Naval Postgraduate School.

Mekdeci, B., Ross, A.M., Rhodes, D.H., and Hastings, D.E., "Investigating Alternative Concepts of Operations for a Maritime Security System of Systems," INCOSE International Symposium 2012, Rome, Italy, July 2012.

Nickel, J. (2010). *Using Multi-Attribute Tradespace Exploration for the Architecting and Design of Transportation Systems*. Cambridge: Massachusetts Institute of Technology.

Pina, A. L. (2014). *Applying Epoch-Era Analysis for Homeowner Selection of Distributed Generation Power Systems*. Cambridge: Massachusetts Institute of Technology.

Ricci, N. (2014). *Dynamic System Perspective on Design: Ility-Driving Elements as Responses to Uncertainty*. Cambridge: Massachusetts Institute of Technology.

Ricci, N., & Ross, A. M. (2012). Developing a Dynamic Portfolio-Based Approach for Systems-of-Systems Composition. Working Paper, Massachusetts Institute of Technology, Systems Engineering Advancement Research Initiative, Cambridge, MA. Retrieved from http://seari/documents/working_papers/SEAri_WP-2012-2-1.pdf

Ross, A. M., & Rhodes, D. H. (2008). Architecting Systems for Value Robustness: Research Motivations and Progress. 2nd Annual IEEE Systems Conference. Montreal, Canada.

Ross, A. M., O'Neill, M. G., Hastings, & D. E., Rhodes, D. H. (2010). Aligning Perspectives and Methods for Value-Driven Design. AIAA Space 2010 Conference & Exposition. Anaheim, CA.

Ross, A. M., McManus, H. L., Rhodes, D. H., & Hastings, D. E. (2010). Revisiting the tradespace exploration paradigm: structuring the exploration process. AIAA SPACE 2010 Conference & Exposition. Anaheim, CA.

Ross, A. M., McManus, H. L., Rhodes, D. H., Hastings, D. E., & Long, A. (2009). Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System. AIAA Space. Pasadena, CA.

Schaffner, M. A., Ross, A. M., & Rhodes, D. H. (2014). A Method for Selecting Affordable System Concepts: A Case Application to Naval Ship Design. Conference on Systems Engineering Research. Redondo Beach, CA: Elsevier.

References

Schaffner, M. A., Wu, M. S., Ross, A. M., & Rhodes, D. H. (2013). Enabling Design for Affordability: An Epoch-Era Analysis Approach. Tenth Annual Acquisition Research Symposium (pp. 252-279). Monterey, CA: Naval Postgraduate School.

Shah, N. B. (2013). *Influence Strategies for Systems of Systems*. Cambridge: Massachusetts Institute of Technology.

Swisher, P., & Kasten, G. W. (2005). Post-Modern Portfolio Theory. Journal of Financial Planning, 25(9), 1-11.

U.S. Government Accountability Office (GAO). (2011). *Trends in Nunn-McCurdy Breaches for Major Defense Acquisition Programs. GAO-11-295R.* Washington, D.C.

Walton, M. A. (2002). *Managing Uncertainty in Space Systems Conceptual Design Using Portfolio Theory*. Cambridge: Massachusetts Institute of Technology.

Wu, M. S. (2014). *Design for Affordability in Defense and Aerospace Systems Using Tradespace-Based Methods*. Cambridge: Massachusetts Institute of Technology.

Wu, M. S., Ross, A. M., & Rhodes, D. H. (2014). Design for Affordability in Complex Systems and Programs Using Tradespace-based Affordability Analysis. Procedia Computer Science, 28, 828-837.