ICEAA
International Cost Estimating and Analysis Association

SEAri
Systems Engineering Advancement Research Initiative

Design for Affordability in Complex Systems and Programs Using Tradespace-based Affordability Analysis*

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*This talk is based on one given by Marcus Wu, Adam Ross, and Donna Rhodes at the Conference on Systems Engineering Research, Redondo Beach, CA, March 2014.

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Systems Engineering Advancement Research Initiative

SEAri is positioned within the MIT Engineering Systems Division and the MIT SSRC MIT Sociotechnical Systems Research Center

Mission:

Advance the theories, methods, and effective practice of systems engineering applied to complex socio-technical systems through collaborative research

Current/Past Sponsors:

Singapore DSTA, NTNU, NPS, SERC UARC, DARPA, US Air Force, US Gov't Agencies, C.S. Draper Lab, MIT-Portugal Program, Singapore DSO Nat'l Lab, MIT LAI, AGI, MITRE

PAST PERFORMANCE

- More than decade of research in value-driven design and tradespace exploration
- Successful research across multi-year projects
- Numerous publications and courses

LEADERSHIP

- **Dr. Donna Rhodes**
  - Director, Principal Investigator
- **Dr. Adam Ross**
  - Lead Research Scientist
- **Prof. Daniel Hastings**
  - Faculty Strategic Advisor

TECHNICAL TEAM

- 8 Graduate Research Assistants
- 4 Affiliated Graduate Students
- 6 Undergraduate Students
- 3 Affiliated Researchers

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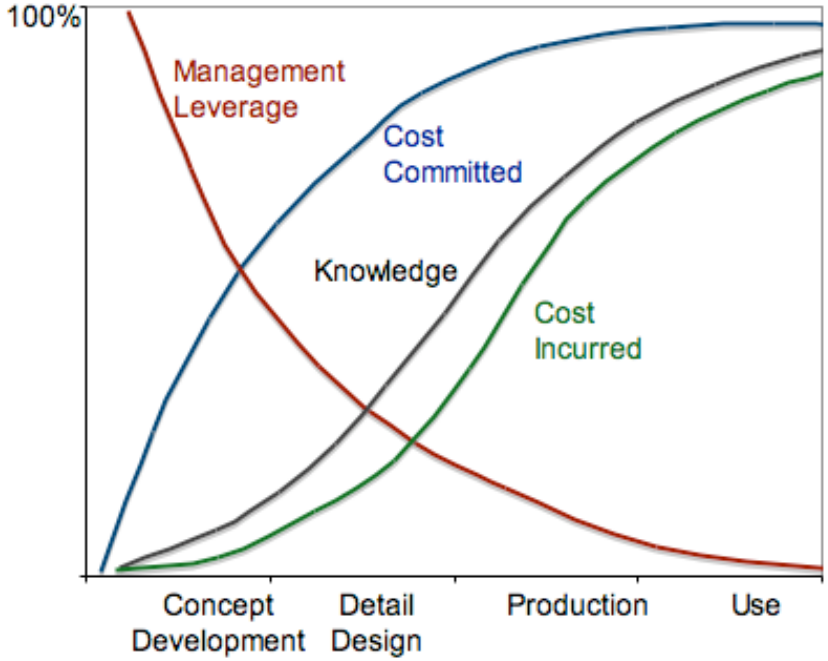
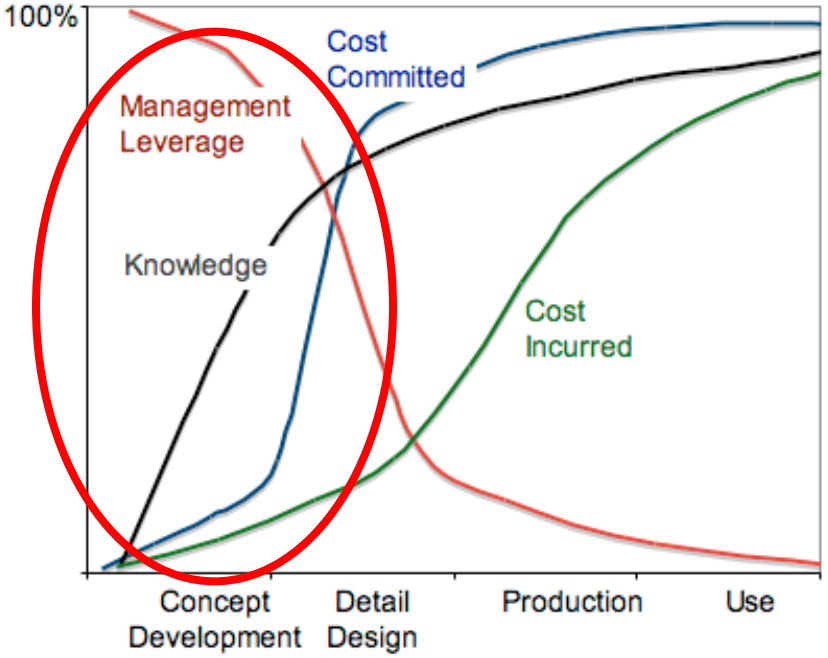
SEAri Research Seeks to "Change the Picture"



Classic paradigm



New paradigm

ESSENTIAL ELEMENTS

Appropriate **competencies** in workforce

Advanced **methods** for anticipatory analysis, decision making, and architecting

Enabling enterprise strategies and model-based **environments**

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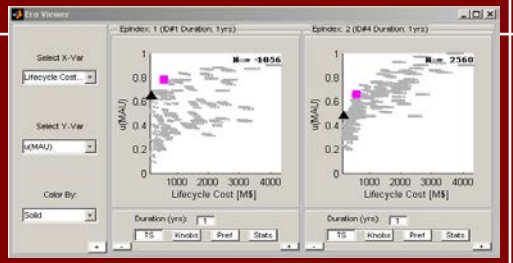
Building Anticipatory Capacity

COMPETENCIES	METHODS	ENVIRONMENT
Ability to think deeply about 'systems in context' Enhance ability to think about 'systems in time' Use *situational leadership* to make decisions at multiple system levels	Perform dynamic tradespace exploration Model-based approach to derive alternative futures Apply methods at varying levels of fidelity	Computing power/toolsets to enact methods Support multi-stakeholder negotiations in tradespace exploration Enable comprehension of complex data sets
		

Rhodes, D.H. and Ross, A.M., "Anticipatory Capacity: Leveraging Model-Based Approaches to Design Systems for Dynamic Futures," 2nd Annual Conference on Model-based Systems, Haifa, IL, March 2009.

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Agenda

- Motivation
- Defining Affordability as an Ility
- Affordability Analysis using Tradespace-based Methods
- Space Tug Case Study
- Results of Single Epoch, Multi-Epoch and Single Era Analysis
- Conclusion & Future Work

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Motivation

- The architecting of complex systems and programs faces much uncertainty
  - Massive cost overruns, schedule delays, failures to anticipate future requirements and ultimately unrealized capabilities (Cordesman and Frederiksen, 2006)
  - Weaknesses in initial program definition and costing (IDA, 2009)
- Leads to *rising costs and schedule slippages*

F-35 Joint Strike Fighter and Ballistic Missile Defense System

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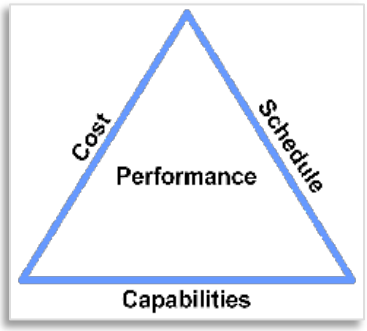
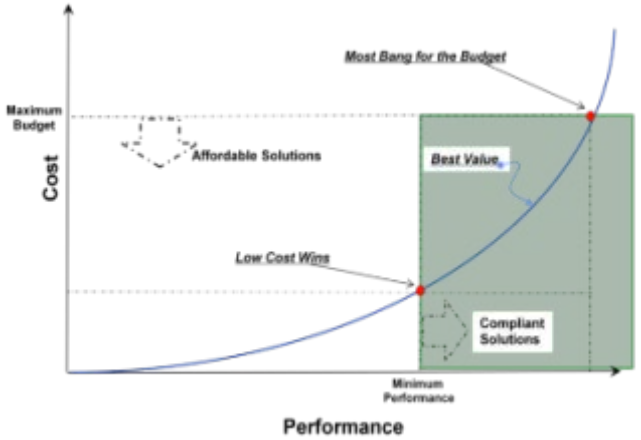
Motivation

- **DESIGN FOR AFFORDABILITY**
  - Account for performance, cost and schedule parameters



(Tuttle and Bobinis, 2012)



- *Affordability mandated as a requirement* at all milestone decision points of program development (Carter, 2010a, 2010b)
- Affordability has emerged as a high priority concept in systems engineering (SE) that directs early stage design process towards greater cost effectiveness and schedule effectiveness

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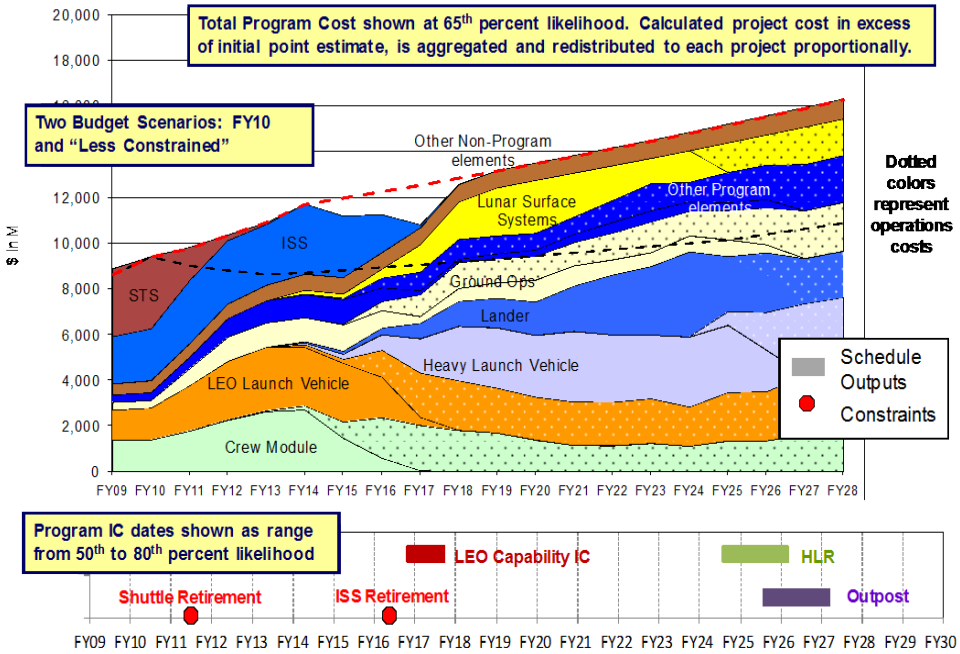
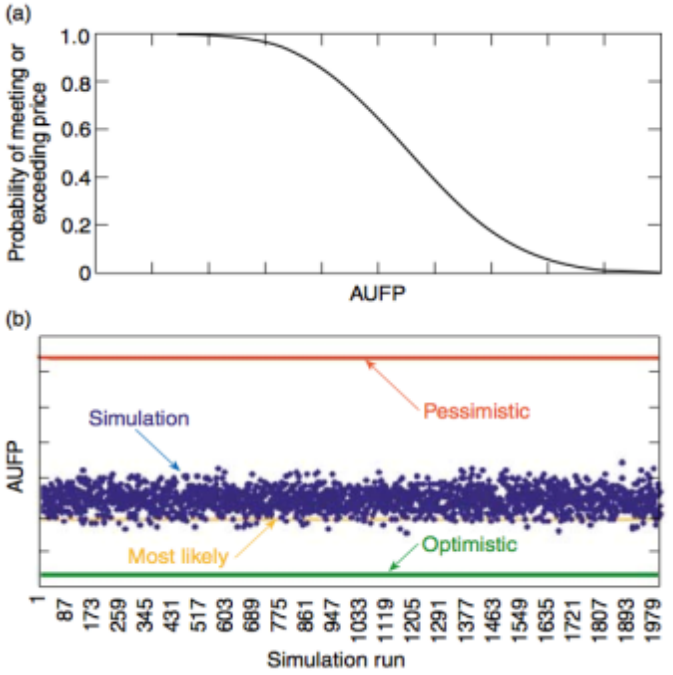
The Affordability Paradigm

- Carter 2010 Memorandum and Better Buying Power Initiative – "*Mandate Affordability as a Requirement*" for defense acquisition
- Many tools and frameworks have been proposed to integrate affordability analysis with existing SE methods



NASA Sand Chart Tool (Emmons et al 2010)



Interval Cost Estimation (Kroshl and Pandolfini 2000)

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The Affordability Paradigm

- Current processes have been limited to static tradeoffs of systems with performance and costs in current operating environments, or in single point futures
- Lack of consensual definition and guiding principles for affordability analysis in the SE community
- Failure to explicitly capture dynamic aspects of system or program and its changing environment over its lifecycle
- Need to have a *complementary set of constructs and methods* for enabling the affordability paradigm

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Affordability as an Ility

- Consider **affordability as an ility**, which is a system property that manifests and determines values after a system is put into initial use (de Weck, Ross and Rhodes 2012)
- Affordability can be treated as an ility that drives the design of more affordable yet technically sound architectures
- It emerges at the nexus of decisions within changing contexts (i.e. what is "right" decision over time?)
- This suggests *tradespace exploration* methods would provide insights in the search for affordable designs

Affordability is the property of becoming or remaining feasible relative to resource needs and resource constraints

(Wu, Ross and Rhodes 2013)

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Affordability as an Ility

(Wu, Ross and Rhodes 2013)

Affordability is the property of becoming or remaining feasible relative to resource needs and resource constraints

- **Resource needs**: Set of resource requirements elicited from stakeholders (tend toward zero, but some preferences w.r.t. more)
- **Resource constraints**: Statements of restrictions on these requirements that limit range of feasible solutions, externally imposed
- **Goal of Affordability Analysis**: ***Identify solutions that remain feasible throughout or for a large part of the system lifecycle***

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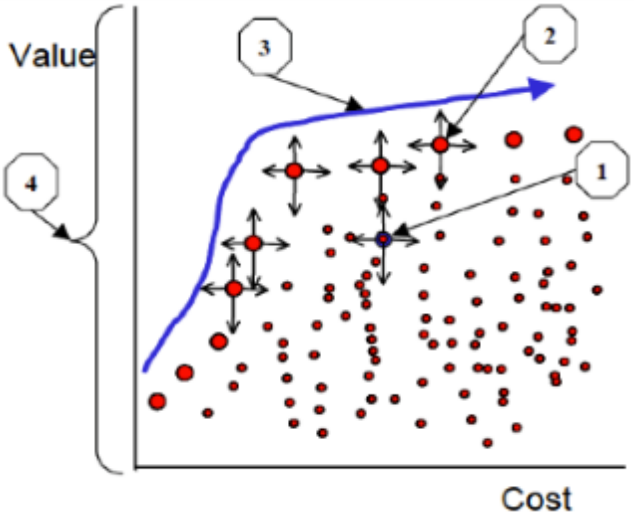
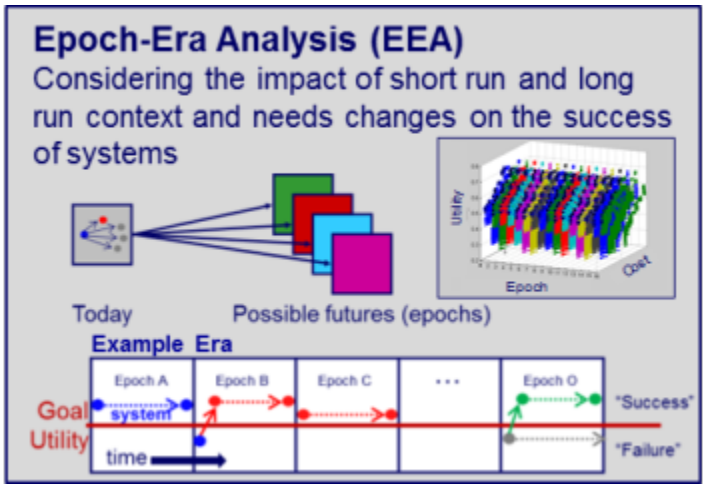
Tradespace-based Methods

- **Affordability analysis can be conducted *using tradespace exploration* (TSE)**
- TSE (Ross and Hastings 2005):
  - Model-based investigation of many design alternatives
  - Avoiding premature fixation on point designs and narrow requirements



TSE– Types of trades: [1] Local points, [2] Frontier points, [3] Frontier Sets, [4] Full TSE (Ross and Hastings 2005)



- EEA (Ross and Rhodes 2008):
  - Model-based investigation of many alternative futures
  - Promotes exploration of impact of short run and long run uncertainties on system/program success

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Methodology for Affordability Analysis

1. Use **Multi-Attribute Tradespace Exploration (MATE)**
2. Use **Multi-Attribute Expense (MAE)** function instead of "cost"
3. Use **constraint levels** to determine affordable solution region
4. Select preferred designs from region
5. Use **Epoch-Era Analysis (EEA)** to account for the evolution of preferred design(s) over time

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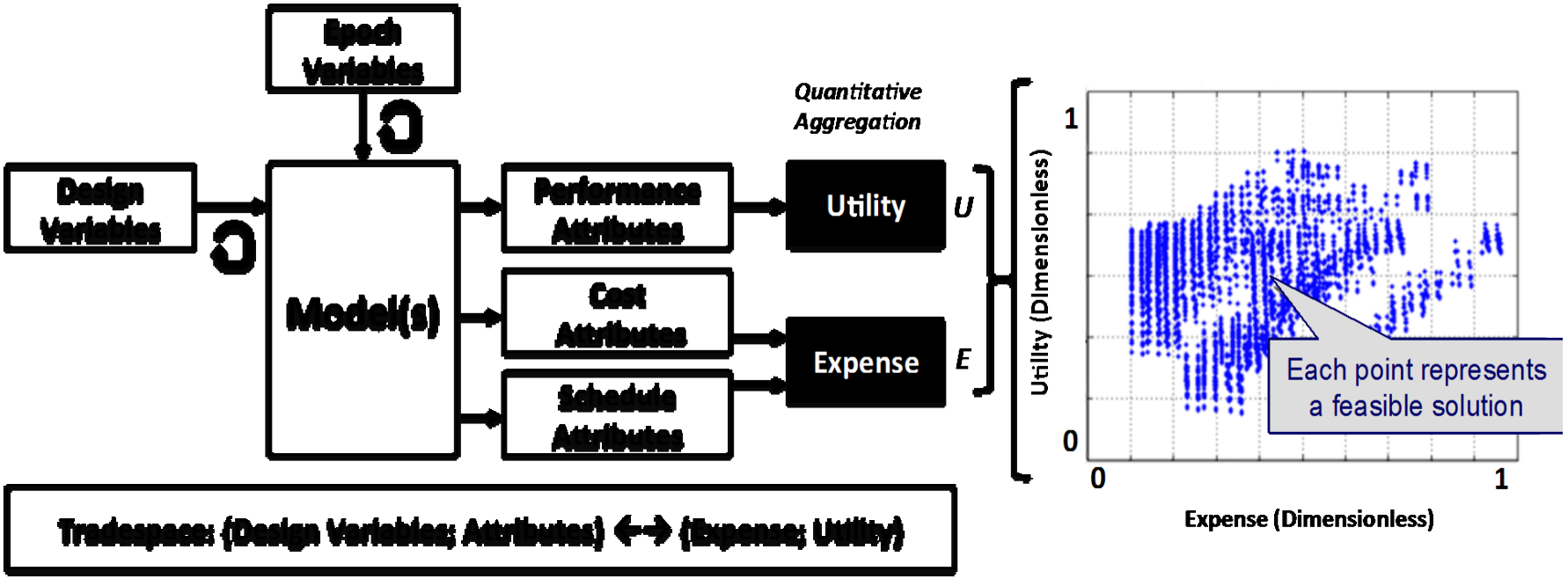
MATE for Affordability



Multi-Attribute Tradespace Exploration data flow for affordability analysis
(Wu, Ross and Rhodes 2013)

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MAE for Affordability

- **Use Multi-Attribute Expense (MAE) instead of "cost" in TSE**
- Break down "cost" into "different colors of money"
- MAE is similar to MAU function by (Keeney and Raiffa 1993)
- A dimensionless, non-ratio scale metric

$$KE(X) + 1 = \prod_{i=1}^{N} [Kk_i E_i(X_i) + 1]$$

(Diller 2002)

- Quantified on a 0 to 1 scale:
  - 0: Minimal dissatisfaction
  - 1: Complete dissatisfaction
- **Modify MATE to compare MAE against MAU for affordability analysis**

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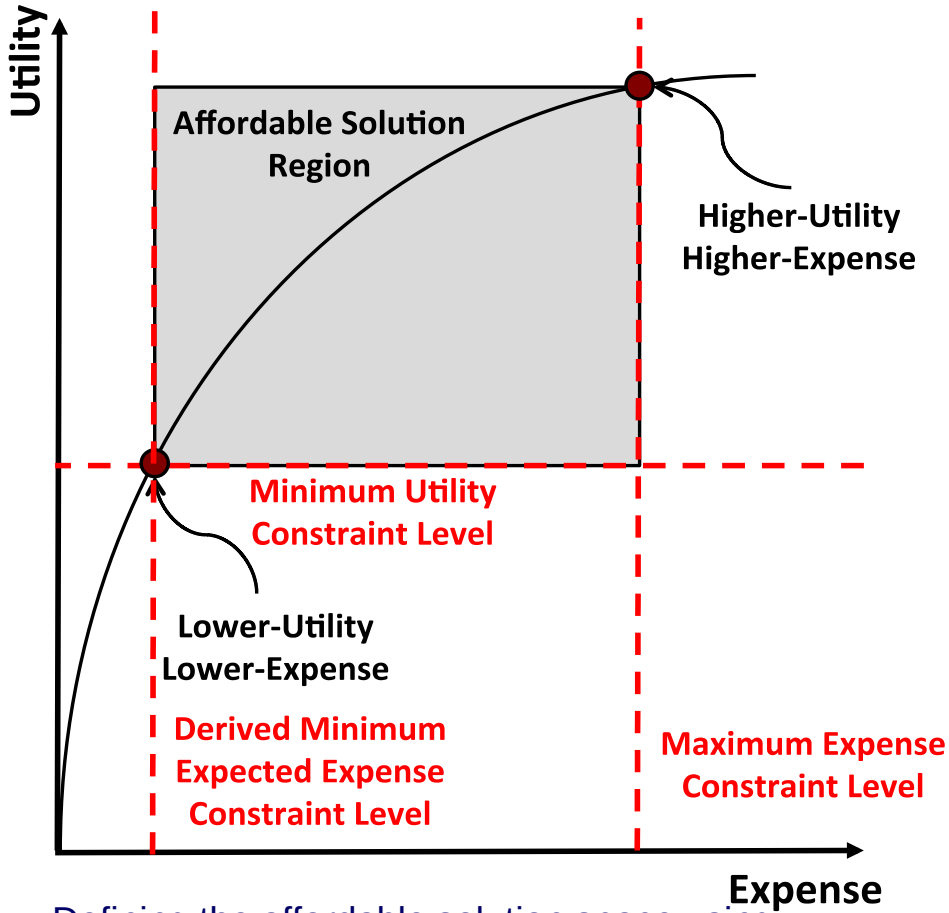
Constraint Levels

- **Constraint levels reflect external constraints that are imposed on stakeholders**
- Establish constraint levels for **minimum utility** and **maximum expense**
- Find **derived minimum expected expense**
- Area bounded by three constraint levels is the **affordable solution region**



Defining the affordable solution space using external constraint levels for a fixed context (Wu, Ross and Rhodes 2013)

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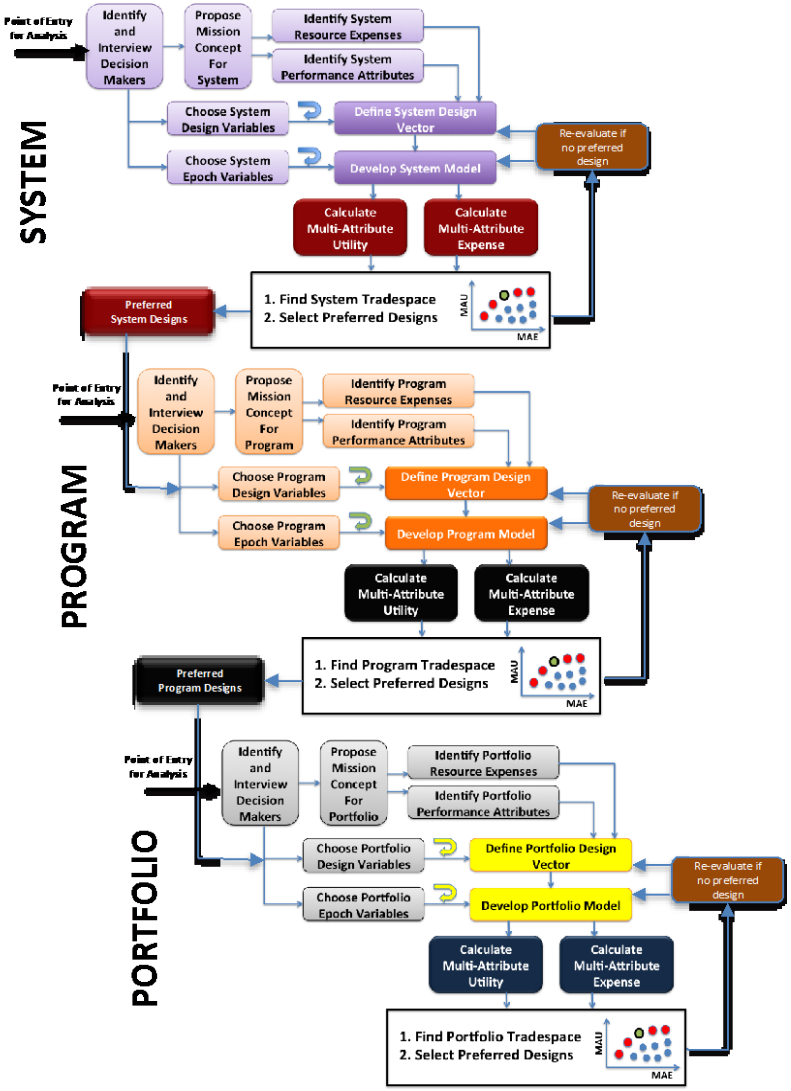
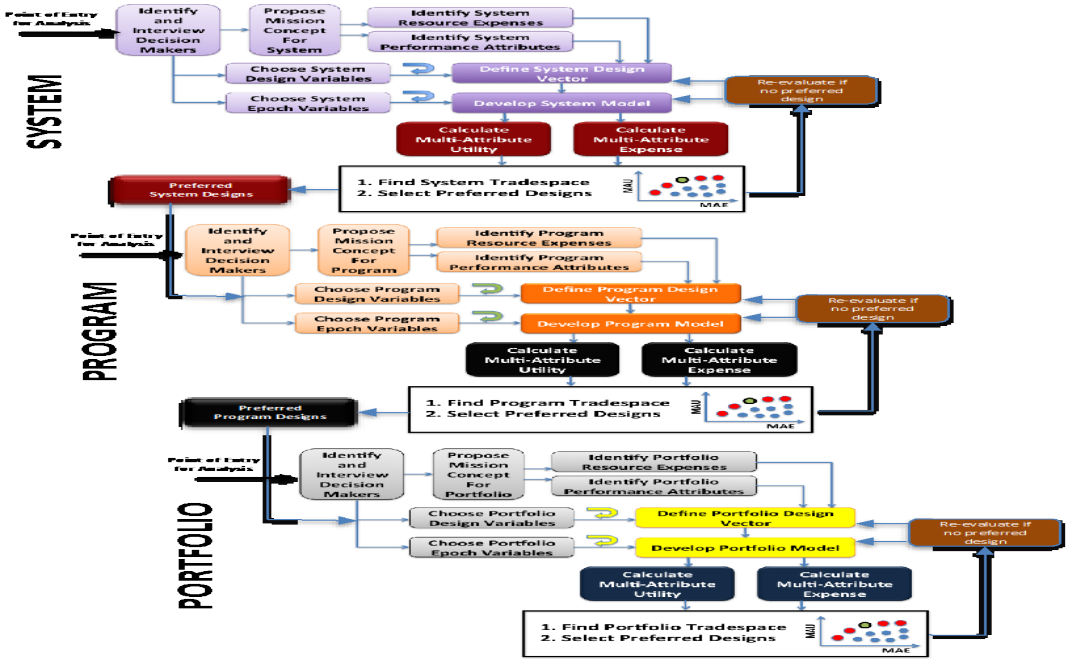
System-Program-Portfolio





Methods are scalable to various layers of application

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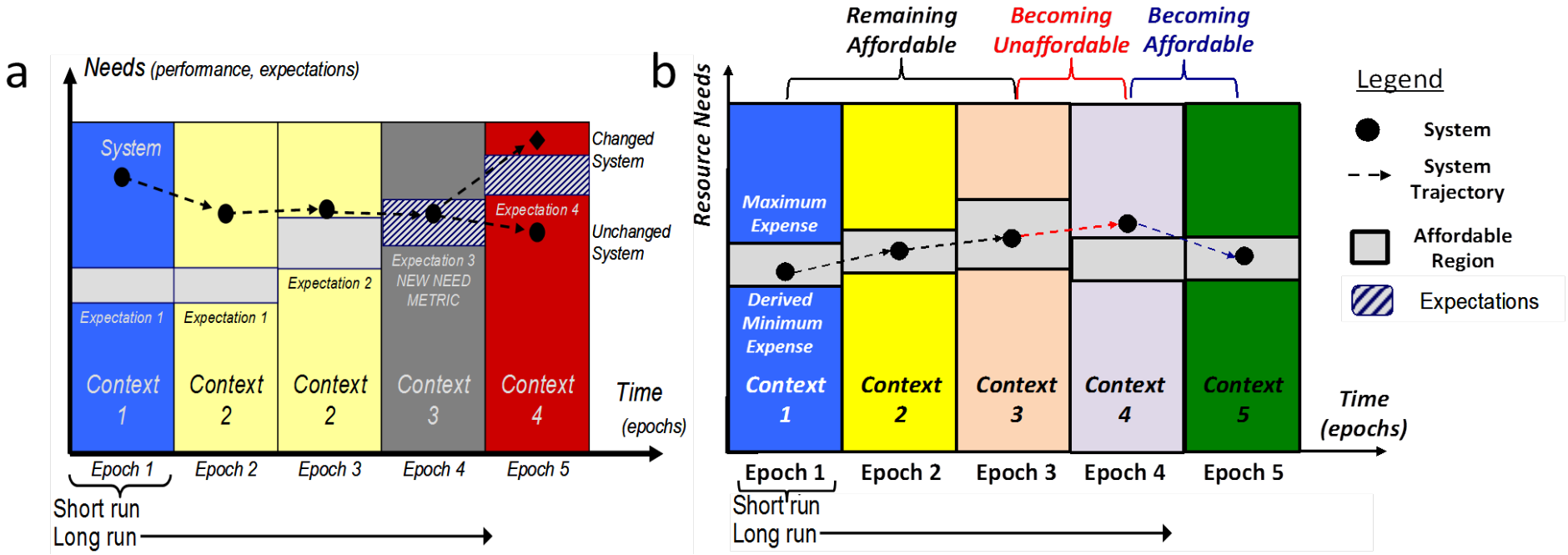
EEA for Affordability

- EEA discretizes system lifecycle into **epochs** (time periods with fixed context and needs) and **eras** (ordered sequence of epochs)
- Consists of single epoch, multi-epoch, and single era analyses
- Permits **resource-centric approach** for evaluating system design concepts



(a) Original Epoch-Era Analysis Diagram by Ross and Rhodes 2008 ; (b) Modified Epoch-Era Analysis diagram for Affordability Analysis (Wu, Ross and Rhodes 2013)

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Summary of Method

- Use ***MATE***
- Use ***MAE*** instead of cost
- Construct tradespaces bounded by MAU and MAE
- Establish **constraint levels** in tradespaces
- Determine **affordable solution region**
- Select preferred designs from region
- Apply ***EEA*** to allow for structured evaluation of design alternatives across many alternative futures
- Complete affordability analysis by ensuring that a potential design's cost, schedule and performance parameters are feasible across the entire lifecycle

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Application to Space Tug

- **Space Tug:** a single general-purpose space transportation vehicle designed to transfer space systems between orbits
- **Why Space Tug?** A simple case study that has been validated and used for concept evaluations in many MIT SEAri theses and publications
- Conduct a **System** and **Program** level analysis

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System Level Analysis

- System design variables

Manipulator Capability	Propulsion Type	Propellant Mass
Low	Storable Bipropellant	30
Medium	Cryogenic	100
High	Electric	300
Extreme	Nuclear	600
		1200
		3000
		10000
		30000

Total of 4 x 4 x 8 = 128 possible designs

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System Level Analysis

- System Attributes

Mass Capability	Transfer Speed	Delta-V
A function of manipulator capability	A function of propulsion type	A function of propulsion type which affects I_{SP}
Contributes to overall dry mass	Simply defined with only 2 levels: “Slow” (Level 0) or “Fast” (Level 1)	A function of wet mass which is determined by the amount of propellant
		A function of dry mass which comprises the base mass and manipulator mass

- MAU calculated as the weighted sum of the above 3 attributes.

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System Level Analysis

- Consider "**Development Cost", "Launch Cost" and "Development Schedule"** as **Expense Attributes**
- Development Cost is calculated as a function of dry mass: Wertz and Larson (2011) estimates $475/kg for development cost of small satellites in FY2010 dollars.
- Baseline development **schedule** of **4, 8, 12, 18** months corresponding to Low, Medium, High, Extreme Capabilities
- Multiplicative factors between **x1.5 to x.3.5** used for schedule in developing Storable Bi, Cryo, Electric and Nuclear Propulsion types

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System Level Analysis

Defining Epochs and Eras

- New Epoch variable of **Technology Level**: **Present** or **Future**
- **Future** technology gives higher I_{SP}, *lower schedule*, higher wet mass launch cost and *higher dry mass development cost*
- Space Tug to perform 8 different missions:
  - 8 different epochs with 8 different SAU functions for each of the 5 performance attributes and 8 different SAE for each of the 3 expenses
- 1st era: 8 different epochs with **Present** technology
- 2nd era: 8 different epochs with **Future** Technology

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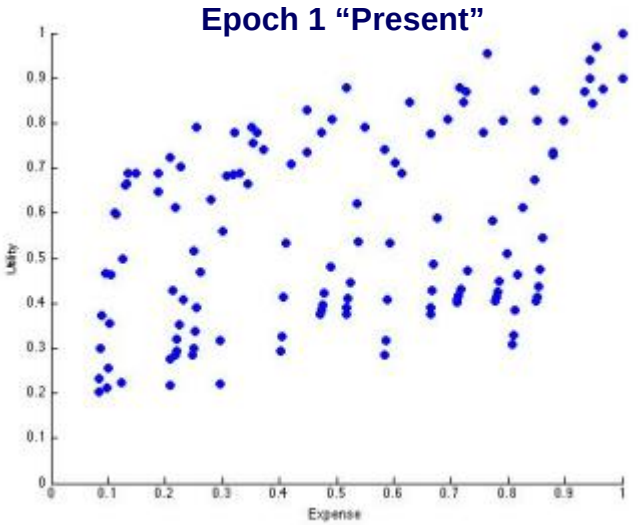
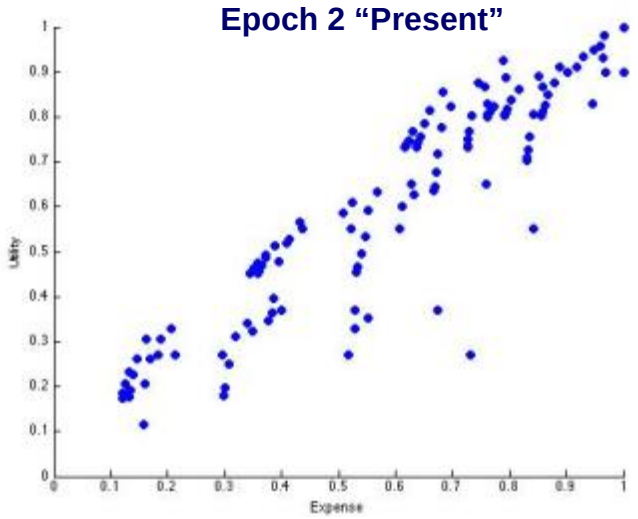
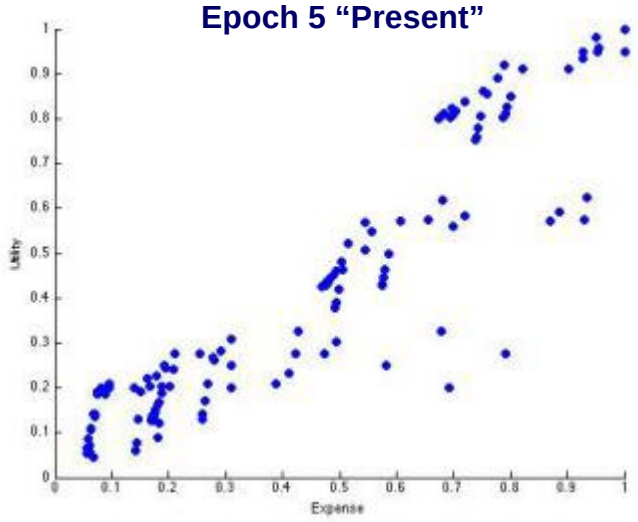
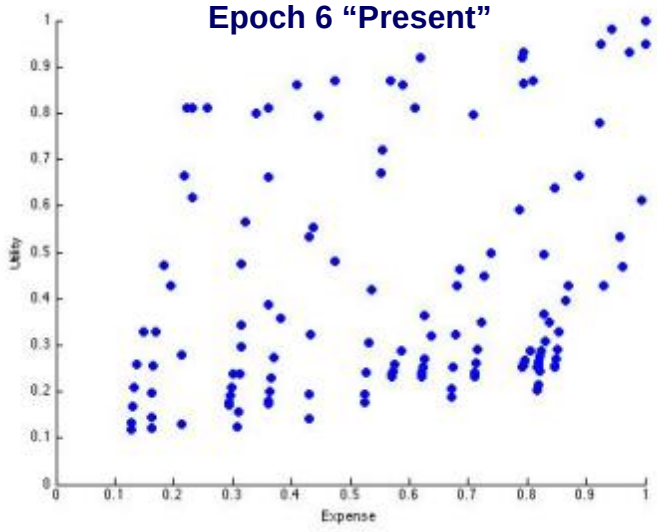
System Level Analysis









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A Space Tug Program

Hypothetical Problem: Due to exogenous disturbances such as solar flares and incoming asteroid debris, many American satellites in Earth orbit have been misaligned from their original orbits. More than 1 pair of misaligned satellites may collide into each other in the following 5 years even after the quickest launch time possible for a Space Tug. A single Space Tug will not be capable of realigning all satellites without incurring any risk of collisions. NASA needs to find a quick, effective but affordable solution to realign these satellites in order to prevent any collision and increase in orbital debris.

Proposed Solution:

Commence on a Space Tug program to develop 2 Space Tugs!

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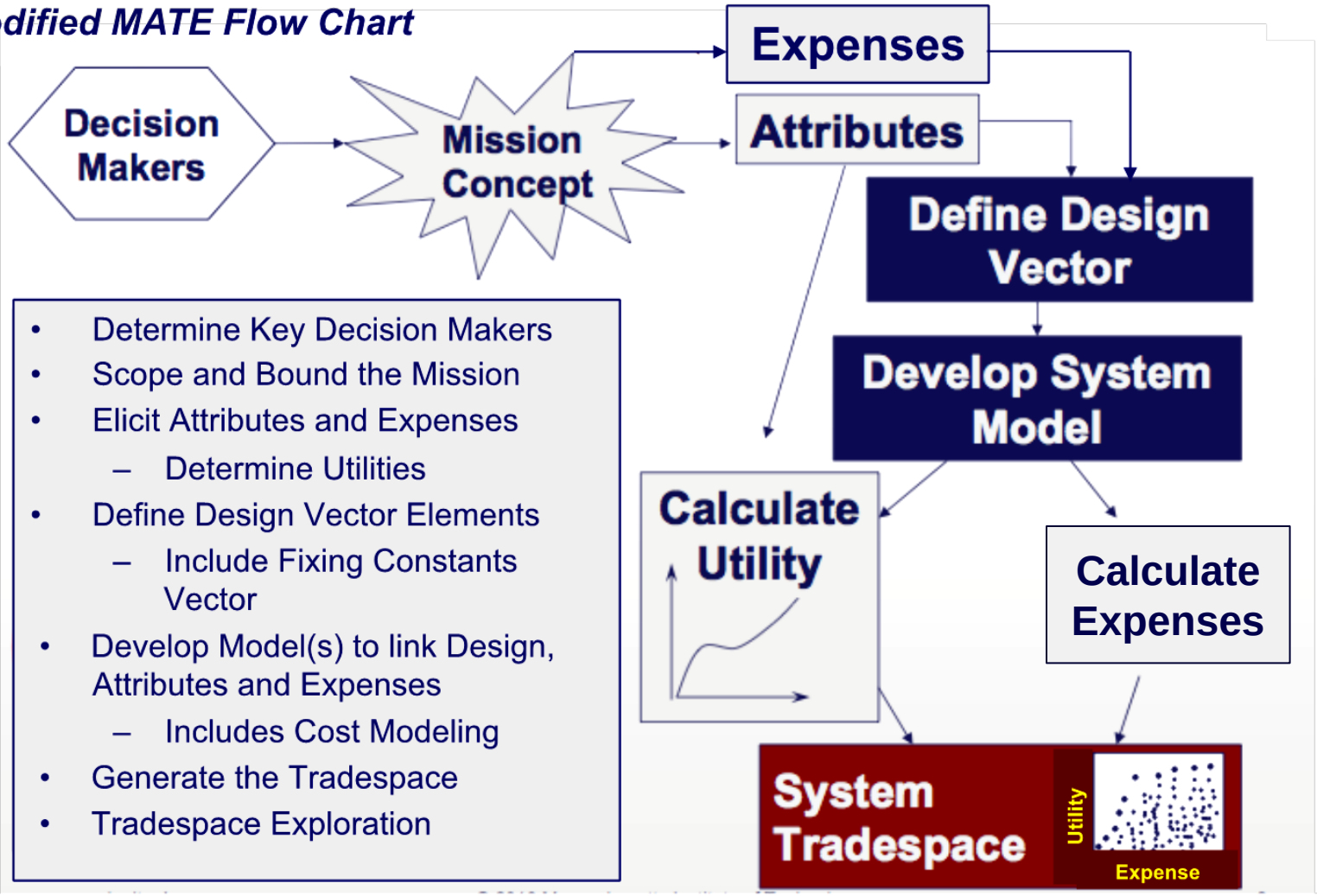
Program Level Analysis

Modified MATE Flow Chart



- Determine Key Decision Makers
- Scope and Bound the Mission
- Elicit Attributes and Expenses
  - Determine Utilities
- Define Design Vector Elements
  - Include Fixing Constants Vector
- Develop Model(s) to link Design, Attributes and Expenses
  - Includes Cost Modeling
- Generate the Tradespace
- Tradespace Exploration

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Program Level Analysis

The same 3 Expense Attributes (EA) Redefined, Introduced 5 New Performance Attributes (PA) to give a total of 8 program attributes

Attributes	Description
(EA-1) Program Development Cost	Sum of development cost of individual Space Tugs
(EA-2) Program Launch Cost	Sum of launch costs of individual Space Tugs if in different orbits, else 2/3 of the value
(EA-3) Program Schedule	Maximum of the schedules of the two Space Tugs if launched to the same orbits, else the minimum
(PA-1) Program Mass Capability	The lower of the 2 Space Tugs in order to guarantee that the other one has higher delta-V
(PA-2) Program Delta-V	The lower of the 2 Space Tugs in order to guarantee that the other one has higher delta-V
(PA-3) Program Transfer Speed	Sum of Speed levels - “Slow-Slow” (Level 0), “Slow-Fast”/”Fast-Slow” (Level 1), “Fast-Fast” (Level 2)
(PA-4) Probability of Success	Probability of 2 Space Tugs being able to perform their missions at the same time
(PA-5) Mission Time	Duration taken to prevent the first predicted collision or multiple collisions predicted to occur at the same time

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Program Level Analysis

- **MAU** = f [PA-1, PA-2, PA-3, PA-4, PA-5]
- **MAE** = f [EA-1, EA-2, EA-3]
- **128 designs x 128 designs x 4 orbit location pairs x 4 reliability level pairs = 262, 144 program design solutions**
- Space Tug program to perform 8 different missions:
  - 8 different epochs with 8 different SAU functions for each of the 5 attributes and 8 different SAE for each of the 3 expenses
- 1st era: 8 different epochs with **Present** technology
- 2nd era: 8 different epochs with **Future** Technology

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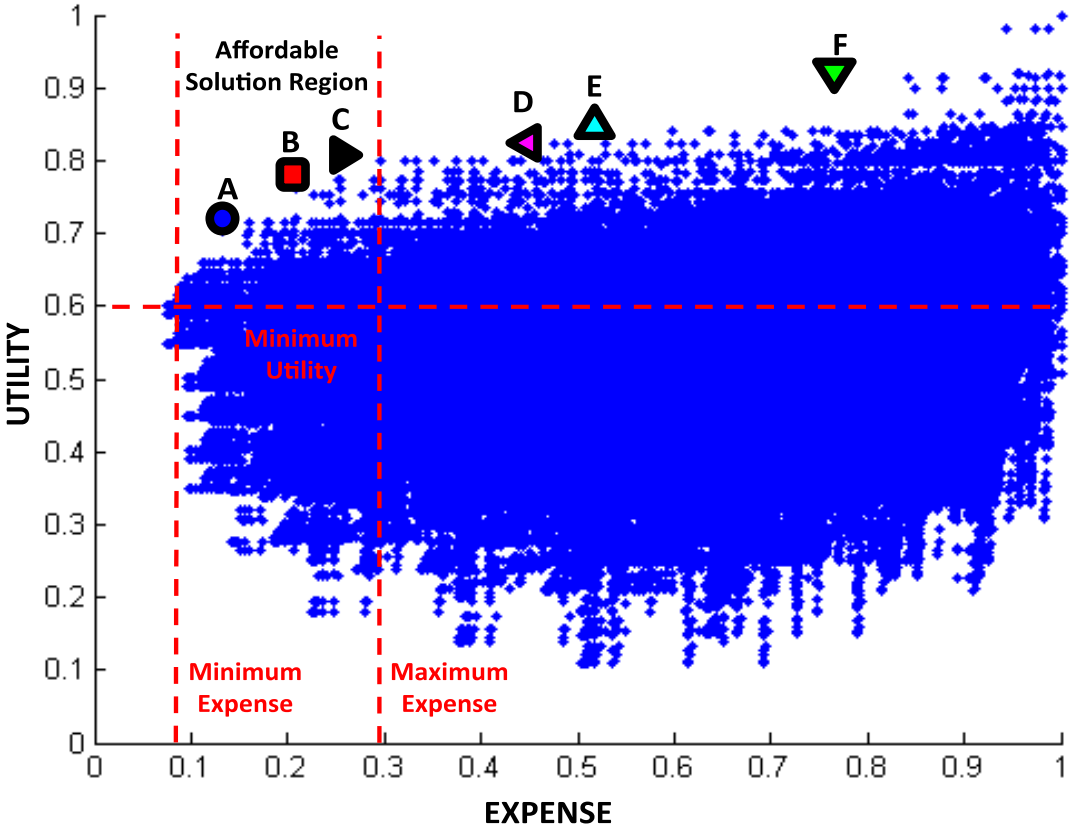
Single-Epoch Analysis

- Generate tradespace for Epoch 1
- 6 designs along the Pareto front were chosen and labeled A to F.
- Constraint levels are set using Design A as reference.
- Maximum Expense is arbitrarily set at 1.5-2.0x above its resource expenditure and Minimum Utility is set at 1.5-2.0x below its utility
- **Designs A, B, C are affordable**



Tradespace for a Space Tug program in Epoch 1.
(Wu, Ross and Rhodes 2013)

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Characteristics of Designs A to F

	Performance Attributes					*Resource Attributes*				
Design (Number)	Program Payload (*kg*)	Program Speed	Program Delta-V (ms^{-1})	Prob. Success	Mission Time	PDC (*$mil*)	PLC (*$mil*)	PDS (*mths*)	Utility	Expense
A (26836)	300	Fast/Fast	6147	0.96	Short	940.5	376.8	8	0.715	0.131
B (28900)	300	Fast/Fast	8091	0.96	Short	1805	808	8	0.774	0.208
C (59860)	300	Fast/Fast	12645	0.92	Short	2090	764	14	0.800	0.254
D (125908)	1000	Fast/Fast	8910	0.88	Short	3420	1212	28	0.823	0.448
E (127972)	1000	Fast/Fast	16150	0.88	Short	4750	1800	28	0.840	0.517
F (194020)	3000	Fast/Fast	10984	0.86	Short	8550	3080	42	0.915	0.763

Performance and Resource Attributes for Designs A to F in Epoch 1
(Wu, Ross and Rhodes 2013)

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Multi-Epoch Analysis

- To find out how utility and expense of program changes across multiple epochs
- Find out how many epochs during which designs remain affordable
- Epochs 1, 5, 6, 13, 14 chosen
- Varying constraint levels were chosen for each epoch to yield different affordable solution regions

	Performance Constraints					*Resource Constraints*			*Constraint Levels*		
Epoch	Program Payload (*kg*)	Program Speed	Program Delta-V (ms^{-1})	Prob. Success	Mission Time	PDC (*$mil*)	PLC (*$mil*)	PDS (*mths*)	Minimum Utility	Derived Minimum Expense	Maximum Expense
1	300	Fast/Fast	5500	0.95	Short	2000	500	12	0.605	0.087	0.294
5	300	Fast/Fast	7000	0.90	Short	3000	900	12	0.661	0.178	0.349
6	1000	Fast/Fast	4000	0.90	Short	4000	1000	12	0.576	0.293	0.389
13	300	Fast/Fast	6500	0.95	Short	5000	1200	24	0.643	0.079	0.583
14	1000	Fast/Fast	7000	0.90	Short	3000	1600	24	0.681	0.175	0.527

Performance and Resource Constraints for a Set of Epochs (sequenced as an Era) (Epochs 1,5,6,13,14) (Wu, Ross and Rhodes 2013)

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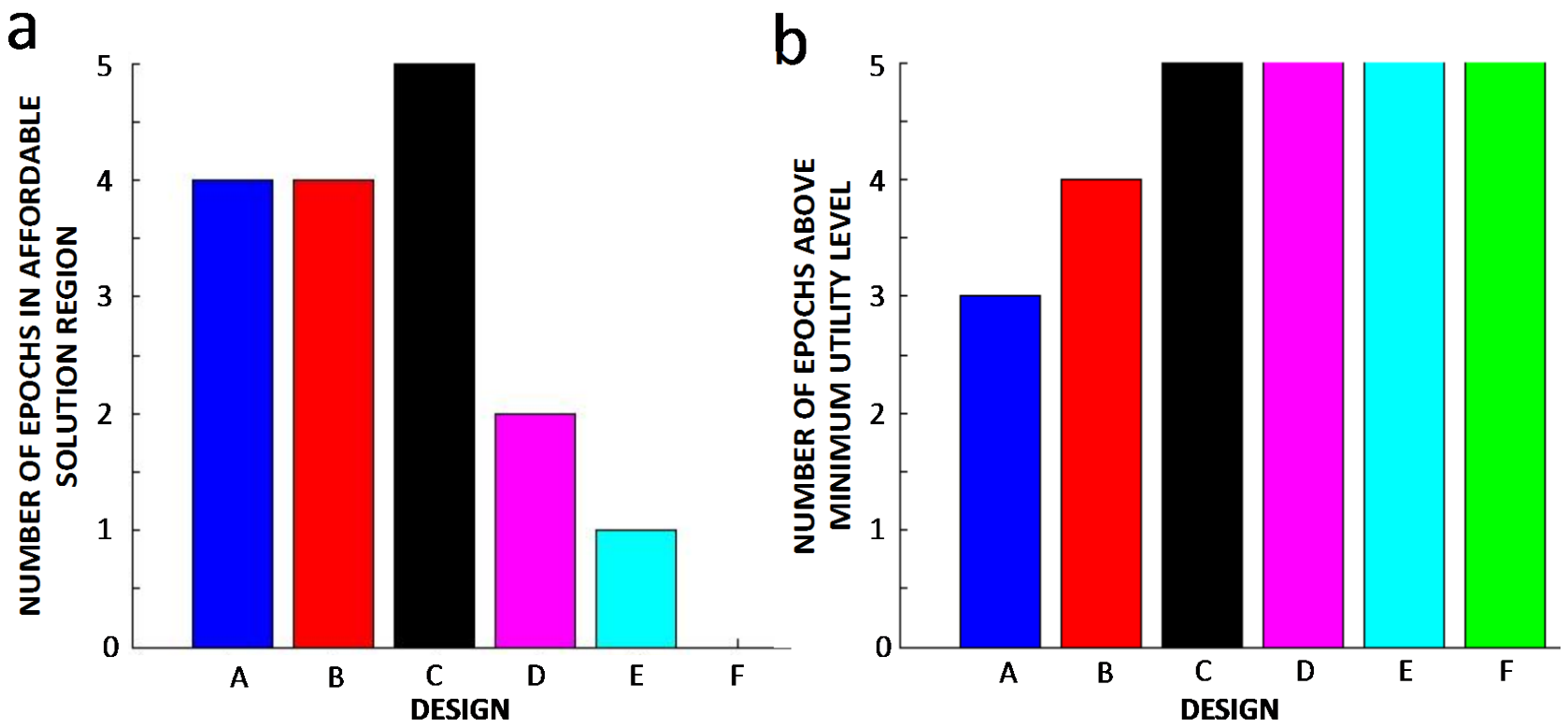
Multi-Epoch Analysis



(a) Number of epochs in affordable solution region for every design
(b) Number of epochs above minimum utility level for every design
(Wu, Ross and Rhodes 2013)

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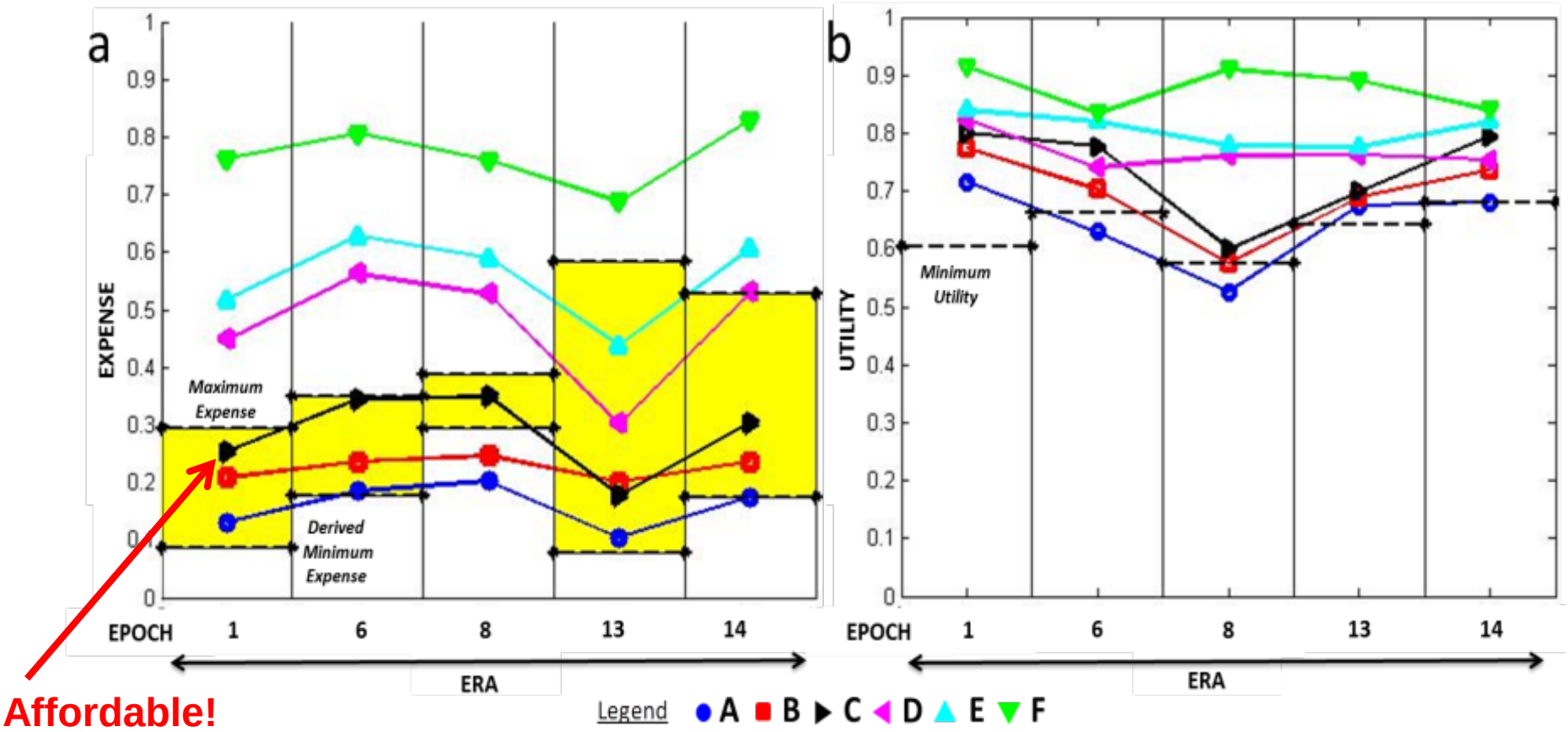
Single-Era Analysis

Plot both expense and utility trajectories of designs over defined era



(a) EEA with expense considerations in a single era (b) EEA with utility considerations in a single era (Wu, Ross and Rhodes 2013)

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Single-Era Analysis

- Combining results from both utility and expense trajectories, **Design C** has the best tradeoffs among performance, cost and schedule attributes
- Both Space Tugs have '**Low**' mass capability, use '**Nuclear**' propulsion, propellant mass of **3000kg**, in **LEO-LEO** orbit configuration, **high reliability**, and are carried on the **same launch vehicle**.
- The PDC is **$2.09 billion**, PLC is **$0.764 billion**, and development schedule is at least **14 months**.

	Performance Attributes					*Resource Attributes*				
Design (Number)	Program Payload (*kg*)	Program Speed	Program Delta-V (ms^{-1})	Prob. Success	Mission Time	PDC (*$mil*)	PLC (*$mil*)	PDS (*mths*)	Utility	Expense
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B (28900)	300	Fast/Fast	8091	0.96	Short	1805	808	8	0.774	0.208
C (59860)	300	Fast/Fast	12645	0.92	Short	2090	764	14	0.800	0.254
D (125908)	1000	Fast/Fast	8910	0.88	Short	3420	1212	28	0.823	0.448
E (127972)	1000	Fast/Fast	16150	0.88	Short	4750	1800	28	0.840	0.517
F (194020)	3000	Fast/Fast	10984	0.86	Short	8550	3080	42	0.915	0.763

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Conclusion & Future Work

- Defined affordability as an ility
- Introduced tradespace-based methods to conduct affordability analysis
  - Methods are scalable from systems to programs to portfolios
- Demonstrated methods on system and program levels for Space Tug
- Further examples and details can be found in:

Wu, M.S., "Design for Affordability in Defense and Aerospace Systems Using Tradespace-Based Methods," SM thesis in Technology and Policy and Aeronautics and Astronautics, MIT, June 2014. (accessible via http://seari.mit.edu)

MATE, EEA and MAE can be used in the design for affordability to avoid cost overruns and schedule slippages in the long run

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THANK YOU VERY MUCH!

ANY QUESTIONS?

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Design For Affordability In Complex Systems And Programs Using Tradespace-based Affordability Analysis

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References

Carter, A. B. (2010a). Better buying power: Guidance for obtaining greater efficiency and productivity in defense spending [Memorandum].

Carter, A. B. (2010b). Better buying power: Mandate for restoring affordability and productivity in defense spending [Memorandum].

Cordesman, A.H. and Frederiksen, P.S., America's Uncertain Approach to Strategy and Force Planning. Working Draft Center submitted to Center for Strategic and International Studies, 2006.

de Weck, O.L., Ross, A.M., and Rhodes, D.H., "Investigating Relationships and Semantic Sets amongst System Lifecycle Properties (Ilities)," 3rd International Conference on Engineering Systems, TU Delft, the Netherlands, June 2012.

Diller, N.P., *Utilizing Multiple Attribute Tradespace Exploration with Concurrent Design for Creating Aerospace Systems Requirements*, Master of Science Thesis, Aeronautics and Astronautics, MIT, June 2002.

Emmons, D.L., Lobbia, M., Radcliffe, T., and Bitten, R.E. (2010). *Affordability assessments to support strategic planning and decisions at NASA*. Aerospace Conference, 2010 IEEE, vol., no., pp.1,13, 6-13March 2010. doi: 10.1109/AERO.2010.5446893

Institute of Defense Analyses (IDA) (2009). The Major Causes of Cost Growth in Defense Acquisition. Volume I: Executive Summary. IDA Paper P-4531 Log: H 09-001671, December 2009.

Keeney, R. L. and Raiffa, H. (1993). *Decisions with Multiple Objectives-Preferences and Value Tradeoffs*. Cambridge, UK, Cambridge University Press.

Kroshl, W.M. and Pandolfini, P.P. (2000). *Affordability Analysis for DARPA Programs*. John Hopkins APL Digest, Volume 21, Number 3 (2000).

Rhodes, D.H. and Ross, A.M., "Anticipatory Capacity: Leveraging Model-Based Approaches to Design Systems for Dynamic Futures," 2nd Annual Conference on Model-based Systems, Haifa, IL, March 2009.

Ross, A.M. and Hastings, D.E., "The Tradespace Exploration Paradigm," INCOSE International Symposium 2005, Rochester, NY, July 2005.

Ross, A.M., and Rhodes, D.H., "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," INCOSE International Symposium 2008, Utrecht, the Netherlands, June 2008.

Schaffner, M.A., Wu, M.S., Ross, A.M., and Rhodes, D.H., "Enabling Design for Affordability: An Epoch-Era Analysis Approach," Proceedings of the 10th Annual Acquisition Research Symposium- Acquisition Management, April 2013.

Tuttle,P. and Bobinis, J., Affordability Specification. 2012 MORS Symposium: Affordability: How Do We Do It?, October 2012.

Wertz, J.R. and Larson, W.J. (2011). *Space Mission Analysis and Design (SMAD)*. Microcosm Press.

Wu, M.S., Ross, A.M., and Rhodes, D.H., "Design for Affordability in Complex Systems and Programs Using Tradespace-Based Affordability Analysis," 12th Conference on Systems Engineering Research, Redondo Beach, CA, March 2014.

Wu, M.S., "Design for Affordability in Defense and Aerospace Systems Using Tradespace-Based Methods," Master of Science Thesis, Technology & Policy and Aeronautics and Astronautics, MIT, June 2014.

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