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

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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
- 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

- 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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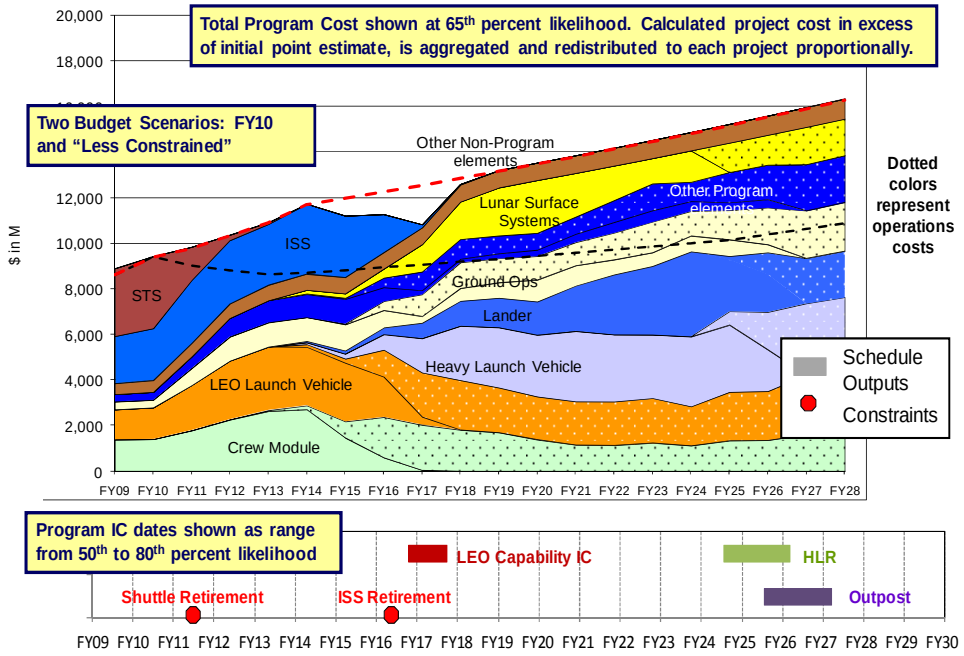
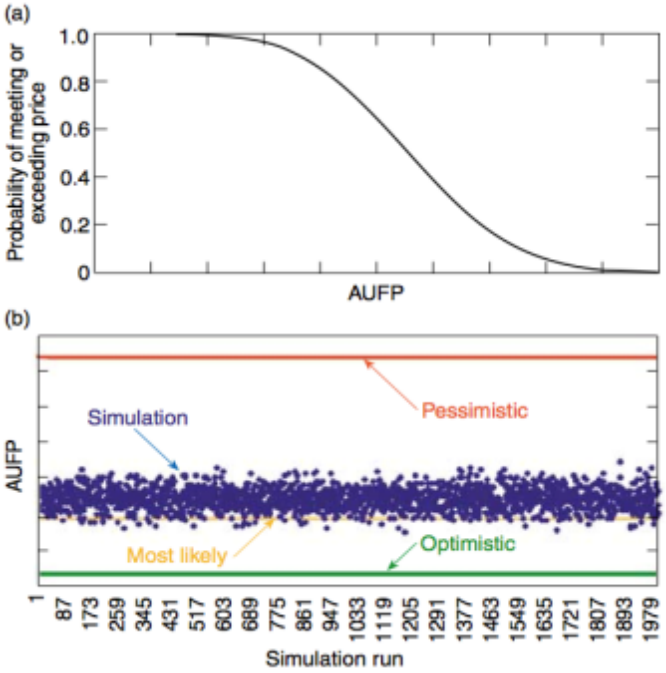
The Affordability Paradigm

- 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
- Fail to explicitly capture dynamics elements of system or program and its operating environment over its lifecycle
- Need to have a *common definition* and a *common set of principles* for affordability analysis
- Need to have a *new philosophy* for treating the affordability paradigm

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Affordability as an Ility

- Define **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
- This facilitates the application of *tradespace exploration* methods 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
- **Resource constraints**: Statements of restrictions on these requirements that limit range of feasible solutions
- **Goal of Affordability Analysis**: ***Identify solutions that remain feasible throughout or for a large part of the system lifecycle***

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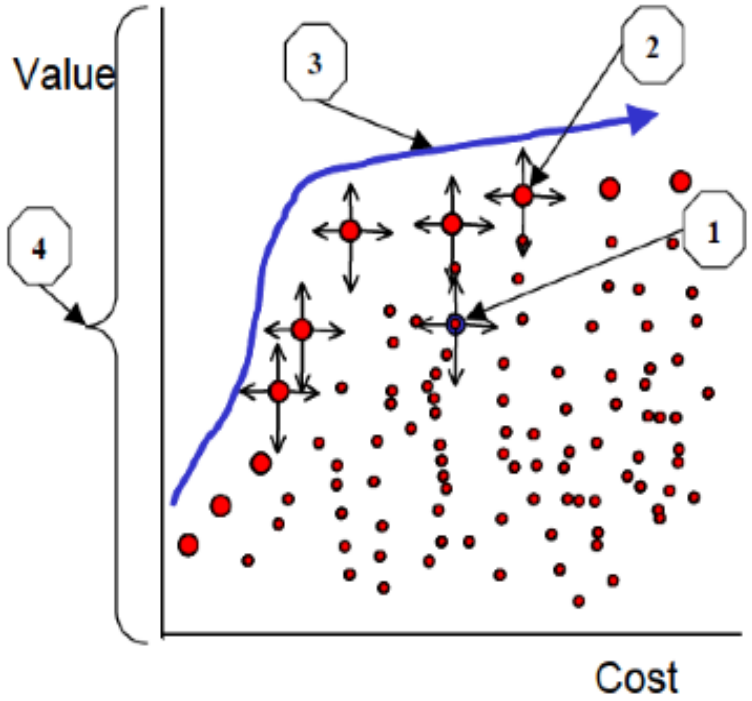
Tradespace-based Methods

- **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



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

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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. Use **Epoch-Era Analysis (EEA)** to account for the evolution of a system or program over time

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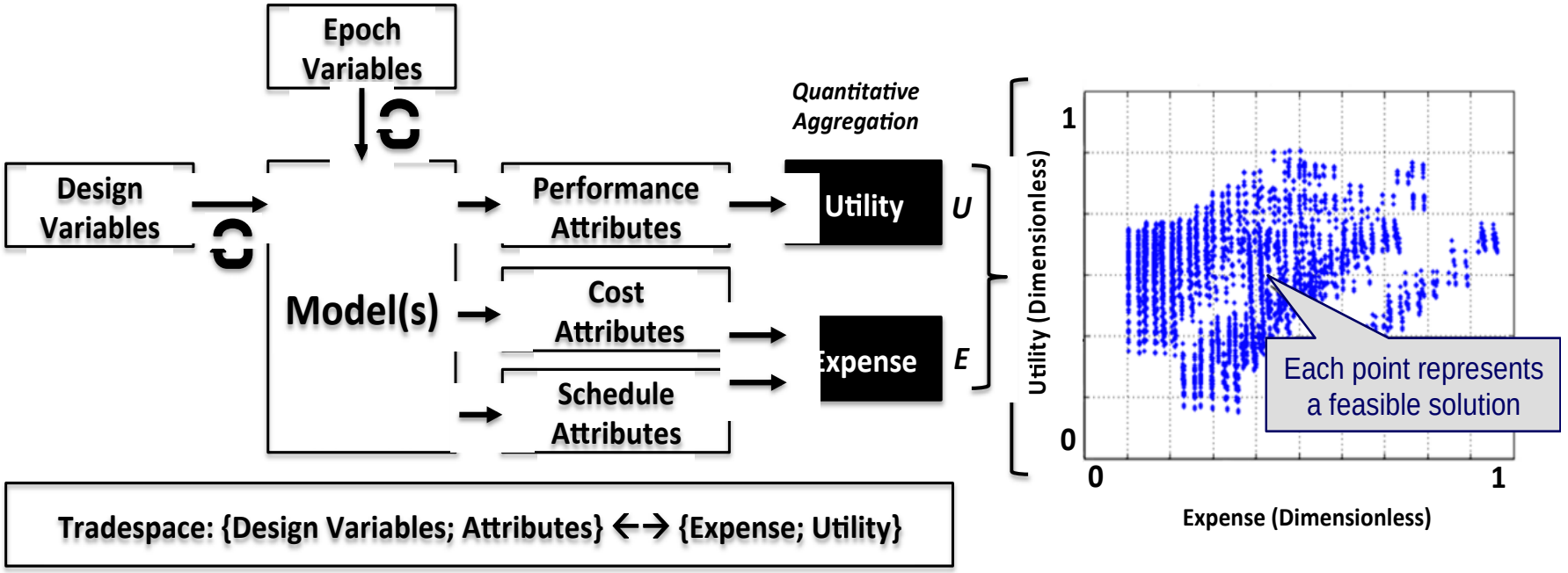
MATE for Affordability



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", which may be spent with differing degrees of ease and have different levels of acceptability to stakeholders

$$KE(X) + 1 = \prod_{i=1}^{N} [Kk_i E_i(X_i) + 1]$$ (Nathan P. Diller 2002)

- MAE is similar to Multi-Attribute Utility (MAU) function by (Keeney and Raifa 1993) and it is a dimensionless, non-ratio scale metric
- 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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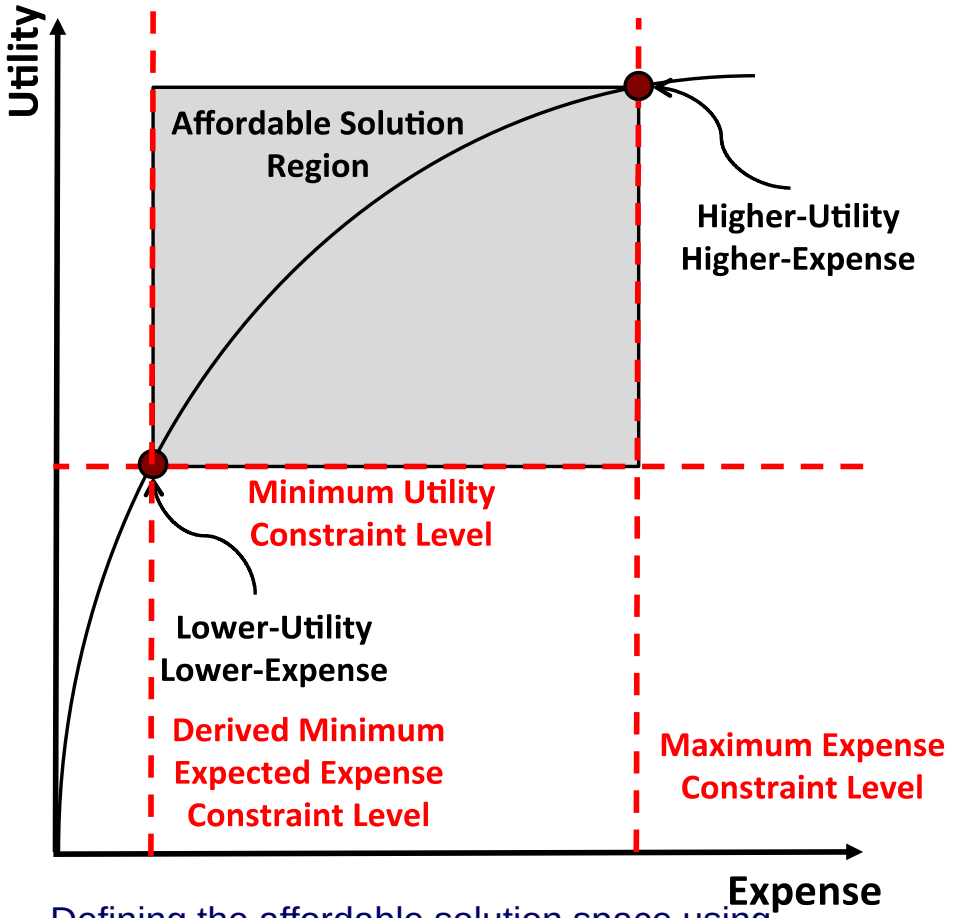
Constraint Levels

- **Constraint levels reflect external constraints that are independent of stakeholder preferences**
- 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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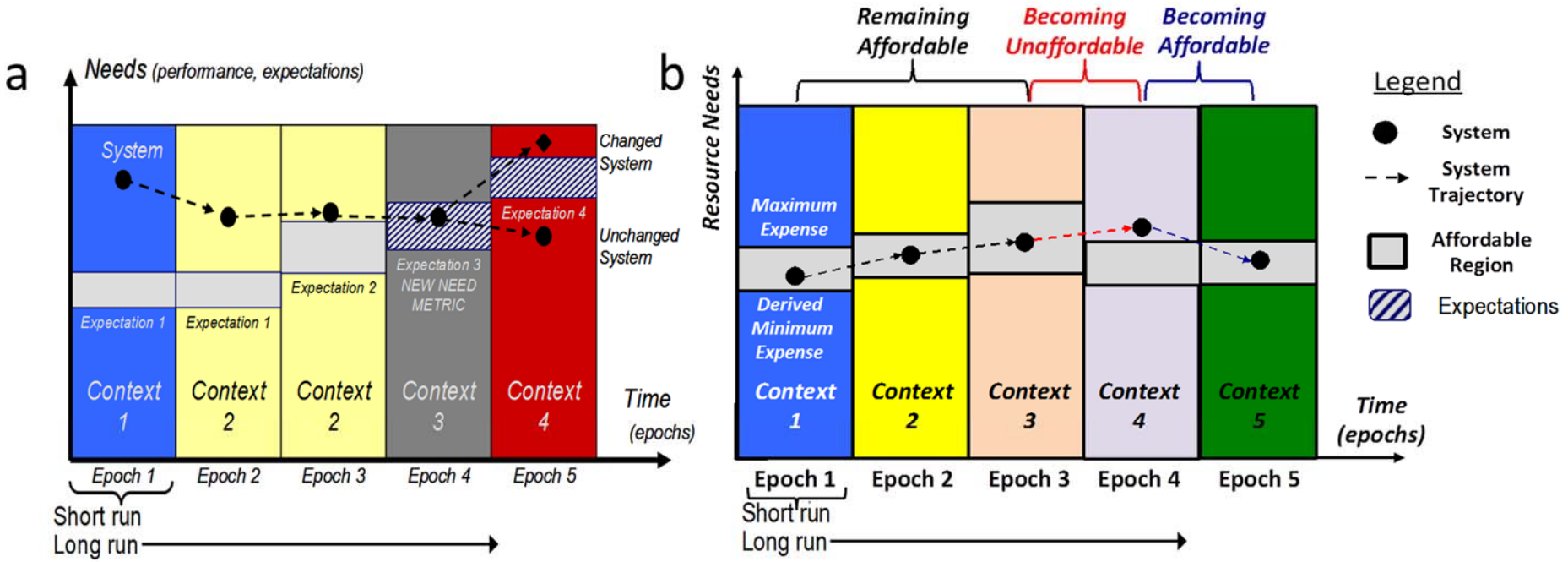
EEA for Affordability

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



(a) Original Epoch-Era Analysis Diagram by Ross and Rhodes 2012 ; (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**
- 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 Larsson 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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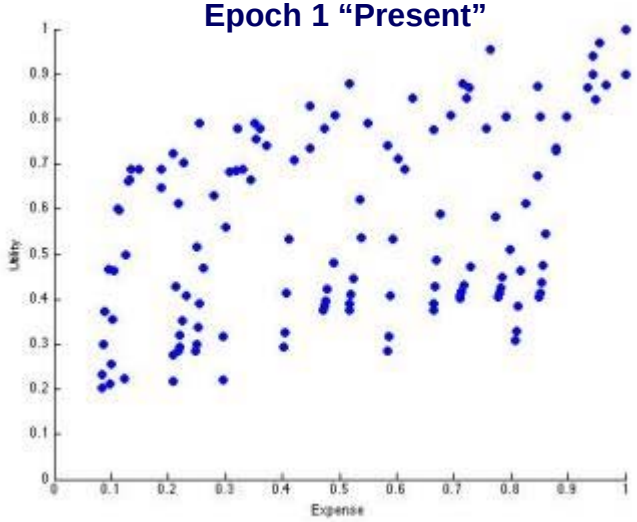
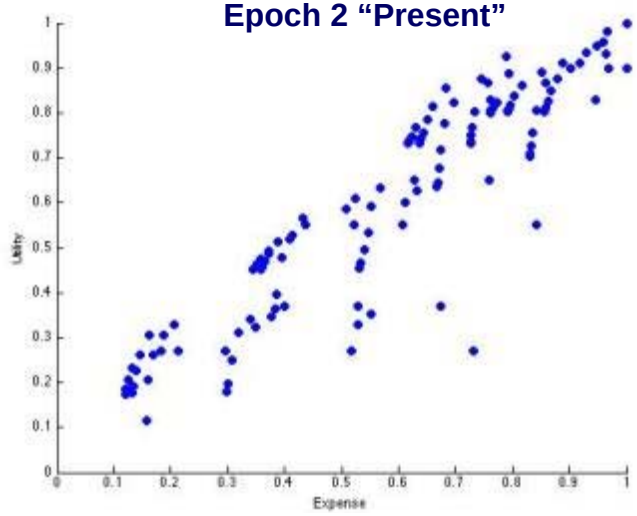
System Level Analysis

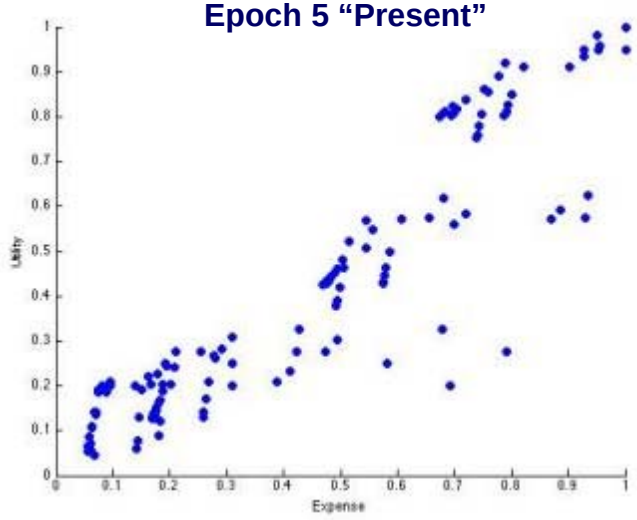
Epoch 1 "Present"



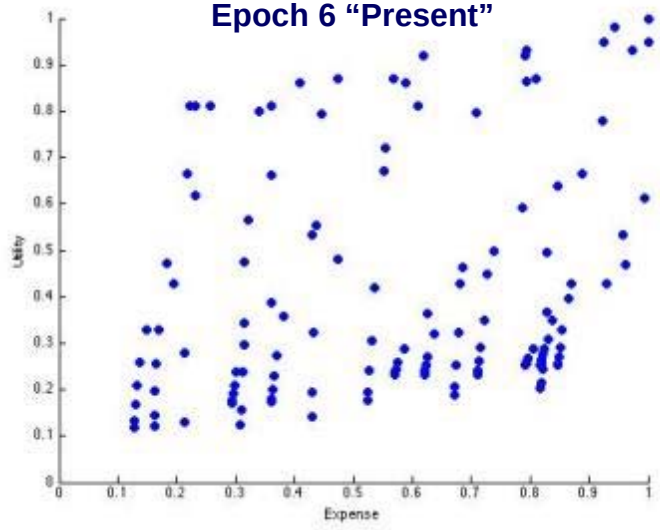
Epoch 2 "Present"



Epoch 5 "Present"



Epoch 6 "Present"



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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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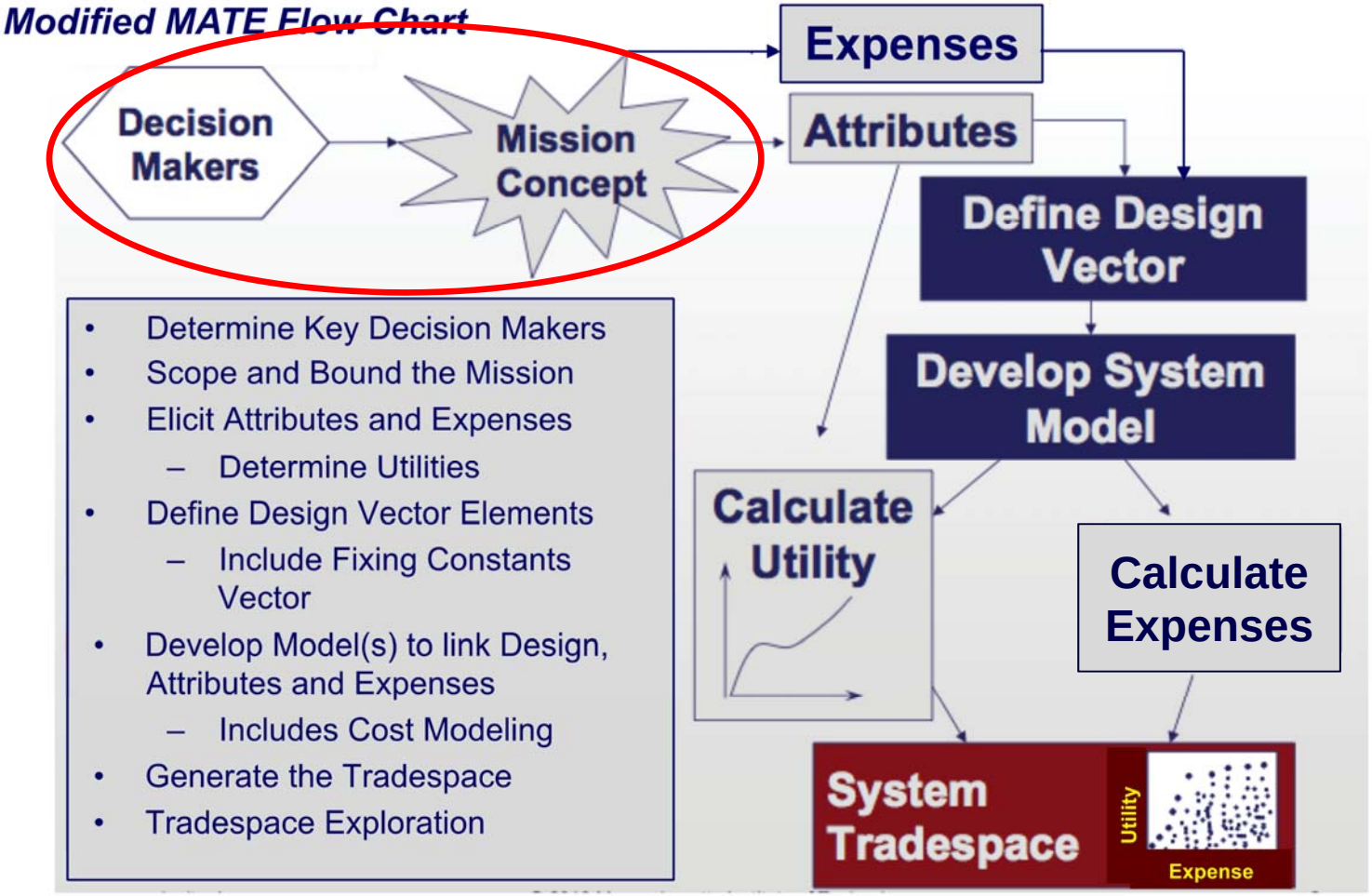
Program Level Analysis



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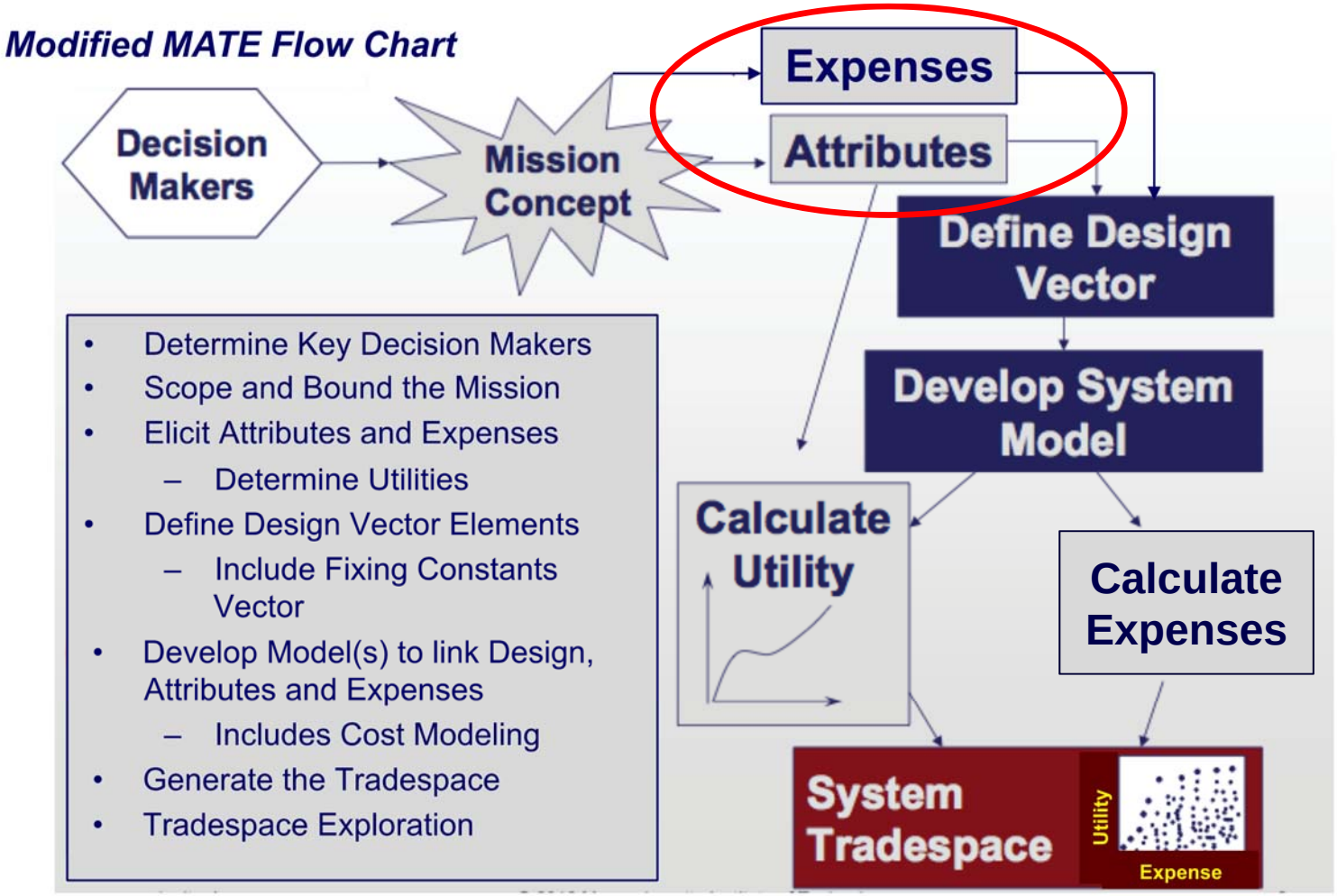
Program Level Analysis



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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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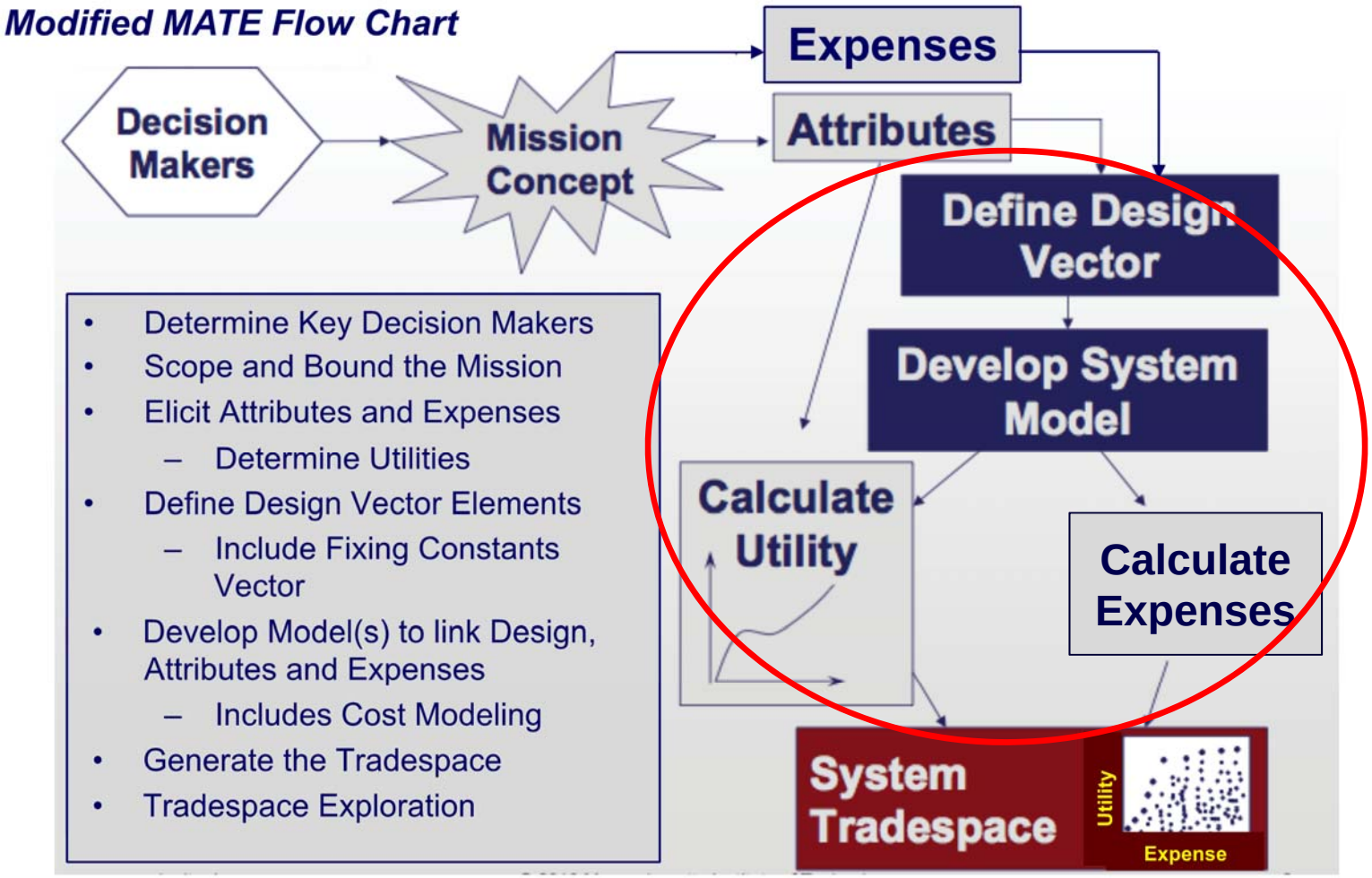
Program Level Analysis



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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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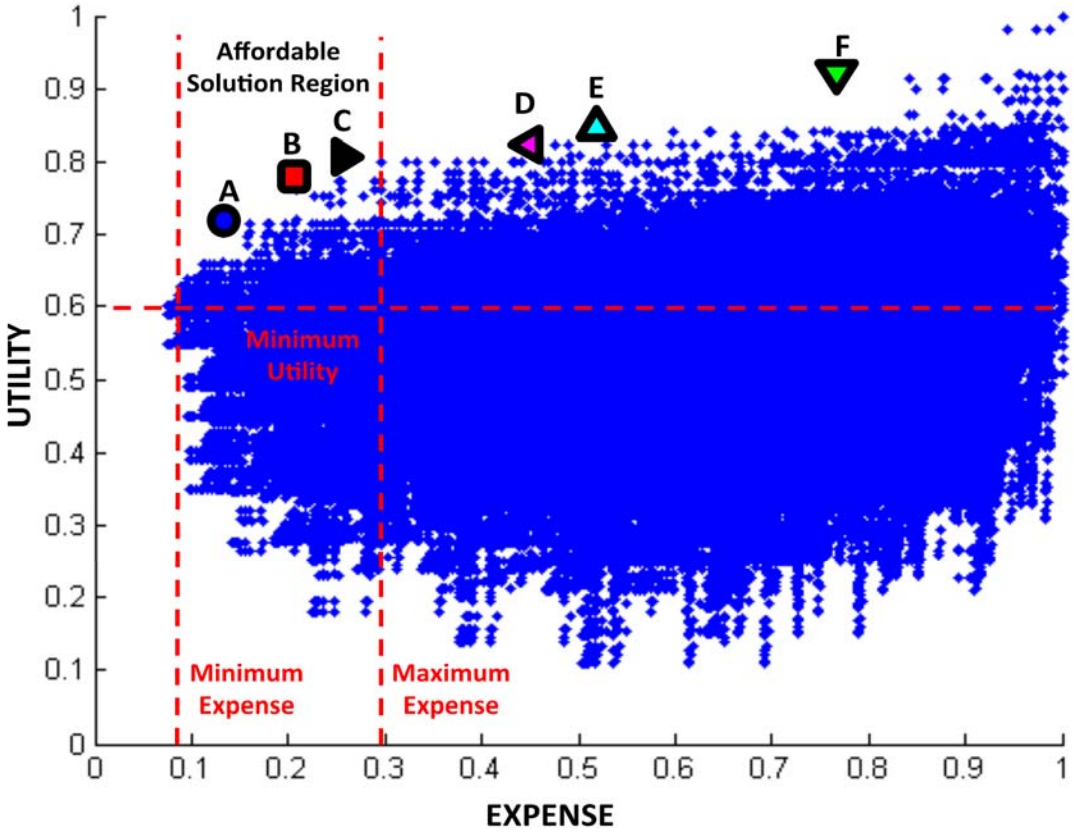
Single-Epoch Analysis

- 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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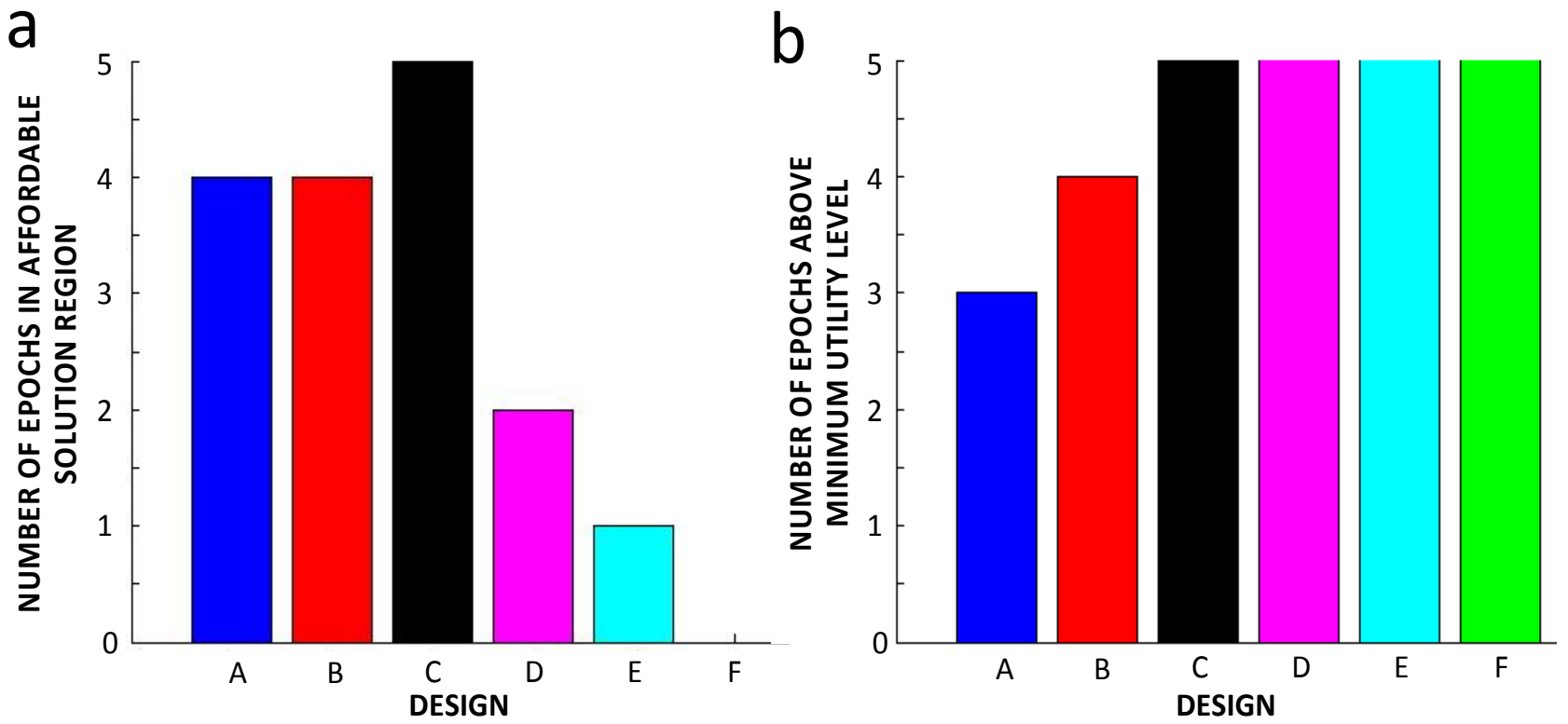
Multi-Epoch Analysis



(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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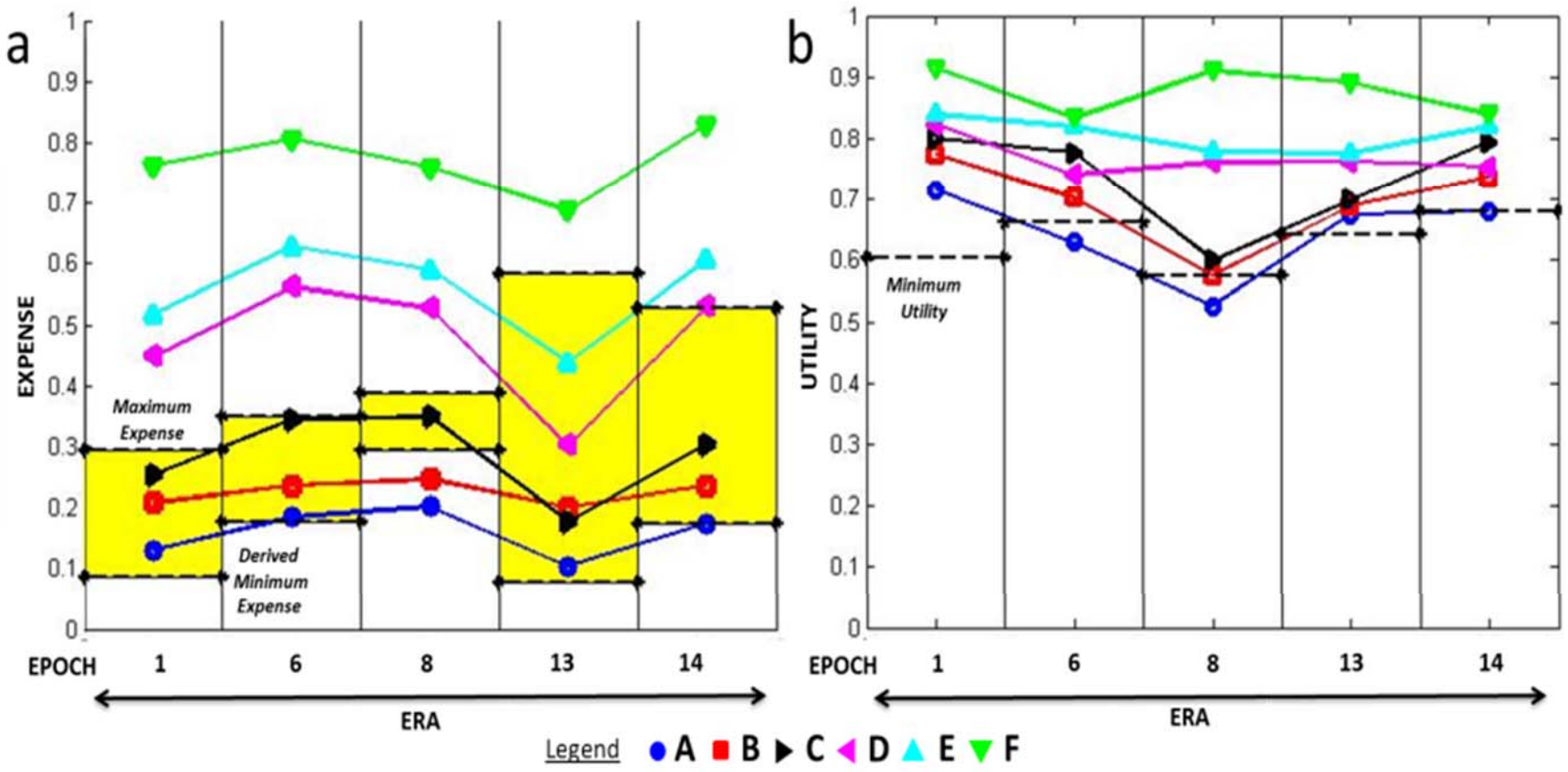
Single-Era Analysis

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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Conclusion & Future Work

- Defined affordability as an ility
- Introduced tradespace-based methods to conduct affordability analysis and to search for affordable solutions dynamically using a resource-centric approach
- Constructed system and program tradespaces for Space Tug
- Conducted Single-Epoch, Multi-Epoch and Single-Era Analysis
- Can be extended to Multi-Era Analysis and complement with studies on other ilities
- Scalable from systems to programs to portfolios

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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