SEAri Short Course Series

Course: PI.27s Value-driven Tradespace Exploration for System Design

Lecture: Lecture 14: Summary of a New Method

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Systems Engineering Advancement Research Initiative

[PI.27s] Value-Driven Tradespace Exploration for System Design

Summary of a New Method

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PROFESSIONAL EDUCATION

Massachusetts Institute of Technology

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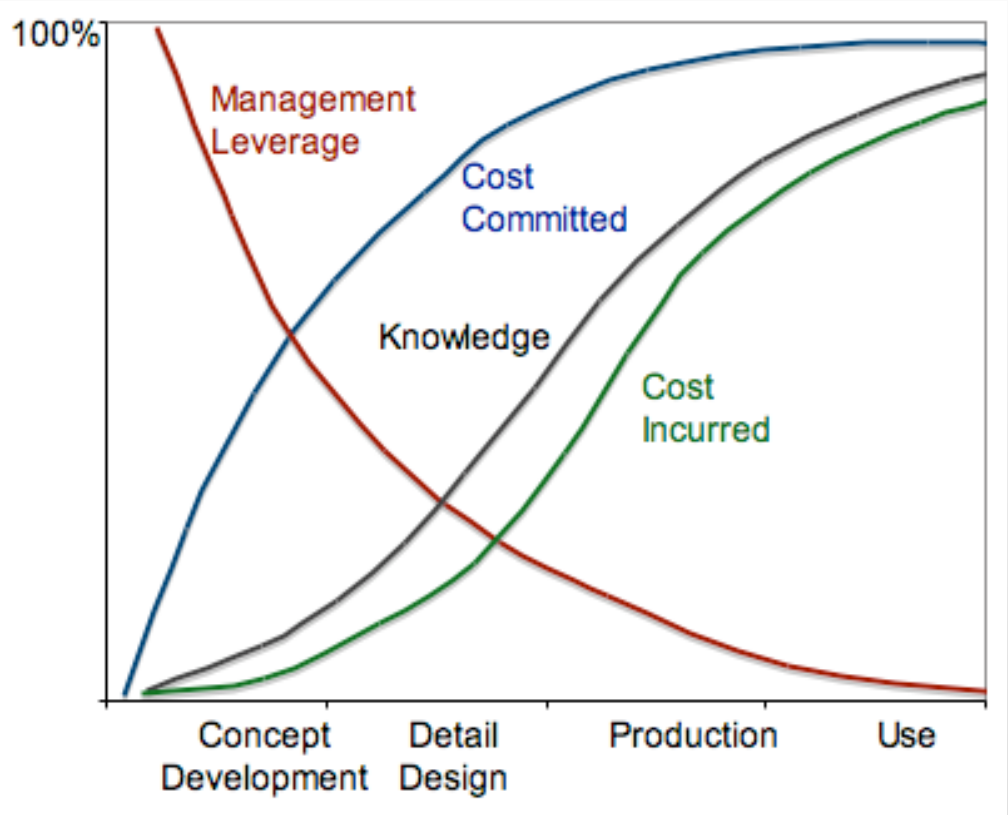
Outline

- Summary of key concepts
- Research directions
- Where to find more information

The Design Knowledge Gap

Value is primarily determined at the beginning of a program



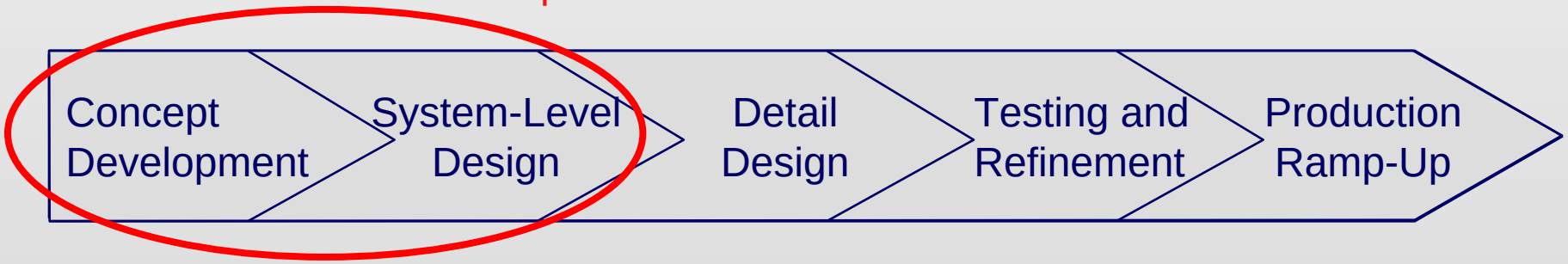
Adapted from Fabrycky and Blanchard 1991

How can we make good decisions?

A Method for the Front End

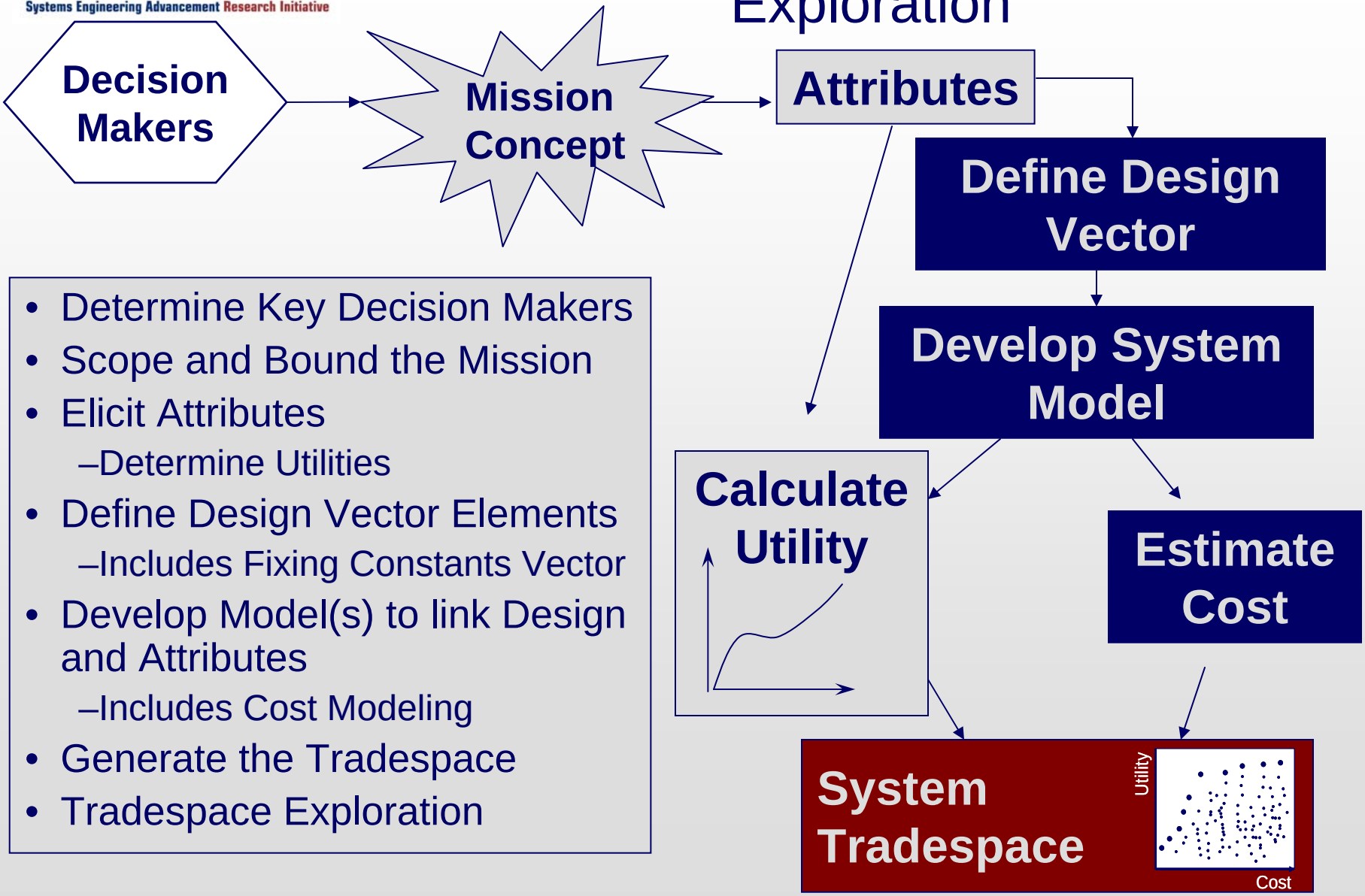
- MATE Method for Tradespace Exploration
  - Means for understanding complex solutions to complex problems
- ICE Integrated Concurrent Engineering
  - Rapid Conceptual/Preliminary Design Method
- Allows informed upfront decisions and planning

Most relevant to processes in these phases



Phases of Product Development From Ulrich & Eppinger, *Product Design and Development*, 1995

Steps for Multi-Attribute Tradespace Exploration



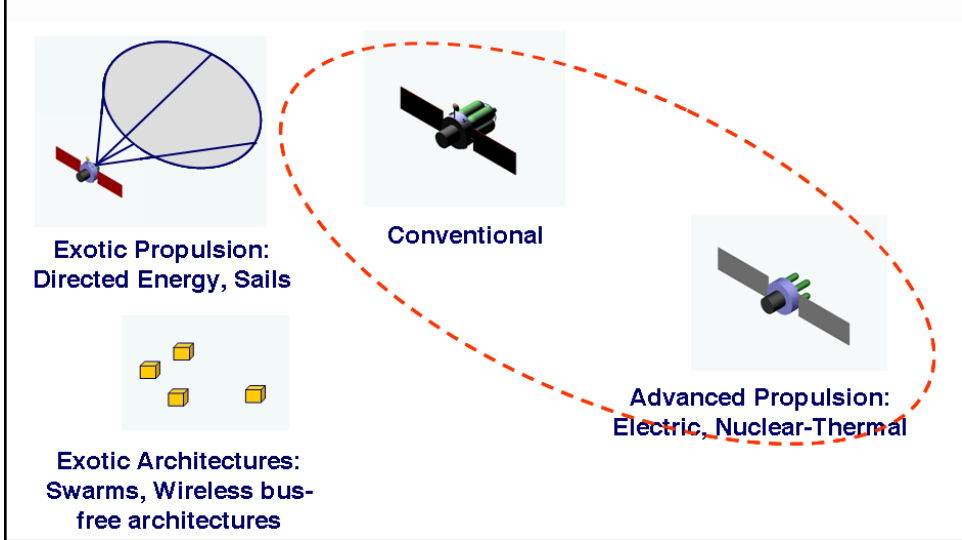
- Determine Key Decision Makers
- Scope and Bound the Mission
- Elicit Attributes
  - –Determine Utilities
- Define Design Vector Elements
  - –Includes Fixing Constants Vector
- Develop Model(s) to link Design and Attributes
  - –Includes Cost Modeling
- Generate the Tradespace
- Tradespace Exploration

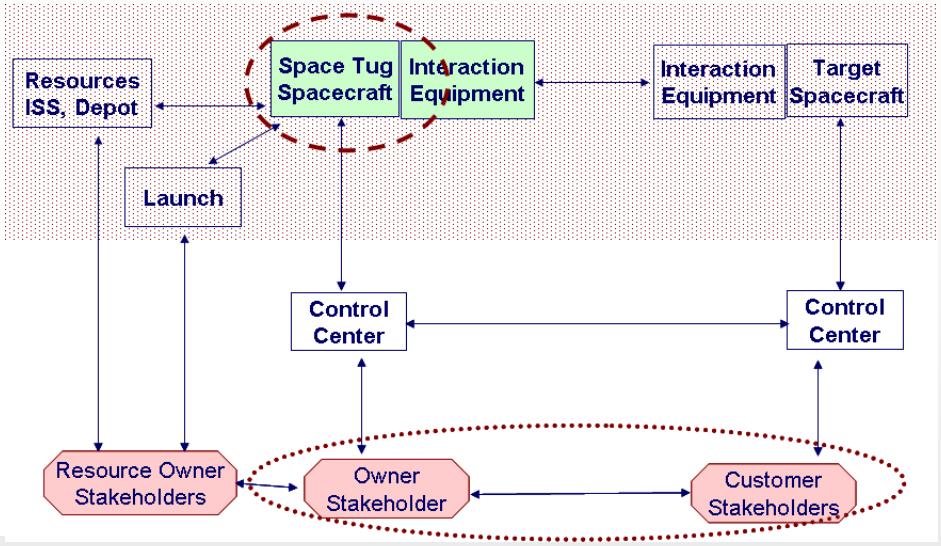
Decision Makers and Mission Concept

- Choose Decision Makers that you have to satisfy - *they will define the utility*
- Choose Mission Concept(s) - the basic framework you will use to define the design vector
  - Open enough so that creative solutions are not excluded
  - Defined enough to be tractable

Space Tug Example:
- (potential) Stakeholder need is for infrastructure to maintain on-orbit assets
- Mission concept is vehicle that can rendezvous with and interact with on-orbit assets
- Project Mission is to assess how potential systems could satisfy potential stakeholders

Bound and Scope: Space Tug





Choose finite (but as open as possible) set of potential solutions

Choose the parts of the overall system that you will design

Define Attributes

- **<u>Defined by the decision maker</u>**, with designer assistance
- Define units, lowest acceptable value, highest meaningful value
- Set of 3-7 attributes should obey, to the extent possible, perceived independence and other rules
- Ideally:
  - Reflect what the decision maker cares about
  - Computable
  - Sensitive to design decisions

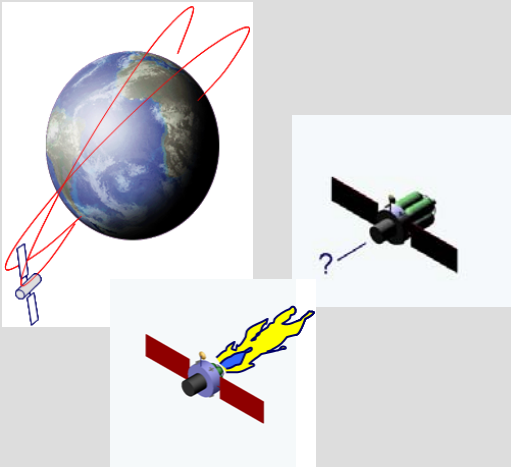
You will probably have to iterate

Space Tug Example:

1) **Delta-V**: How much velocity can the vehicle impart on itself and/or the target? (km/sec) [>0→12]

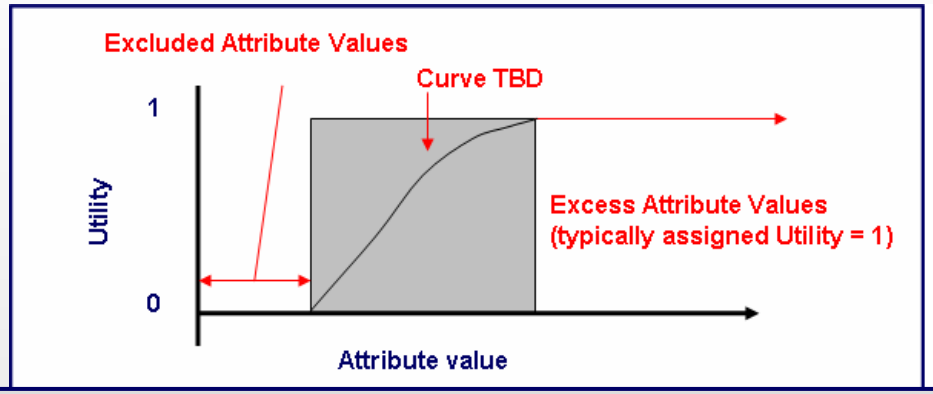
2) **Interaction Capability**: What can the vehicle do to the target? (kg of equipment carried) [>0→5000]

3) **Speed**: Can the Space Tug change orbits in days? Months? (binary) [0→1]

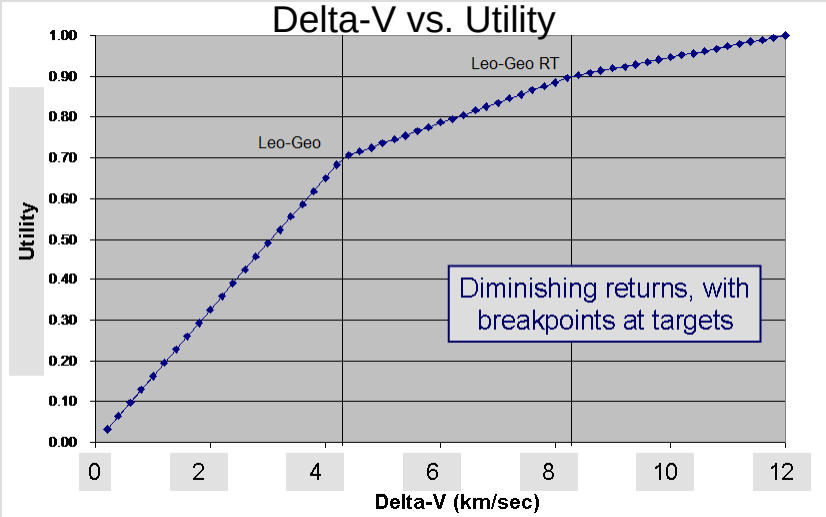


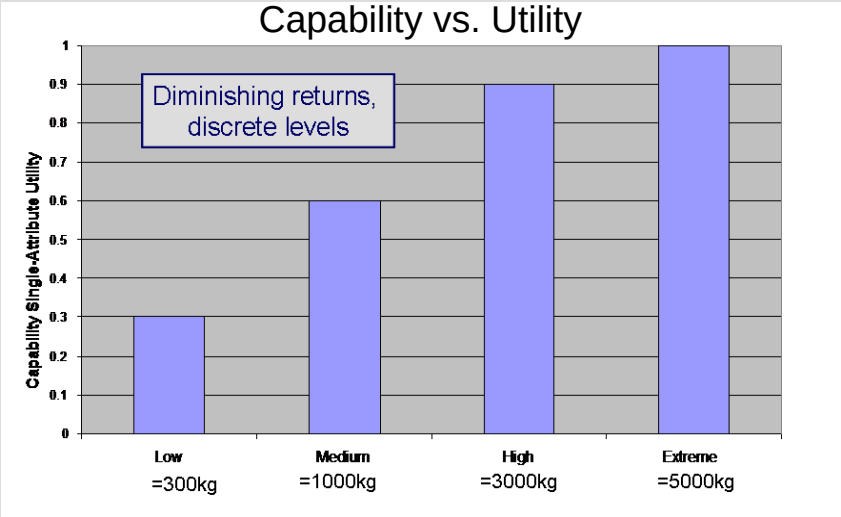
Defining Utilities

- Each attribute (worst to best value) monotonically maps to utility (0 to 1)
- Need rule for under/over values

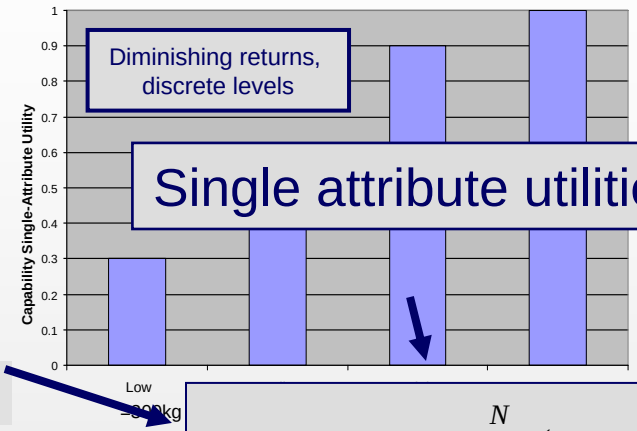


Space Tug Example:

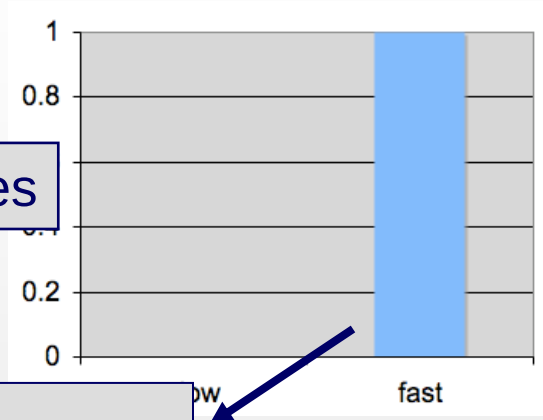




Aggregating Utilities

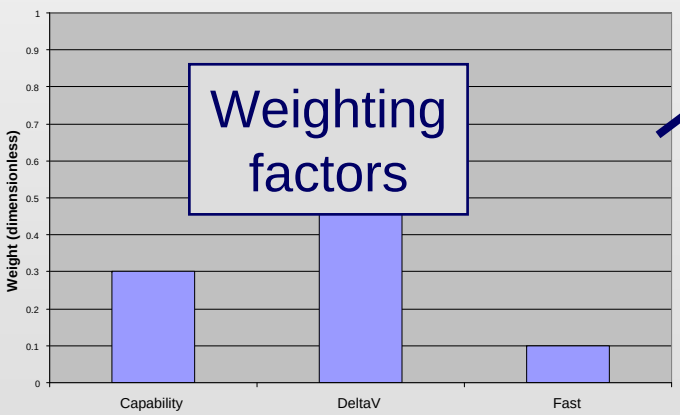


Single attribute utilities



$$KU(\underline{X})+1=\prod_{i=1}^{N}\left(Kk_iU(X_i)+1\right)$$

Aggregating Function



Weighting factors

- *If possible*, define an aggregating function
  - Weighted sum often used (iff $\Sigma k_i=1$!)
  - MAUT Keeney-Raiffa function best
  - Weights defined by decision maker

Defining the Design Vector

- The design vector defines the space of designs that will be considered - a key step!
- Define units, range to be considered, sampling levels
- Good design vector elements (DV)
  - Capture the range of possible solutions
  - Are realistic, physically or in terms of available technology or components
  - Are under the direct control of the designer
  - Impact the attributes
- Steps:
  - Brainstorm individually & in groups, consider *how to best affect the attributes*
  - Use a DVM to map DV to attributes to screen out unnecessary DV and to motivate creation of more DV if attributes are not affected

Space Tug Example:

- Manipulator Mass (=Capability)
  - Low (300kg), Medium (1000kg), High (3000 kg), Extreme (5000 kg)
- Propulsion Type
  - Storable bi-prop, Cryogenic bi-prop, Electric (NSTAR), Nuclear Thermal
- Fuel/Reaction Mass Load
  - 8 levels, geometric progression (30 to 30000kg)

The Constants Vector

- To keep modeling general and adaptable to later changes, *do not "hardwire" assumptions into code*
- Instead, keep list (data structure) of "constants"
- Five types (at least):
  - True constants (g, π), value may change if your units change…
  - Constraints (policies, standards…)
  - Modeling assumptions ($/kg, W/GHz, Margins…)
  - Quantities associated with design vector choices
  - Potential design vector elements (things under designers control) that have been fixed - *record reason*

Space Tug Example:

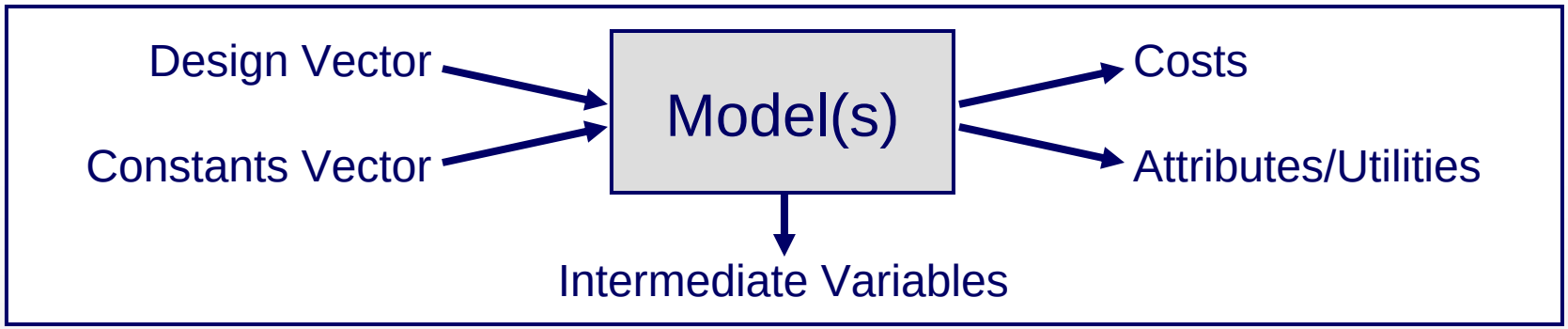
Design Var. Associated Quantities

Propulsion System	I_{sp} (sec)	Base Mass m_{p0} (kg)	Mass Fract. m_{pf}	High Impulse
Storable biprop	300	0	0.12	Y
Cryo	450	0	0.13	Y
Electric	3000	25	0.30	N
Nuclear	1500	1000	0.20	Y

- True constants
  - g Acceleration due to gravity (9.8 m/sec^2)
- Modeling assumptions
  - c_d Dry mass cost coefficient ($/kg)
  - c_w Wet mass cost coefficient ($/kg)
  - m_{bf} Bus mass fraction coefficient
- Quantities associated with design vector choices
  - I_{sp} Specific impulse (sec)
  - m_{p0} Propulsion system base mass (kg)
  - m_{pf} Propulsion system mass fraction coefficient
- Potential design vector elements (things under designer's control) that have been fixed - *record why*

  (examples) Launch cost and time, operations cost - mostly scope and resources

Modeling



- Calculate Costs & Attributes from Design Vector & Constants Vector
- Approaches:
  - Tabulation - car example from previous lecture
  - Explicit calculation - Attributes = f(DV, CV)
  - Implicit or iterative calculations
    - May involve local optimizations
  - Simulations/Scenarios
- Calculate single- and multi-attribute Utilities
- All but the simplest models will involve important *Intermediate Variables* (e.g. system mass, power) which should be explicitly calculated and tracked

Motivating the Model: Space Tug

Attributes \ Design Vars	Propulsion System	Fuel Load	Equipment Mass	Total
Delta-V	9	9	9	27
Speed	9	1	1	11
Equipment Capability	0	0	9	9
Total	18	10	19	

DVM can also be used to motivate and identify relationships for models

- Very simple, explicit, physics-based model
- Intermediate Variables (masses):

Propulsion System Mass	$M_p = m_{p0} + m_{pf} M_f$
Bus Mass	$M_b = M_p + m_{bf} M_c$
Dry Mass	$M_d = M_b + M_c$
Wet Mass	$M_w = M_d + M_f$

- Attributes

Delta-V	$\Delta v = g\, I_{sp} \ln(M_w / M_d)$
Capability	*Table lookup*
Speed	*Table lookup*

Purpose of model: Calculate "performance" of each design in terms of attributes, costs, and utilities

Cost Modeling

- Need cost estimates for each design
  - For decision making, *not budget planning*
  - Order of magnitude costs for concepts
  - Relative costs of various concepts
- Many approaches and tools available
- Fidelity will be low in early design (this is OK)
  - Expect +/- 30% error, even in simple stuff
- Need to keep track of limits and weaknesses of cost (and other) models (ROM uncertainties)

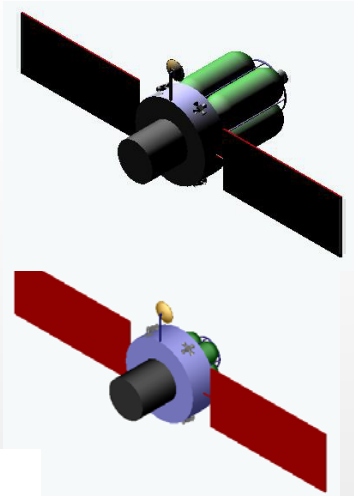
Space Tug Example:

$$C = c_w \; M_w + c_d M_d$$

- Very very simple parametric model
- Appropriate to broad survey
- Important to understand what is *not* modeled
  - Software
  - Launch
  - Technology Development

Baseline Study: Space Tug

- Existing MATE* study of space tug tradespace
  - Three attributes
    - Delta-V
    - Capability
    - Response time
  - Three design variables

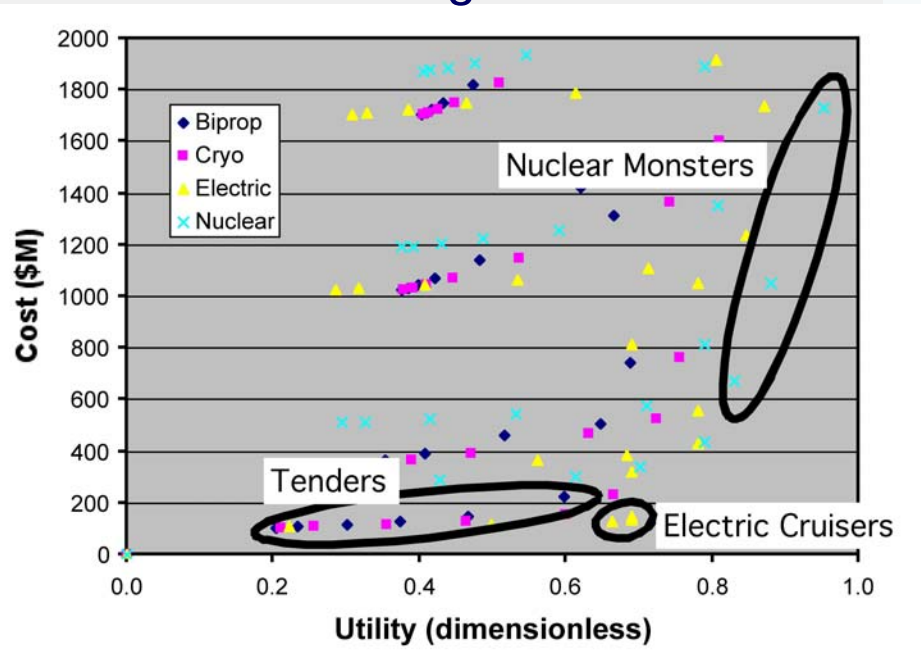


Design Space

>Manipulator Mass
- Low (300kg)
- Medium (1000kg)
- High (3000 kg)
- Extreme (5000 kg)

>Propulsion Type
- Storable bi-prop
- Cryogenic bi-prop
- Electric (NSTAR)
- Nuclear Thermal

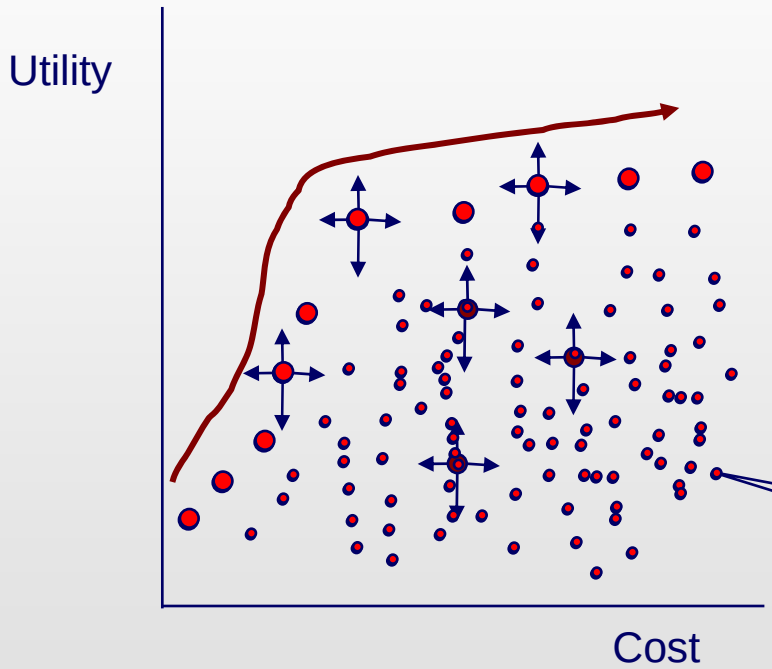
>Fuel Load - 8 levels



>Simple performance model
- Delta-V calculated from rocket equation
- Binary response time (electric propulsion slow)
- Capability solely dependent on manipulator mass
- Cost calculated from vehicle wet and dry mass

* MATE: Multi-Attribute Tradespace Exploration; see McManus, H., and Schuman, T., "Understanding the Orbital Transfer Vehicle Tradespace," AIAA-2003-6370, Sept. 2003..

Architecture Tradespace Analysis: Avoiding Point Designs



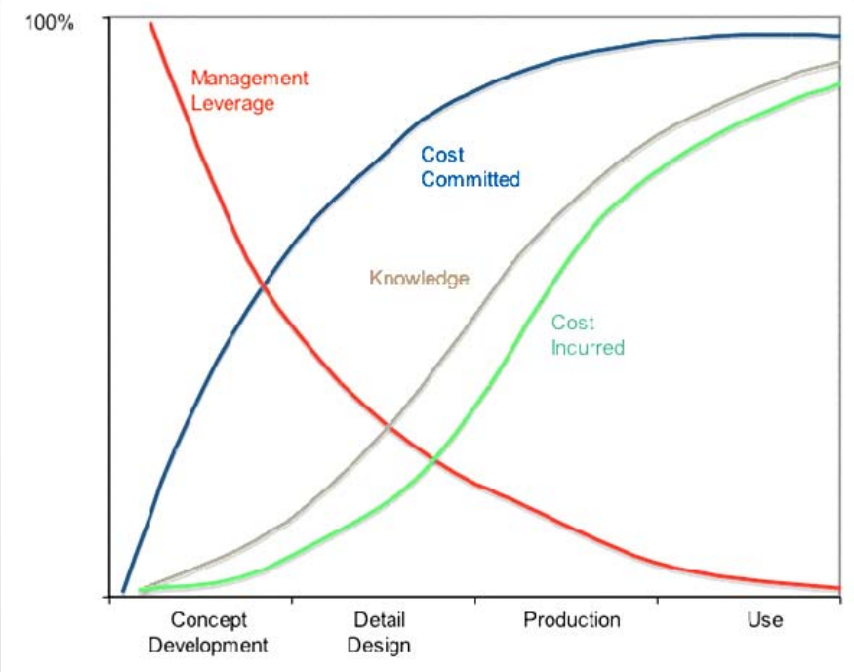
Differing types of trades

1. Local point solution trades
2. Multiple points with trades
3. Frontier solution set
4. Full tradespace exploration

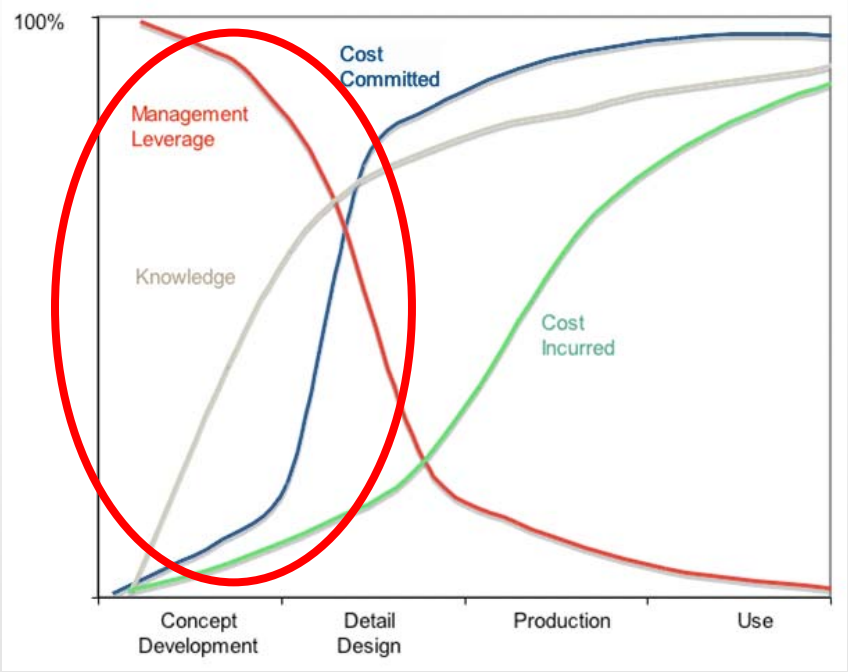
$Design_i = \{X_1, X_2, X_3, \ldots, X_j\}$

Tradespace exploration enables big picture understanding

Changing the Picture



Classic decision impacts



New paradigm decision impacts

Increased knowledge (including understanding of uncertainties) allows better decisions

Tradespace Exploration
Research Directions at MIT SEAri

Dynamic World Motivates Research Directions

Stakeholder needs change as perception of system and value delivered evolves

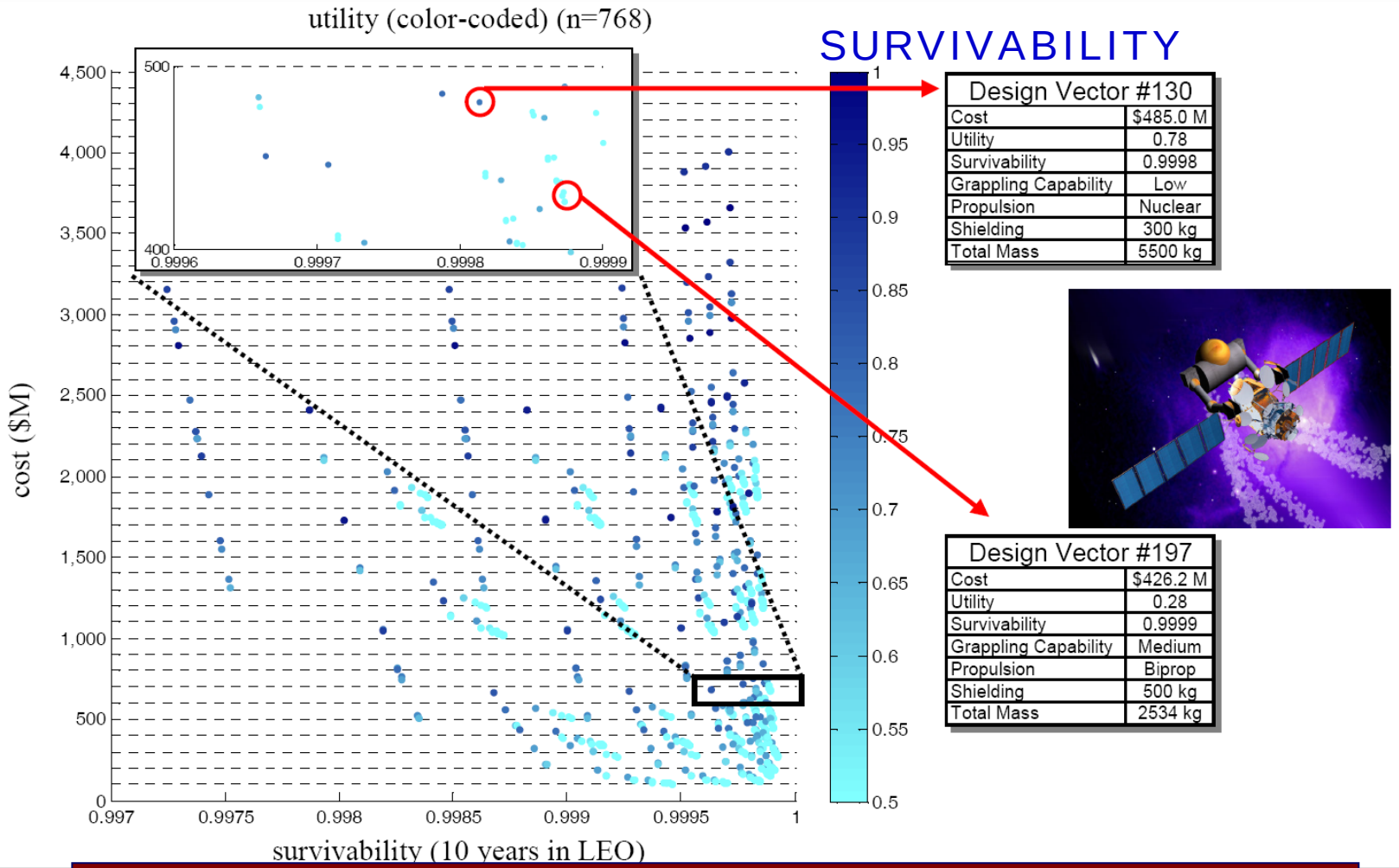
Systems exist in dynamic cultural, political, financial, market environments

Highly complex and interconnected systems with changing technology over long lifespans

Research Across Our Five Aspects Taxonomy

STRUCTURAL	related to form of system components and their interrelationships
BEHAVIORAL	related to function/performance, operations, and reactions to stimuli
CONTEXTUAL	related to circumstances in which the system or enterprise exists
TEMPORAL	related to the dimensions and properties of systems over time
PERCEPTUAL	related to stakeholder preferences, perceptions and cognitive biases

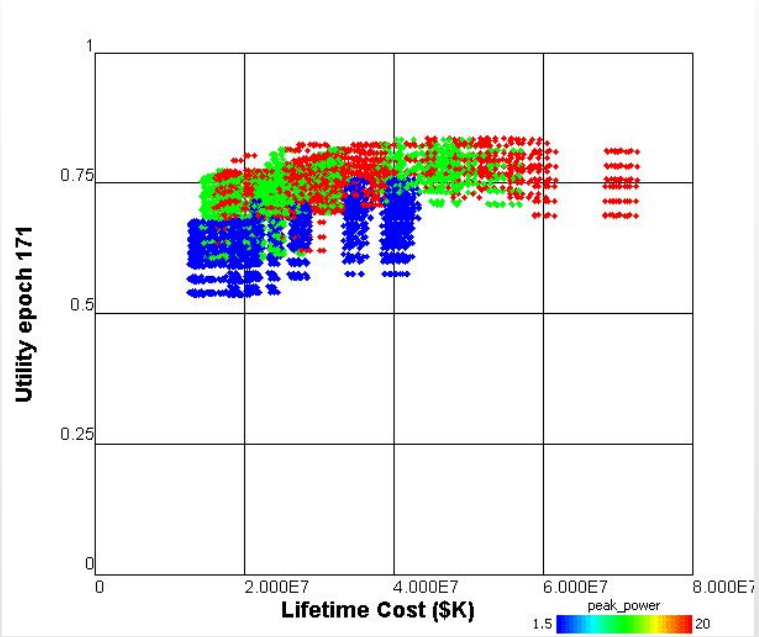
Behavioral Aspect: Incorporating Ilities in Tradespace Exploration



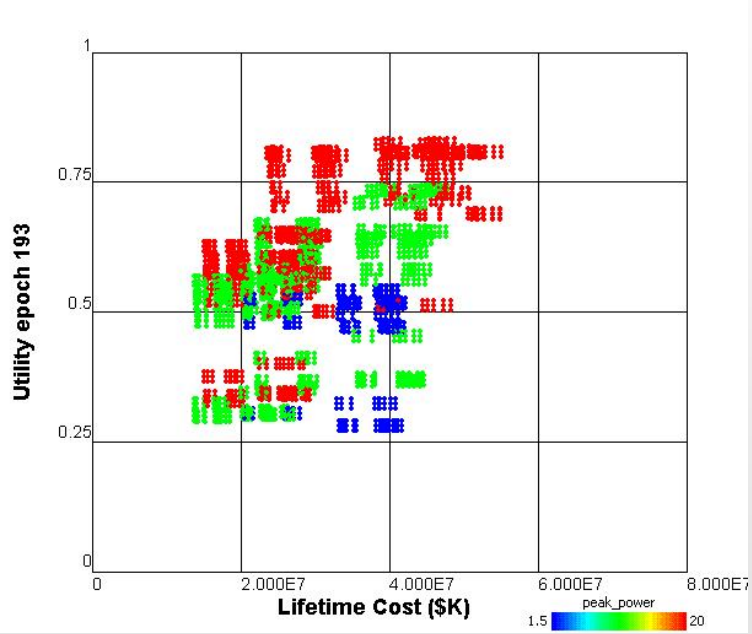
McManus, H., Richards, M., Ross, A., and Hastings, D., "A Framework for Incorporating "ilities" in Tradespace Studies," *AIAA Space 2007*, Long Beach, CA, September 2007.

Contextual Aspect Example: Multi-Epoch Tradespaces

Epoch "171"
Baseline Program Context:
Standalone capability needed, Imaging mission (primary)



Epoch "193"
New Program Context:
Cooperative capability needed, Tracking mission (primary)

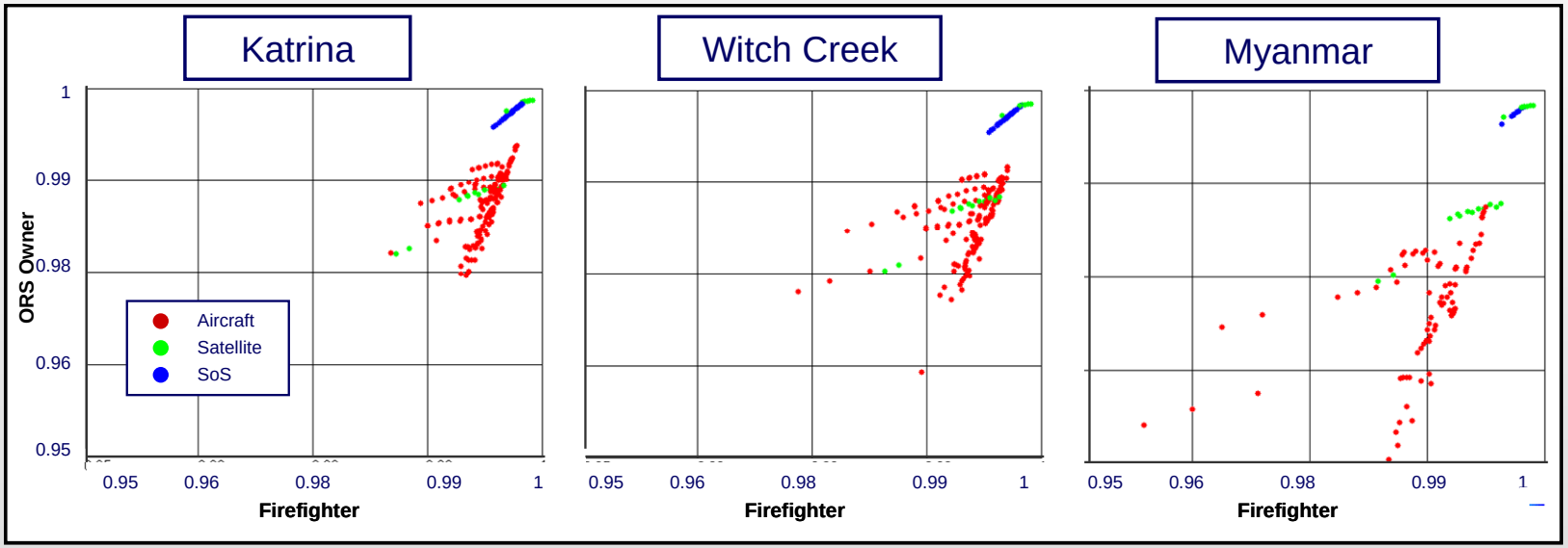


Epoch variables are defined in regard to uncertainties (for example, resources, policy, technology availability, and others). Epochs are computationally generated using the possible permutations of the epoch variable set values. This approach has enabled deeper analysis for assessing performance of concept designs across multiple epochs.

A.M. Ross and D.H. Rhodes, "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis,"18th *INCOSE International Symposium*, Utrecht, the Netherlands, June 2008

Contextual Aspect: Multiple System Concepts in Multiple Contexts

Illustrates set of design concepts for an *operationally responsive surveillance system* shown for three epochs (where epoch variables vary based on the characteristics of a context shift (different disaster situation)

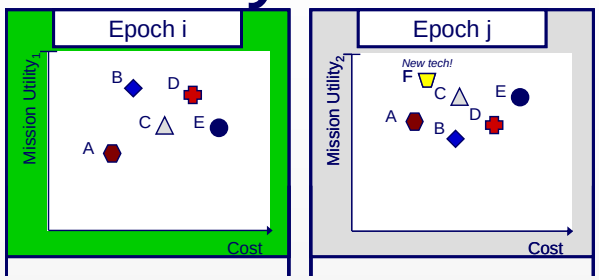


D. Chattopadhyay, A.M. Ross and D.H. Rhodes,“ Demonstration of System of Systems Multi-Attribute Tradespace Exploration on a Multi-Concept Surveillance Architecture," *7th Conference on Systems Engineering Research*, Loughborough University, UK, April 2009

Temporal Aspect Example: Epoch-Era Analysis

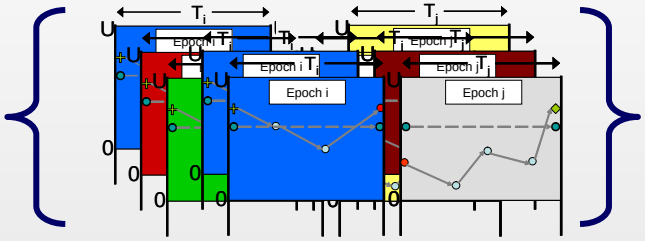
Compare Alternatives

Static tradespaces compare alternatives for fixed context and needs (per Epoch)



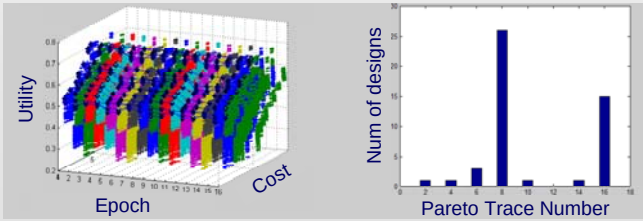
Epoch Characterization

Epoch set represents potential fixed contexts and needs



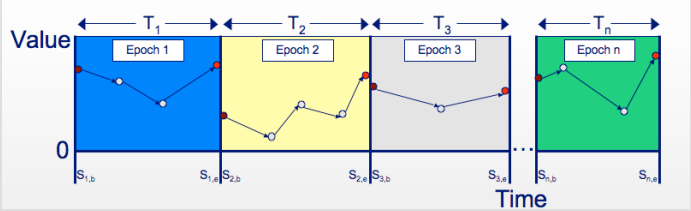
Multi-Epoch Analysis

Analysis across large number of epochs reveals "good" designs



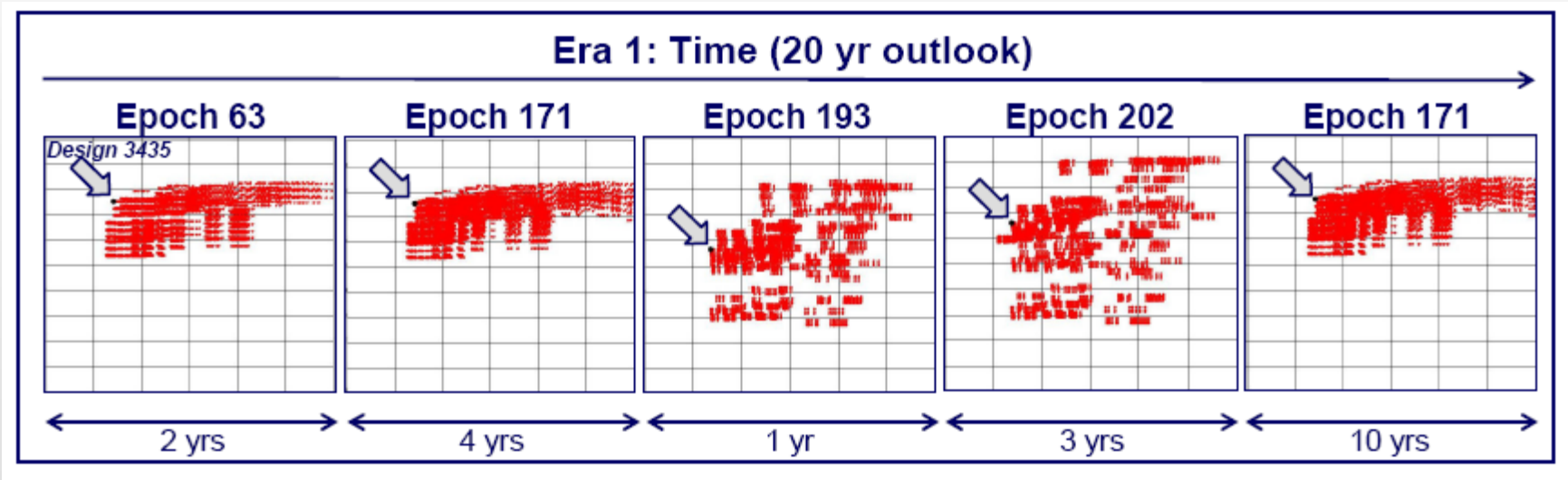
Era Construction

Eras represent ordered epoch series for analyzing system evolution strategies



Temporal Aspect Example: Tradespace Exploration using Epoch-Era Analysis

Value (utility) of designs for cost shown across system era with four epoch shifts (arrow indicates design of interest)



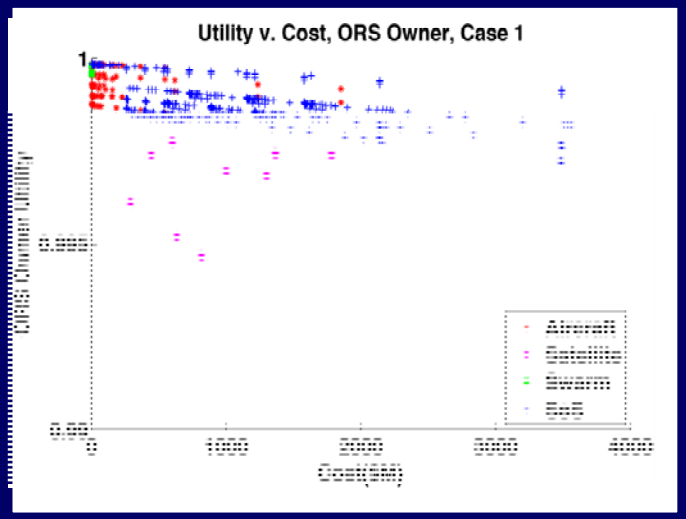
A.M. Ross and D.H. Rhodes, "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis,"18th *INCOSE International Symposium*, Utrecht, the Netherlands, June 2008.

C..J. Roberts, M.G. Richards, A.M. Ross, D.H. Rhodes, and D.E. Hastings, "Scenario Planning in Dynamic Multi-Attribute Tradespace Exploration," *3rd Annual IEEE Systems Conference*, Vancouver, Canada, March 2009

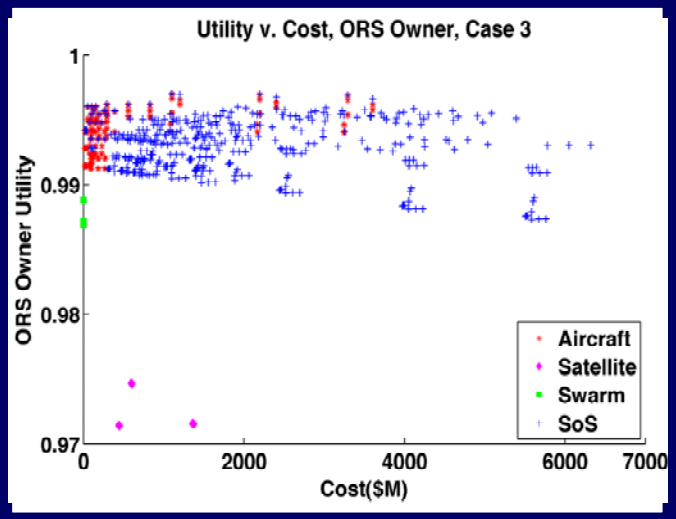
Perceptual Aspect Example: Shift in What Stakeholder Values

Perceptual aspect can relate to need to understand 'goodness' of design concepts as a stakeholder's preferences shift over time. Exogenous factors such as economic changes, available technology, threats and other factors may influence relative importance of what a stakeholder values.

Original Attribute Relative Weights



Changed Attribute Relative Weights



Impact of Change in Stakeholder Weighting of Desired System Attributes in Tradespace showing Utility vs Cost for a Multi-Concept System

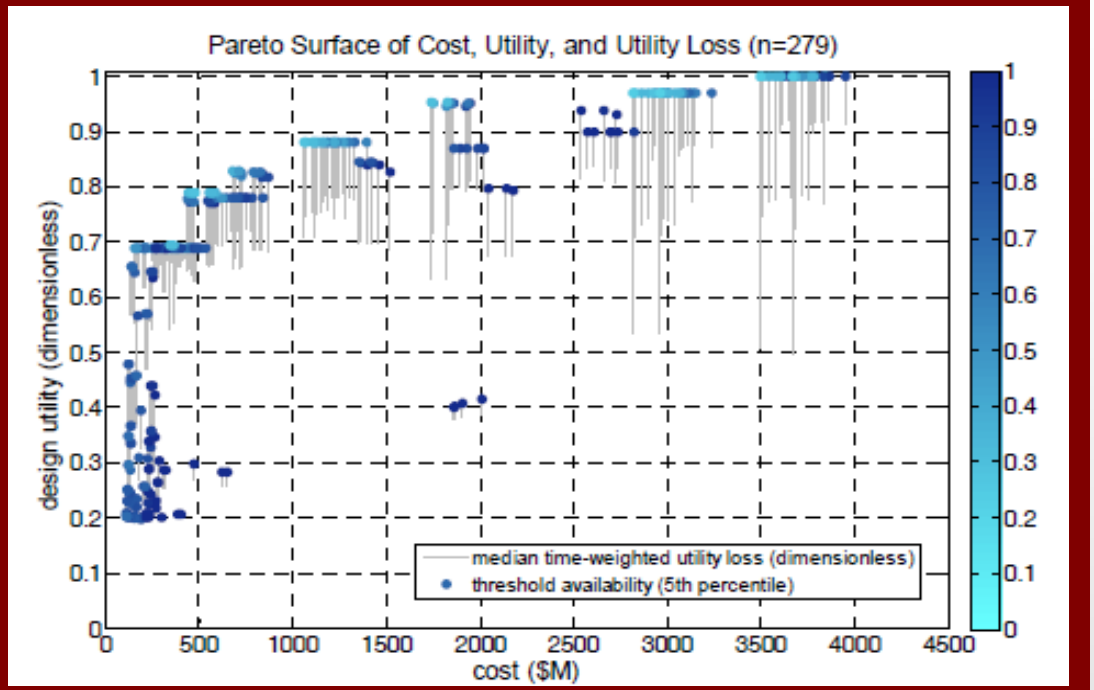
D. Chattopadhyay, A.M. Ross and D.H. Rhodes," Demonstration of System of Systems Multi-Attribute Tradespace Exploration on a Multi-Concept Surveillance Architecture," *7th Conference on Systems Engineering Research*, Loughborough University, UK, April 2009

Combining Aspects Example:

Temporal and Perceptual

What visual construct can combine:

- ***temporal aspect*** (effective display of time-based impacts) *and*
- ***perceptual aspect*** (ability of decision maker to cognitively process complex tradespace information)?



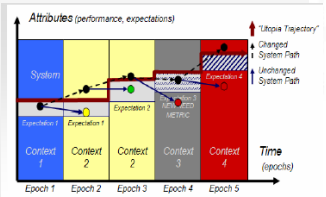
Richards (2009): Perceptually understandable display of value for cost of satellite radar designs with time-based information on survivability of system as it experiences possible finite disturbances over its lifespan

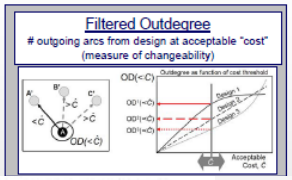
Amount of information and complexities within a set of information are challenges, in that human cognitive limits for processing the visual display must be considered, as well as mechanism to compute and display synthesis of temporal analysis (survivability over system life)

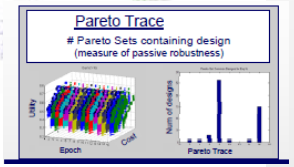
Multi-Aspect Synthesis Example:

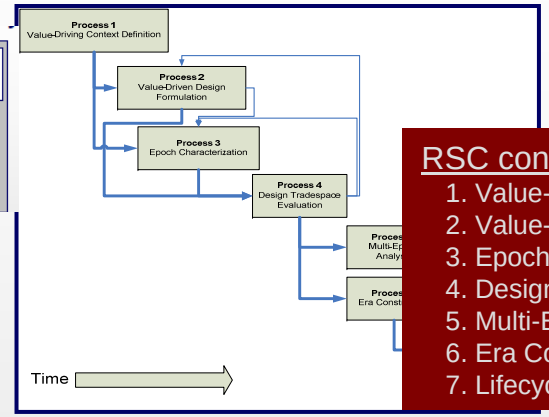
Responsive Systems Comparison (RSC)

Using Multi-Attribute Tradespace Exploration, Epoch-Era Analysis, and other approaches, a coherent set of processes were developed into the RSC method









RSC consists of seven processes:

1. Value-Driving Context Definition
2. Value-Driven Design Formulation
3. Epoch Characterization
4. Design Tradespace Evaluation
5. Multi-Epoch Analysis
6. Era Construction
7. Lifecycle Path Analysis

Seeking ways to combine multiple aspects is a source for further methodological innovation

Synthesis of multi-aspect methods can be used to develop robust methods for engineering complex systems

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

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Thank you for your participation

Feedback on the course is encouraged!

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