



## SEARI Short Course Series

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

Lecture: Lecture 4: Introduction to Tradespace Exploration

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This course was taught at PI.27s as a part of the MIT Professional Education Short Programs in July 2010 in Cambridge, MA. The lectures are provided to satisfy demand for learning more about Multi-Attribute Tradespace Exploration, Epoch-Era Analysis, and related SEARI-generated methods. The course is intended for self-study only. The materials are provided without instructor support, exercises or “course notebook” contents. Do not separate this cover sheet from the accompanying lecture pages. The copyright of the short course is retained by the Massachusetts Institute of Technology. Reproduction, reuse, and distribution of the course materials are not permitted without permission.



**Systems Engineering Advancement Research Initiative**

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

### **Lecture 4 Introduction to Tradespace Exploration**

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# Outline

- What is Tradespace Exploration
- Scoping and Bounding the Mission
- Choosing Attributes
- Choosing Design Vector Elements
  - The Constants Vector
- Modeling Concepts
  - Cost Modeling
- Creating the Tradespace
- Introduction to Tradespace Exploration

# Tradespace Exploration

A method for understanding complex solutions to complex problems

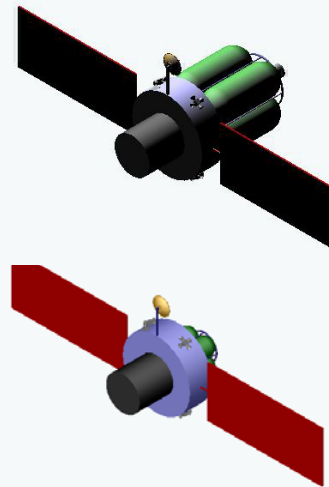
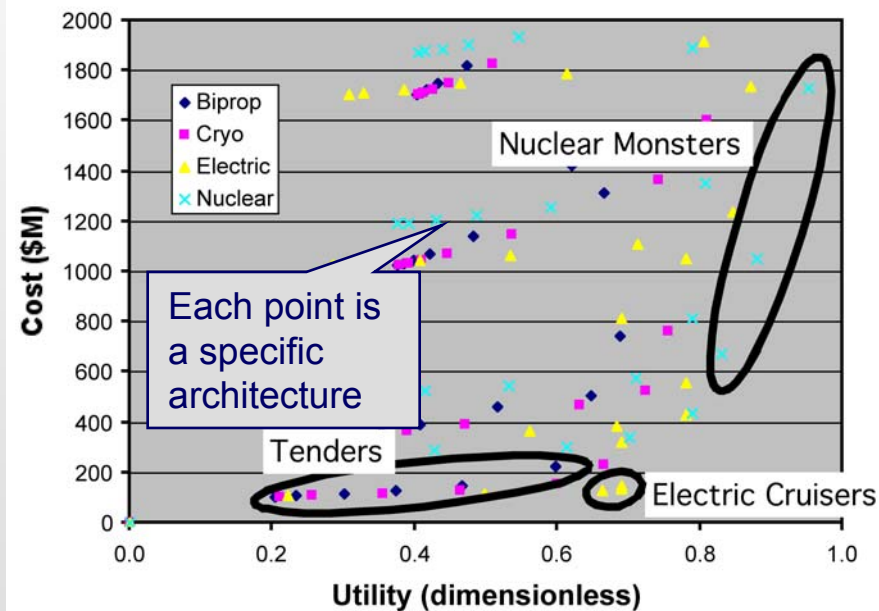
- Model-based high-level assessment of system capability
- Ideally, *many* designs assessed
- Avoids optimized *point solutions* that will not support evolution in environment or user needs
- Provides a basis to explore technical and policy *uncertainties*
- Provides a way to assess the value of *potential* capabilities

Allows informed “upfront” decisions and planning

# What is a Tradespace?

## Attributes

- Delta-V
- Capability
- Response time



## Design Space

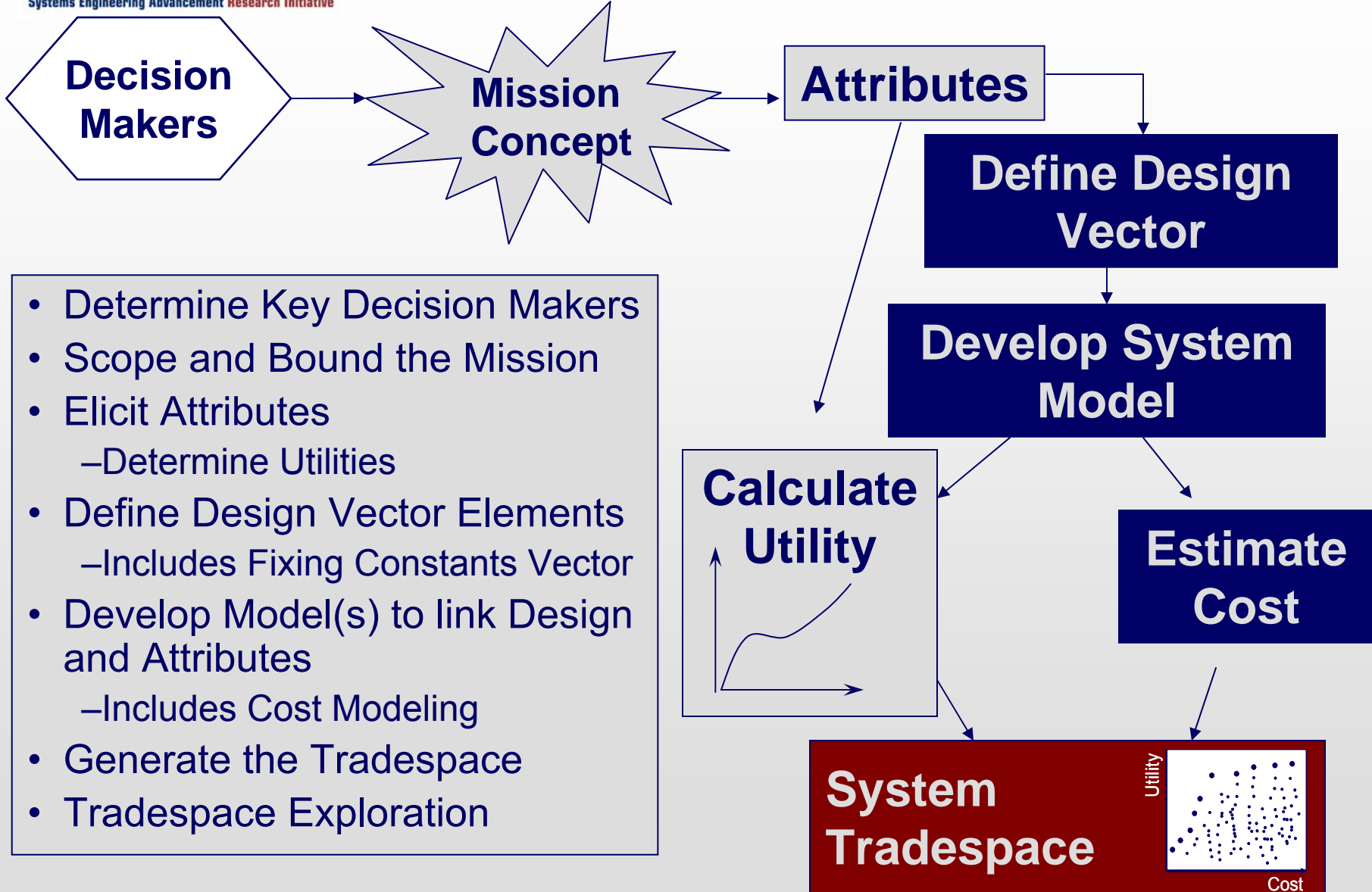
- > Manipulator Mass
  - Low (300kg)
  - Medium (1000kg)
  - High (3000 kg)
  - Extreme (5000 kg)
- > Propulsion Type
  - Storable bi-prop
  - Cryogenic bi-prop
  - Electric (NSTAR)
  - Nuclear Thermal
- > Fuel Load - 8 levels

## > 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

Assessment of the utility and cost of a large space of possible system designs

# Steps for 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

# Bounding and Scoping

# Bounding and Scoping

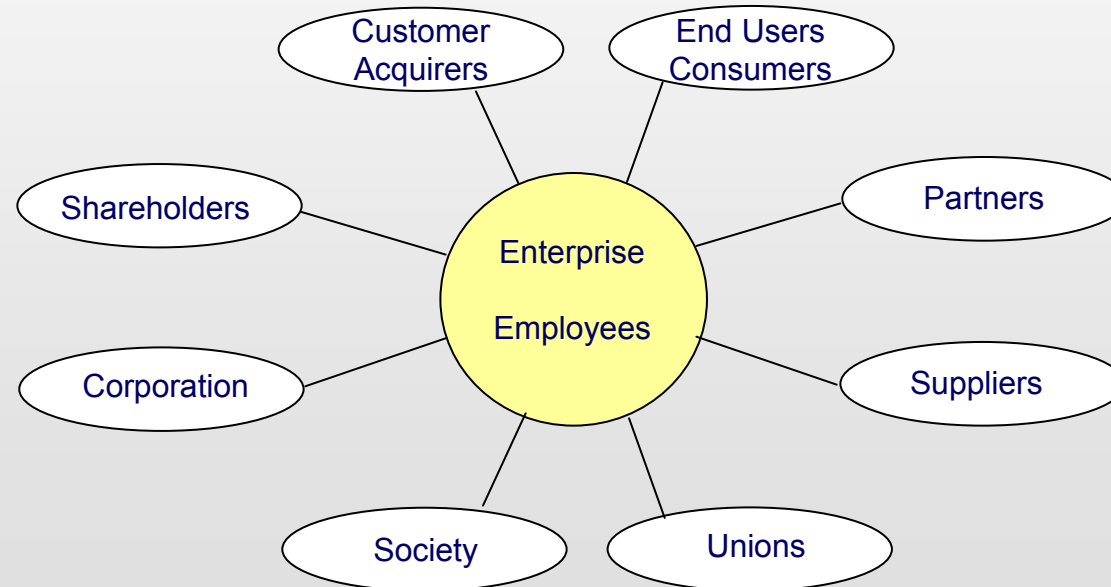
- Need to make key decisions to make problem tractable:
  - What do you want to do (Mission statement)?
  - Who are the stakeholders?
  - What is the mission concept?
  - What are the bounds of possible solutions you will investigate?
  - What parts of the system will you investigate?

Important decisions made based on experience  
May need to be revisited later - this is OK!



# Stakeholders

- Many interested parties in a complex system
- Each “customer” has a set of needs
- They are different, and can be contradictory



**Bottom line:** focus on key decision makers, as they have the primary influence over whether a system will be selected

# Identifying Key Decision Makers

Level 0

External Stakeholders



Level 1

Firm

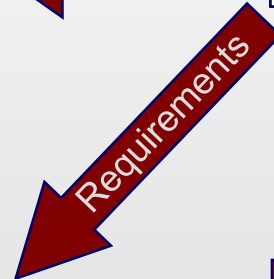


Customer

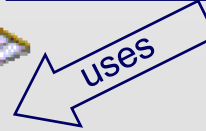


Level 2

Designer



User



## Definition of Levels

- Level 2 – Close connection to System
- Level 1 – Distant connection to System
- Level 0 – Little or no connection to System

From Ross 2003

# Choosing Decision Makers

- Ideally, one decision maker (“dictator”)
- In practice, concentrate on key decision makers
  - Typically, their preferences will NOT be able to be aggregated
- Much more valuable if you have access to real people, and can work with them
  - Experts can be proxy if real decision makers not available

**Decision maker is a stakeholder with significant influence/control over resources and/or driving needs**

# Mission Concept

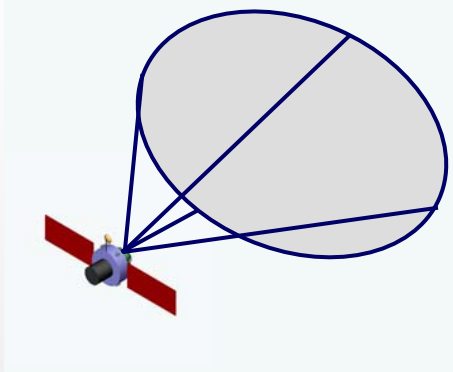
- Basic framework for how you will satisfy stakeholder needs
  - Open enough so that creative solutions are not excluded
  - Defined enough to be tractable

**Space Tug Example:**

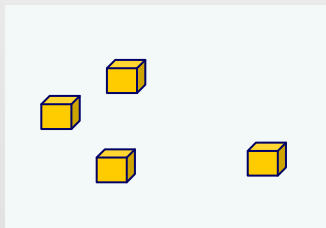
- **Stakeholder need is for infrastructure to maintain on-orbit assets**
- **Mission concept is vehicle that can rendezvous with and interact with on-orbit assets**
  - **Need to assess how potential systems could satisfy potential stakeholders**

# Bounding the Solution Space

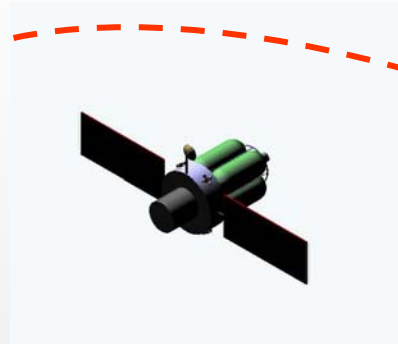
## Example: Space Tug



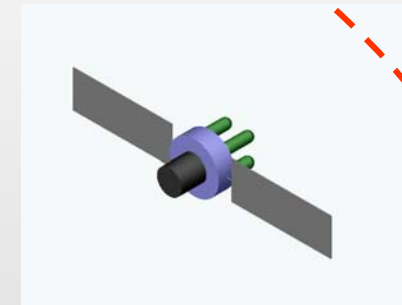
**Exotic Propulsion:  
Directed Energy, Sails**



**Exotic Architectures:  
Swarms, Wireless bus-free architectures**



**Conventional**

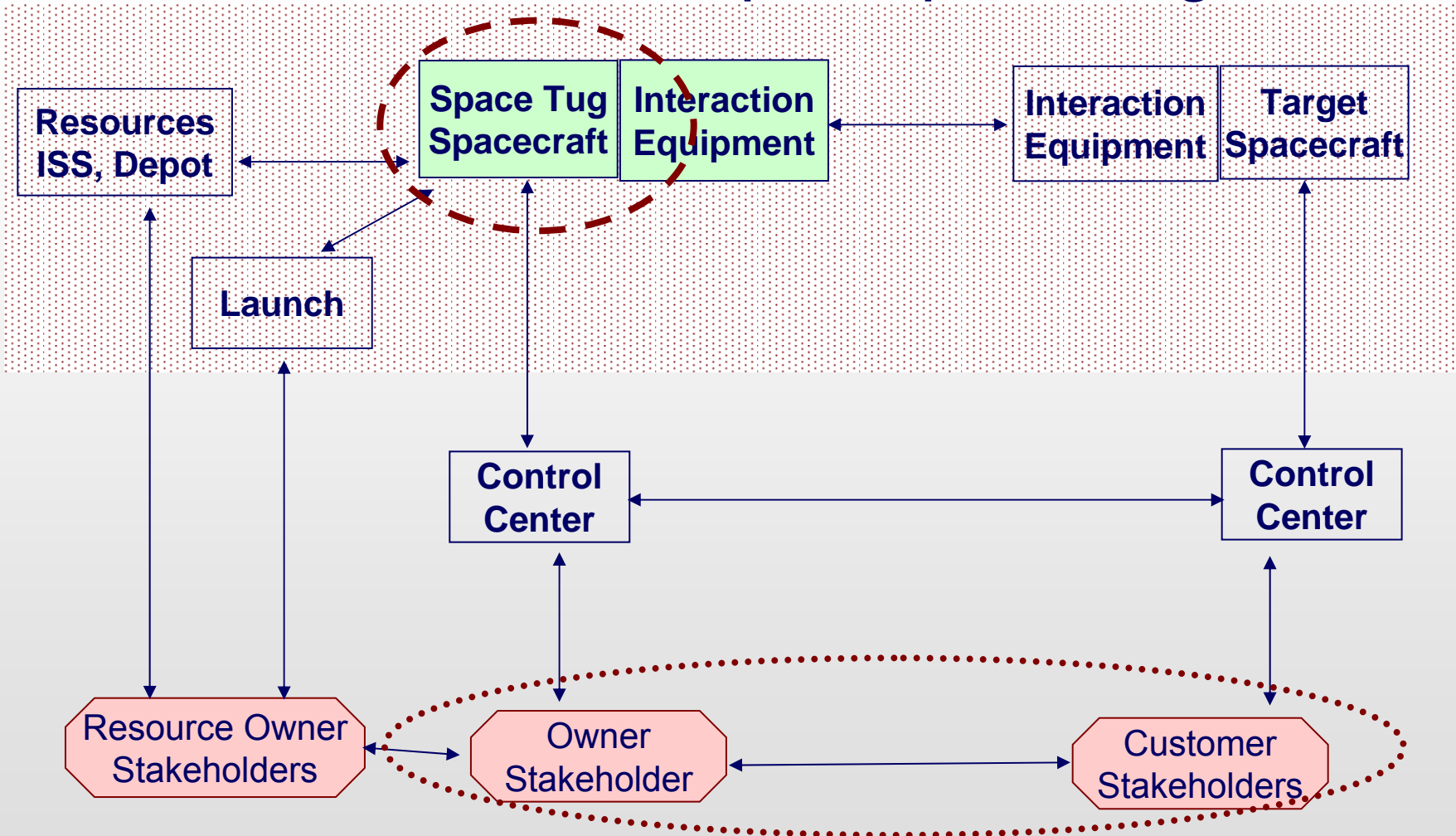


**Advanced Propulsion:  
Electric, Nuclear-Thermal**

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

# Scoping of System Analysis

## Example: Space Tug



Choose the parts of the overall system that you will design

# Guidance for Scoping

- Make scoping decisions explicit and visible
  - Make sure team is working to same scope
- Use scoping to help define attributes, utilities, and models
- Revisit scoping decisions at planned intervals
  - When modeling, is scope too broad? Or could it be easily expanded?
  - When interpreting results, has scoping excluded viable solutions?

# Scope Effort to Resources

*What is needed to perform the tradespace exploration study?*

## Time

- To interview decision makers
- To develop code
- To validate and verify
- To analyze results
- To learn from results
- To repeat the whole process

## Money

- For personnel
- For equipment
- For software
- For travel

## Knowledge

- Of tradespace exploration process
- Of “mission” domain, including constraints and “physics”
- Of stakeholder set over time

## Modeling/simulating ability

- Availability of computers
- Availability of software
- Availability of experts/analysts
- Availability of data/information

## Access to decision makers

- Availability of right people

**Be aware of resources required and scope effort appropriately!**



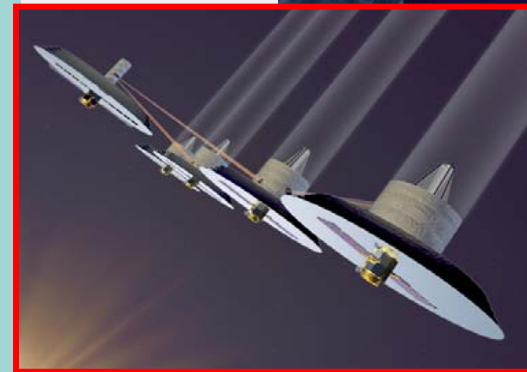
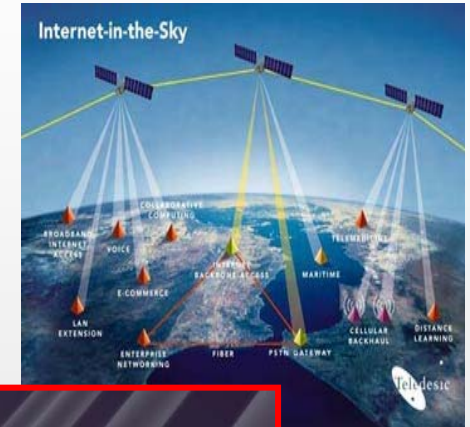
# Defining Attributes and Utility

# Attributes

**“What decision makers need to consider”  
.....and/or what the user truly cares about**

## Examples:

- Communications
  - Billable minutes
  - Service availability and continuity
- Science
  - Pictures, Data, Timeliness
- Space Tug
  - Moving mass, Grappling capability, Timeliness



[Beichman et al, 1999]



# Guidance for Defining Attributes

- Should obey, to the extent possible, perceived independence
- 3-7 attributes best for analysis
- Ideally:
  - Reflect what the decision makers care about
  - Computable
  - Sensitive to design decisions
- Define units from lowest acceptable value to highest meaningful value
- Iteration is likely required

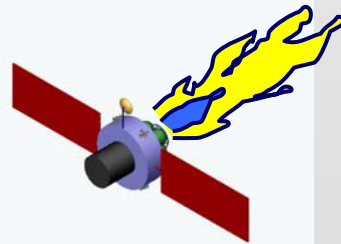
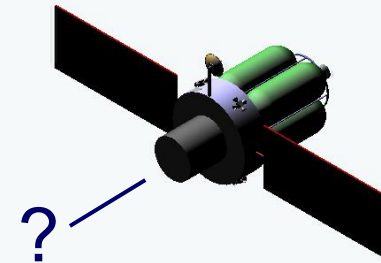
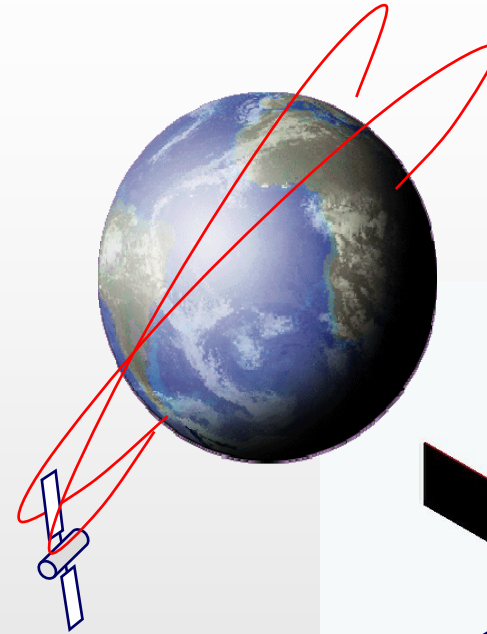
# Space Tug Attributes\*

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

2) **Interface Systems**

**Capability:** What can the vehicle do to the target? (kg of equipment carried)

3) **Speed:** Can the Space Tug change orbits in days or months? (binary)



\*Note: For this study the goal was to assess capability for a “typical” user, so the attributes were not elicited, but rather representative capabilities to help determine whether there was a “market” for such a system

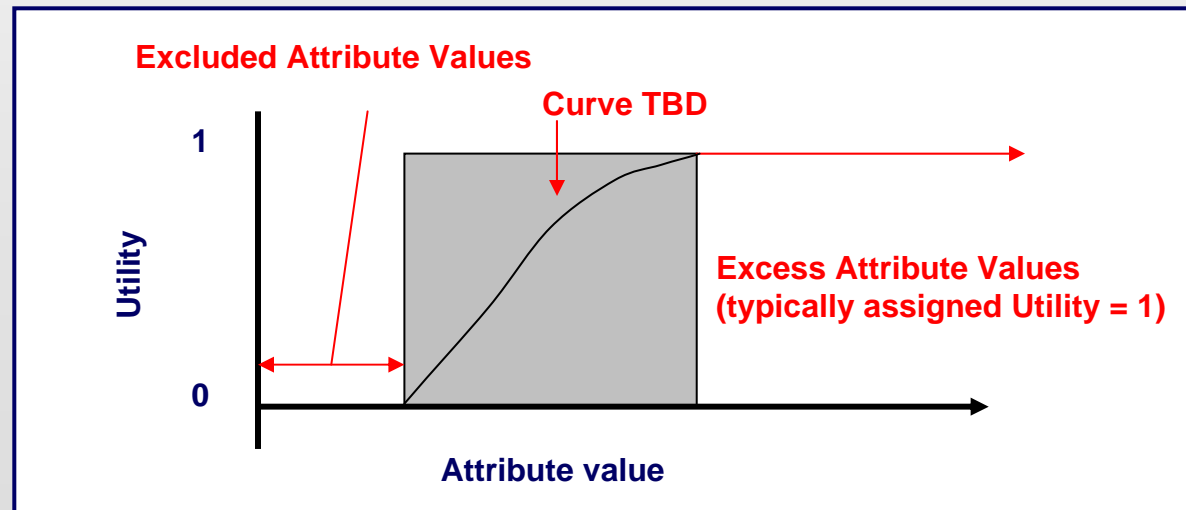
# Space Tug Attributes: Setting Units and High/Low Values

Attribute	Units	Best	Worst
<b>1) Delta-V</b>	km/sec	12*	>0
<b>2) Equipment carrying capability</b>	kg	5000	>0
<b>3) Speed</b>	-	fast	slow

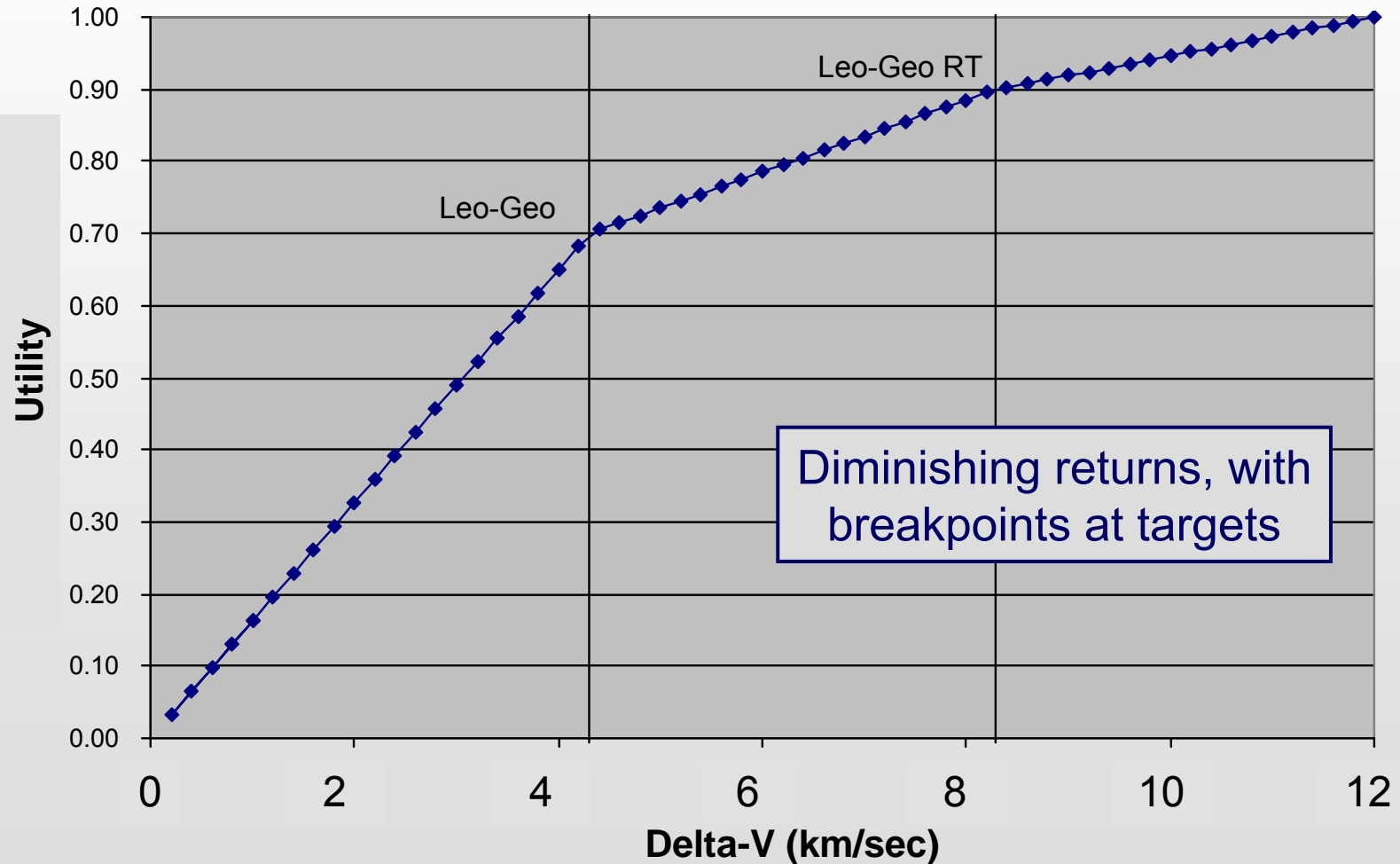
\*for most potential users

# Defining Utilities

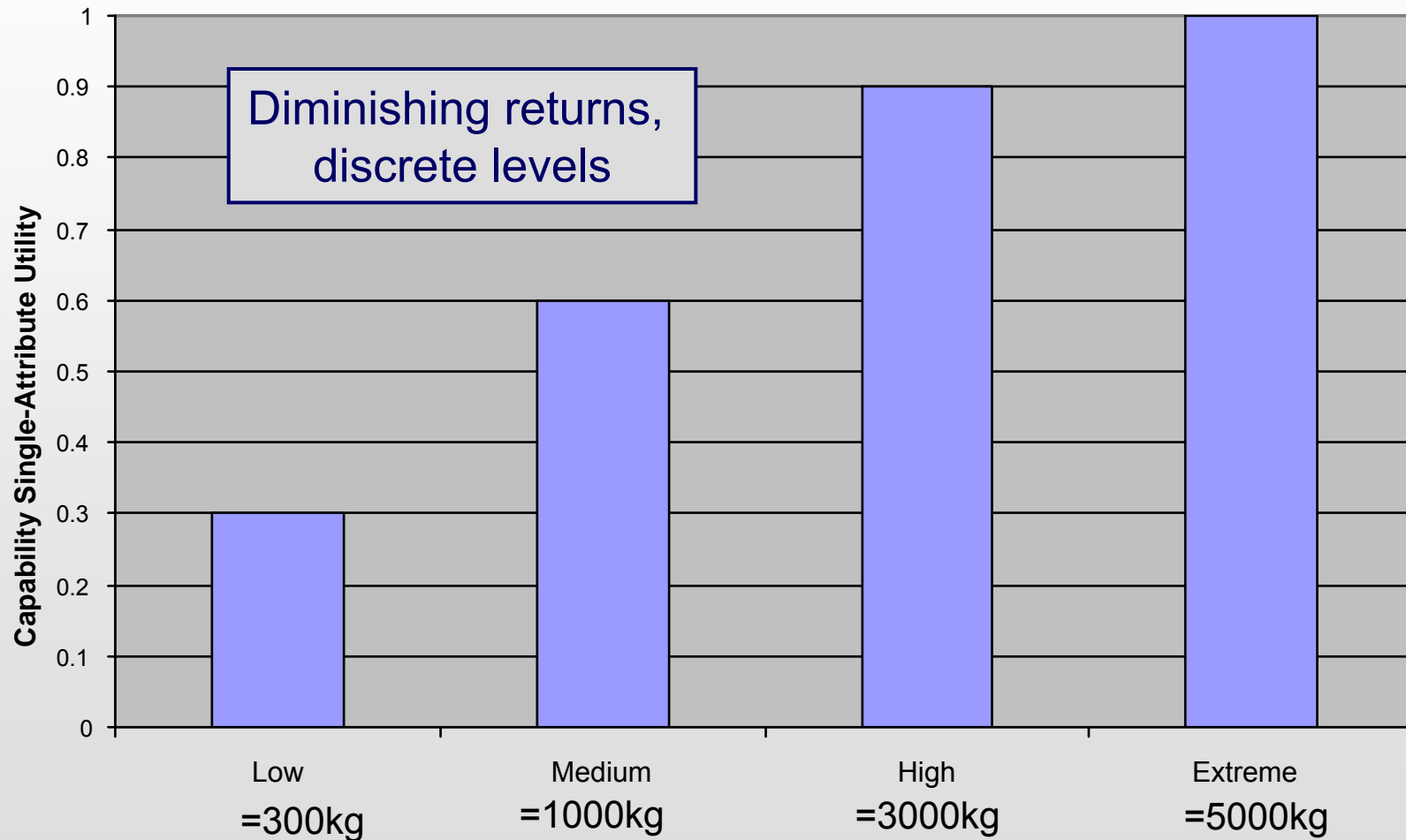
- Each attribute (worst to best value) maps to a utility (0 to 1)
  - rule for under/over values
- Remember monotonicity rule



# Space Tug Delta-V Utility

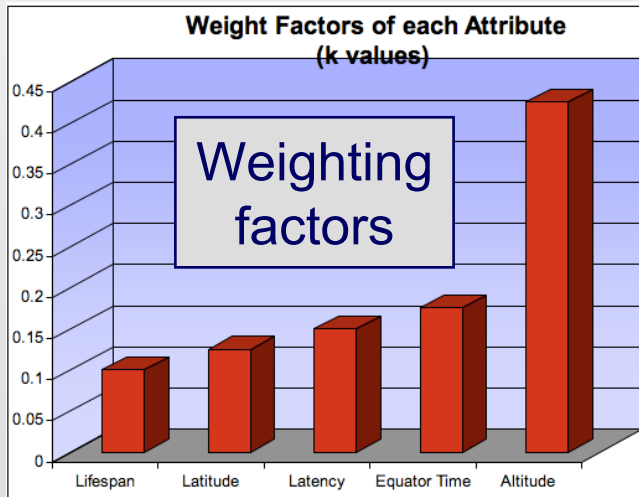
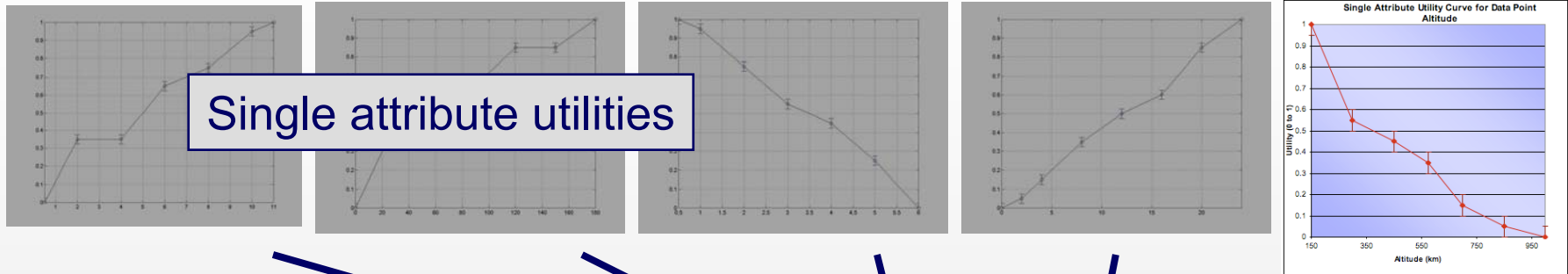


# Capability (Manipulator Mass) Utility





# Aggregating Utilities



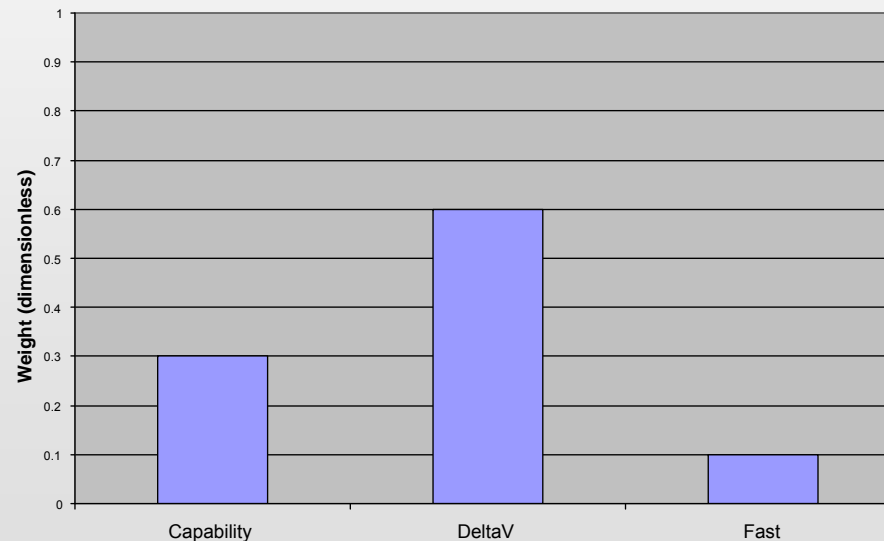
$$KU(\underline{X}) + 1 = \prod_{i=1}^N (Kk_i U(X_i) + 1)$$

Aggregating Function

- *If possible*, define an aggregating function
  - Weighted sum often used
- Difficulties to be discussed...

# Space Tug Aggregated Utility

- Speed utility binary (slow=0 fast=1)
- Total Utility a weighted sum
  - Weights different for every stakeholder

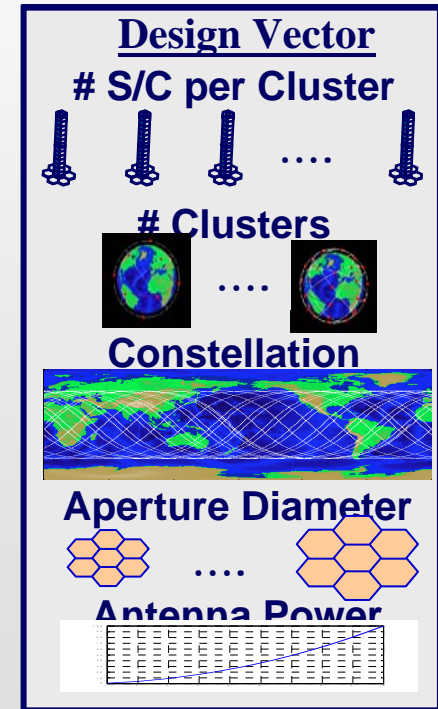
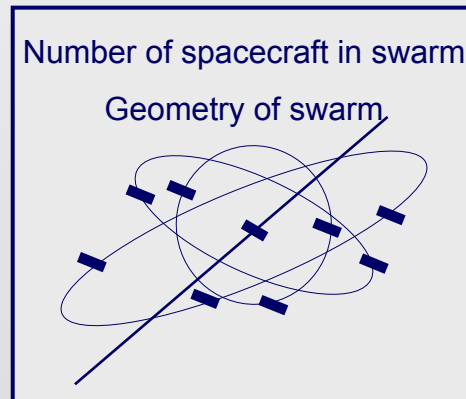
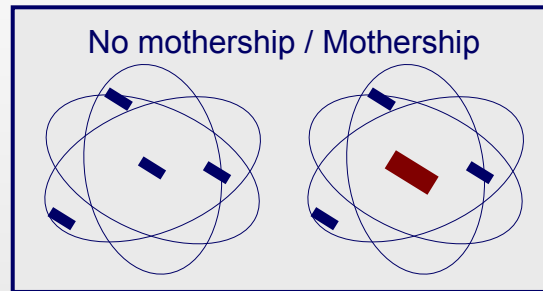
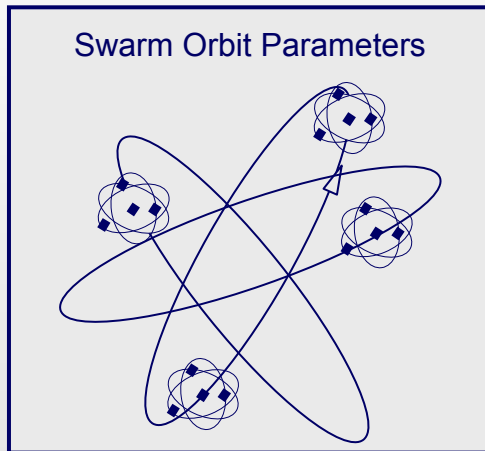


Weights for default stakeholder

# Choosing Design Vector Elements

# Quantified Concepts: Design Variables as Tradable Parameters

**Design Variable**: A designer-controlled quantitative parameter that reflects an aspect of a concept



**Design Variable<sup>i</sup>  $\equiv$  DV<sup>i</sup>**

# Defining the Design Vector

*The design vector defines the space of designs that will be considered - a key step!*

- Good design vector elements:
  - 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
- Define units, range to be considered, discretization

For  $N$  elements with  $M$  discrete levels,  
have  $M^N$  designs - keep this in mind

# Design Vector Elements

- Discrete design choices: e.g. Propulsion System
  - Choice from menu
  - May have a set of associated quantities (e.g. each propulsion system choice has ISP, thrust/weight etc.)
  - May need to pick limited sample from large menus
- Continuous variables: e.g. Fuel Mass
  - Pick high and low points and steps in-between
  - May need to iterate on discretization scheme (finer “mesh” in areas of interest)

# Space Tug Design Vector

- 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
- Complete survey of design vector:
    - $4 \times 4 \times 8 = 128$  designs
  - Several specific designs of special interest incorporated into study
    - Added 11+ more

# Process for Relating Design Vector to Attributes

1. Create a design-value matrix (DVM) showing the relationship between design vector elements and the attributes
2. Assess the impact of the first on the second
  - Typical scale: 9 (strong) 3 (some) 1 (weak) 0 (none)
  - Sum rows and columns to assess overall role
3. Use to iterate Attribute and Design Vector choices
4. Once they are stable, use to plan model



# Attribute vs. Design Vector

## DVM - Space Tug

Caution: For this case, manipulator mass is both a design variable (equipment mass) and attribute (equipment capability)

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

Identify key interactions for modeling

Sums identify Attributes and Design Variables that are likely to be (or not be) distinguishers

# Iterating the Attributes and Design Vectors

- Attributes with a low total score are not affected by the Design Vector (DV)
  - If no design choice that affects them, they are undriven attributes
  - If there are design choices that affect them, add to DV
- DV elements with a low total score are not impacting the attributes - drop or survey only coarsely
- “Diagonal” pairs - a DV element that effects only one Attribute (and is the only DV element to do so) represent *independent* choices and *may* be removed from the trade study and considered separately

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

# The Constants Vector

- To keep modeling general and adaptable to later changes, *do not “hardwire” assumptions into code*
- Instead, keep a list (data structure) where “constants” are kept
- Five types (at least):
  - True constants ( $g$ ,  $\pi$ ) These might still change if your unit system does...
  - Constraints (policies, standards...)
  - Modeling assumptions ( $\$/\text{kg}$ ,  $\text{W}/\text{GHz}$ , Margins...)
  - Quantities associated with design vector choices
  - Potential design vector elements (things under designers control) that have been fixed - *record why*

# Space Tug Constants Vector

## True constants

$g$  Acceleration due to gravity (9.8 m/sec<sup>2</sup>)

## 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*

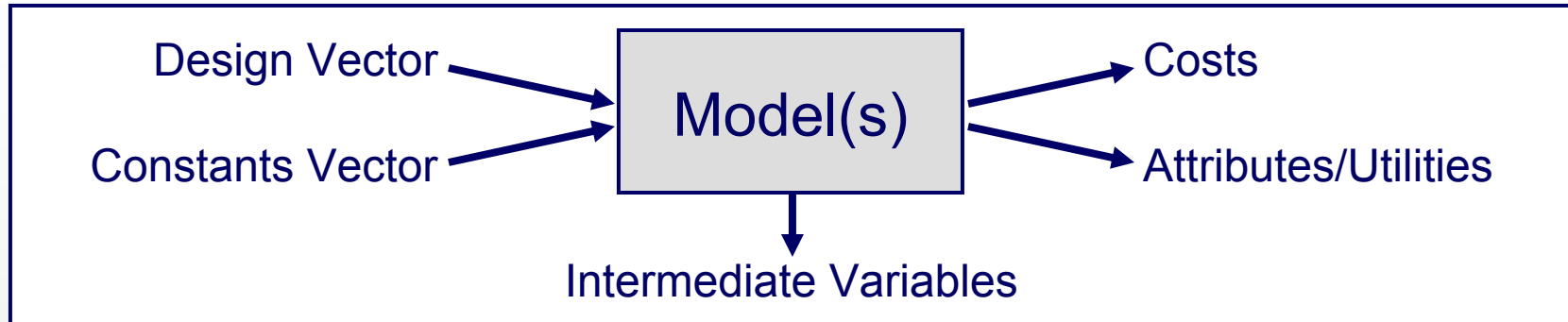
## Associated Quantities: Propulsion System

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

Capture key quantities associated with a design choice  
Often, represents specifications of subsystem

# Modeling Concepts

# Modeling



- Calculate Costs & Attributes from Design Vector & Constants Vector
- Approaches:
  - Tabulation - car example from previous lecture
  - Explicit calculation -  $\text{Attributes} = f(\text{DV}, \text{CV})$
  - 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

# Space Tug Modeling

- 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	<i>Table lookup</i>
Speed	<i>Table lookup</i>



# 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
  - Will be discussed in Lecture 5
- 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 Cost Modeling

- Very very simple parametric model
  - Cost based on vehicle wet and dry masses

$$C = c_w M_w + c_d M_d$$

- Appropriate to broad survey
- Important to understand what is *not* modeled
  - Software
  - Launch
  - Technology Development

Even simple models appropriate to broad concept surveys  
Can produce very rich tradespaces!

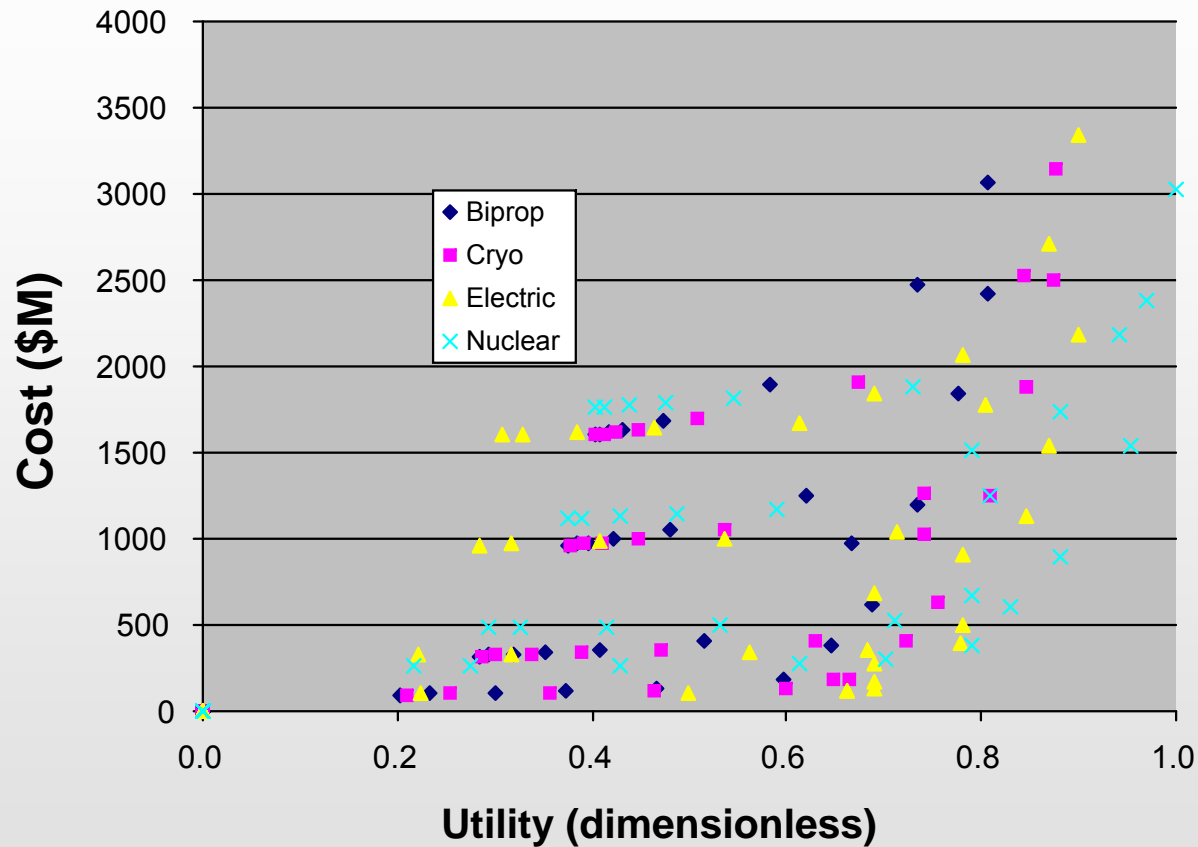
# Now for the Tradespace...

# The Tradespace

- Now have a lot of information:
  - Design Vector (many possible designs)
  - Constants Vector
  - Attributes (for each design)
  - Utilities (for each design)
  - Cost (for each design)
- This is, collectively, the *tradespace*

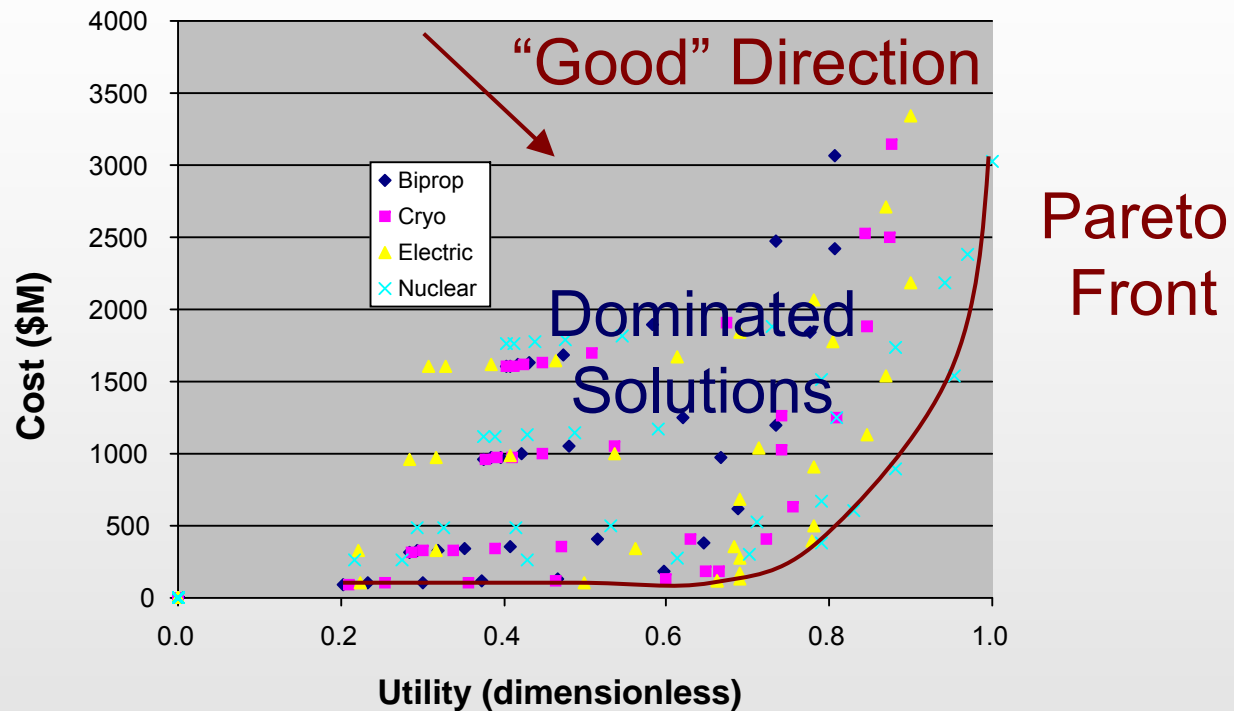
Need to distill this *information* into *knowledge*  
useful to decision makers

# Space Tug Tradespace Aggregated Utility vs. Cost



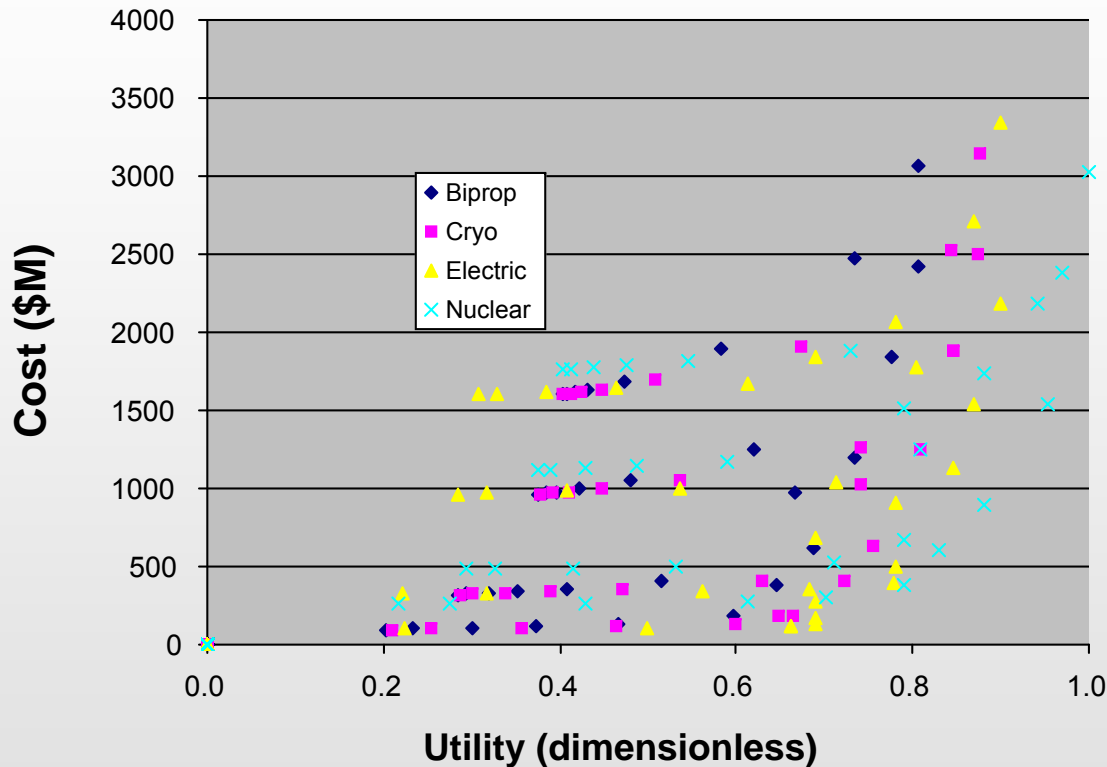
Each point is a complete design

# The Pareto Front



Points on the front give best Utility for Cost  
Other points are *dominated* - better utility for same cost or  
same utility for less cost available

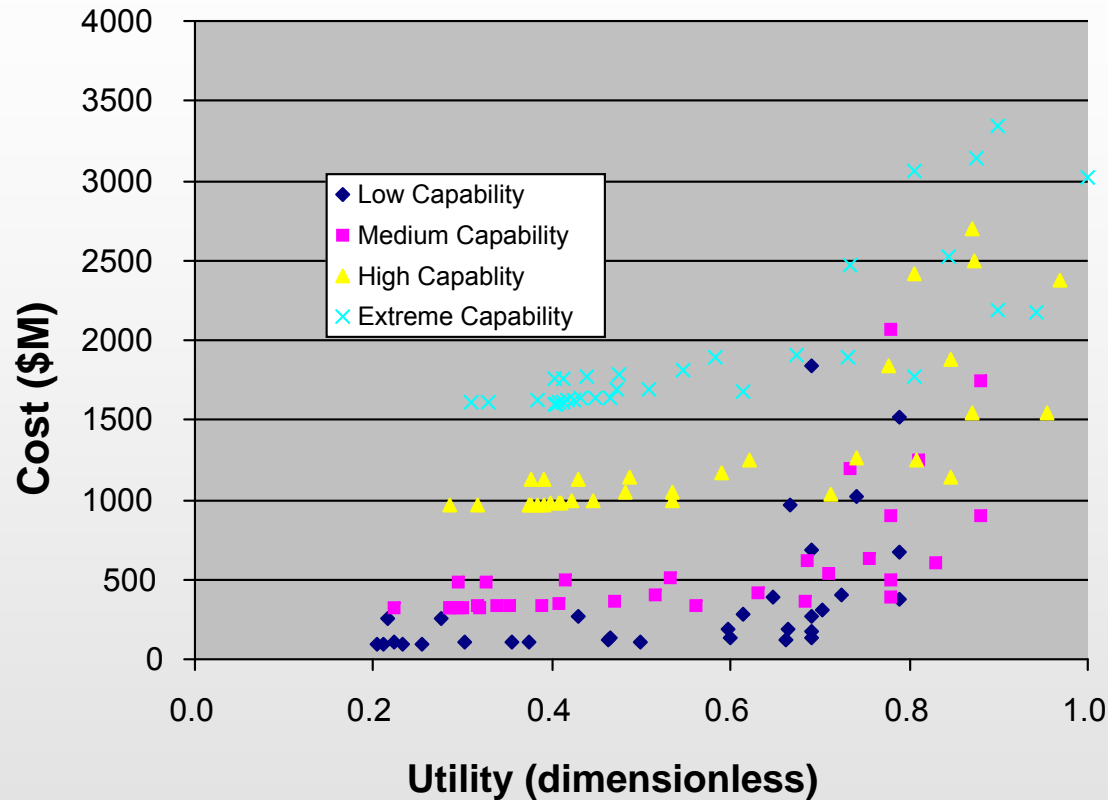
# Understanding Design Choices



- Propulsion system identified by color
- Different parts of the Pareto front favor different propulsion systems

Identifying design choices by color identifies good/bad choices, sensitivities

# Understanding Design Choices: Example II

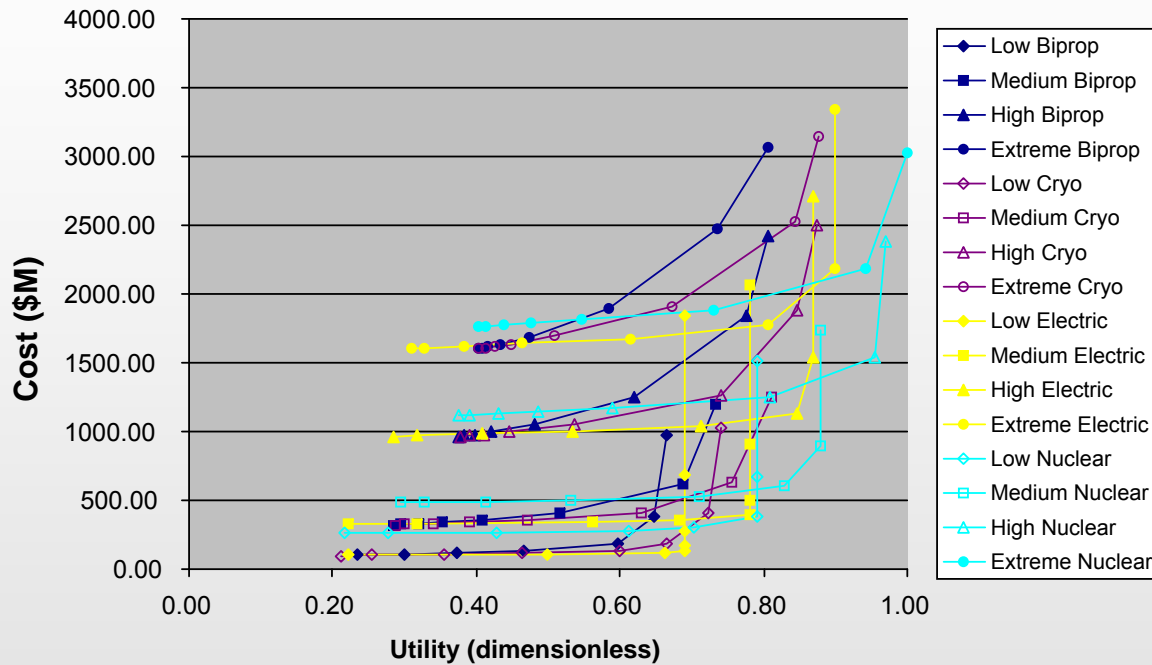


- Interface system capability identified by color
- More capability costs more money
- Low capability (=small) designs dominate low cost/utility systems
- Only a meaningful choice at the high utility end

Interdependency of choices a sign of a “rich” tradespace



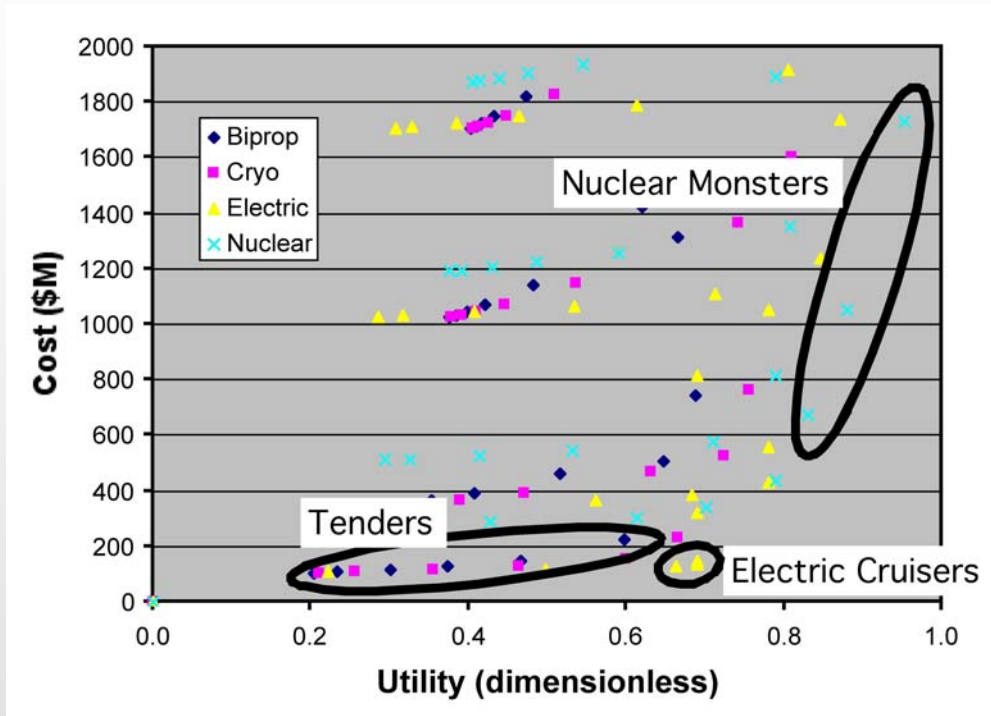
# Understanding Design Choices: Example III



- Line represents a set of designs differing only by fuel/reaction mass load
- More fuel, more utility *but very non-linear*
- At high end, hit “walls”
  - some are physics (rocket equation)
  - some utility (electric vehicles can “max out” the utility functions)

Physical phenomena create patterns; must look at full data set to find root causes

# Tradespace Reveals Promising Designs



- Small, light, cheap vehicles with low-mid  $\Delta V$  capability (tenders)
- Small, slow, high- $\Delta V$  electric propulsion vehicles (cruisers)
- Big, fast vehicles require nuclear power (expensive)

Sets of “good” designs share features/architectures  
Often insight is emergent - the tradespace can reveal good design concepts

# Summary

- MATE includes an ordered set of steps for creating an information-rich Tradespace:
  - Scoping and Bounding the Mission
  - Choosing Attributes
  - Choosing Design Vector Elements
  - Modeling Concepts
  - Creating the Tradespace
  - Tradespace Exploration

Goal is the extraction of knowledge  
that decision makers can use