Systems Engineering Advancement Research Initiative

Concept Design and Tradespace Exploration

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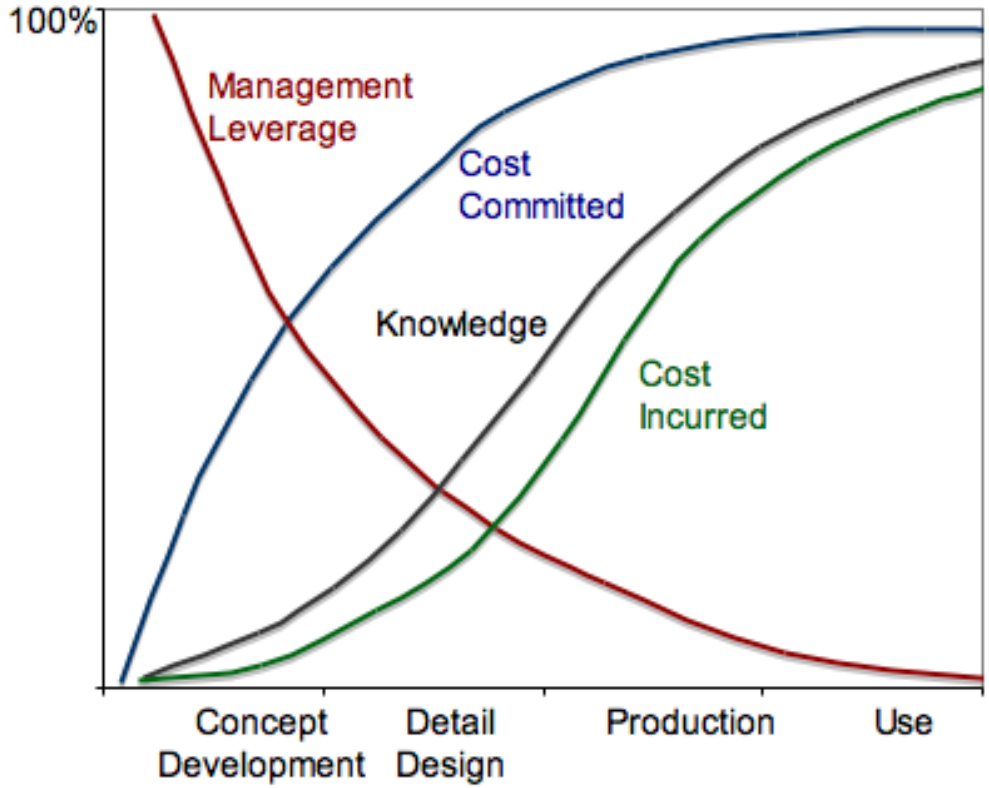
Dr. Donna H. Rhodes
rhodes@mit.edu

Dr. Adam M. Ross
adamross@mit.edu

The following slides are an excerpt from this lecture

The Design Knowledge Gap

Value is primarily determined at the beginning of a program

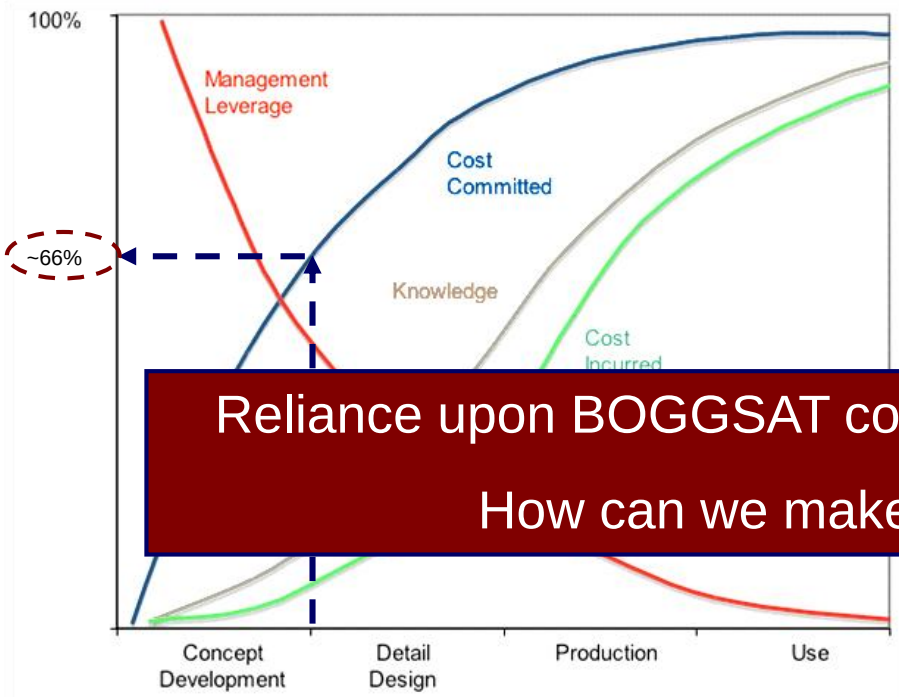


Adapted from Fabrycky and Blanchard 1991

How can we make good decisions and design choices?

The Scope of Upfront Decisions

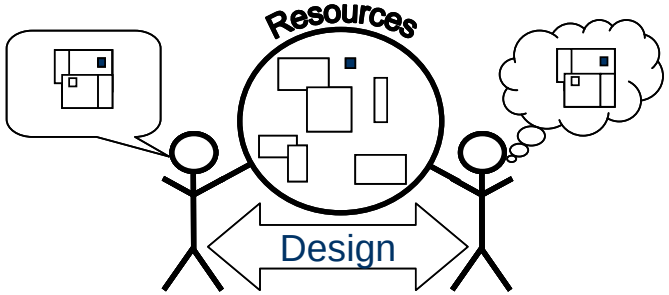
Conceptual Design is a high leverage phase in system development



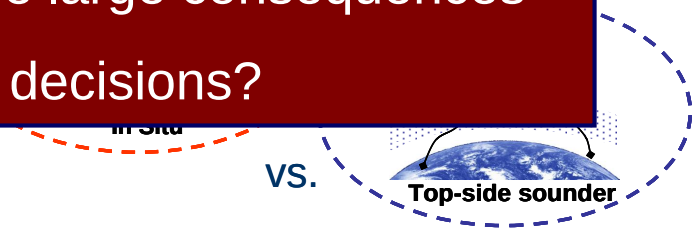
After Fabrycky and Blanchard 1991

Key Phase Activities

Needs Captured



Resources Scoped



Concept(s) Selected

Reliance upon BOGGSAT could have large consequences

How can we make better decisions?

Three keys to good upfront decisions

- Structured program selection process
  - Choosing the programs that are right for the organization's stakeholders
- Systems engineering
  - Determining stakeholder needs, generating concept of operations, and deriving requirements
- Conceptual design practices
  - Finding the right form to maximize stakeholder value over the product (or product family) lifetime

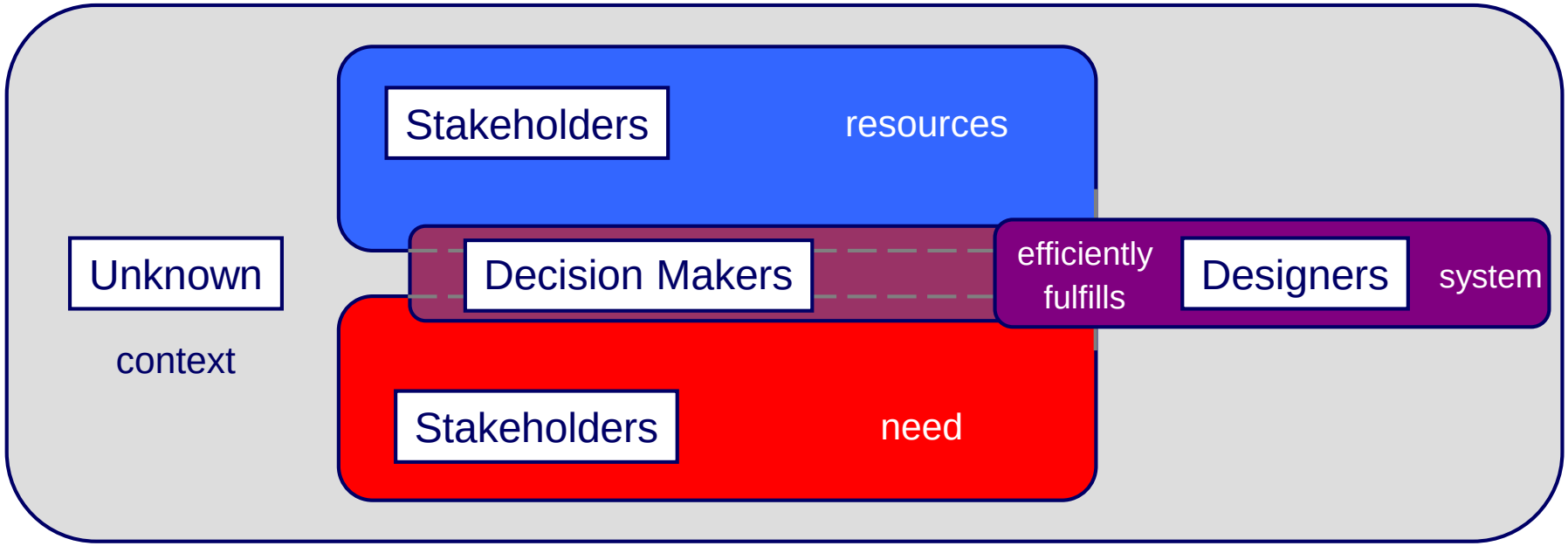
"Good" system decisions *must* both answer the *right questions* as well as answer the *questions right*

What is involved in getting the right questions?
Decision Maker defined objectives

What is involved in getting the questions right?
Rigorous decision and analytic methods

Determining "Value" Proposition

Create a system that fulfills some need while efficiently utilizing resources within some context

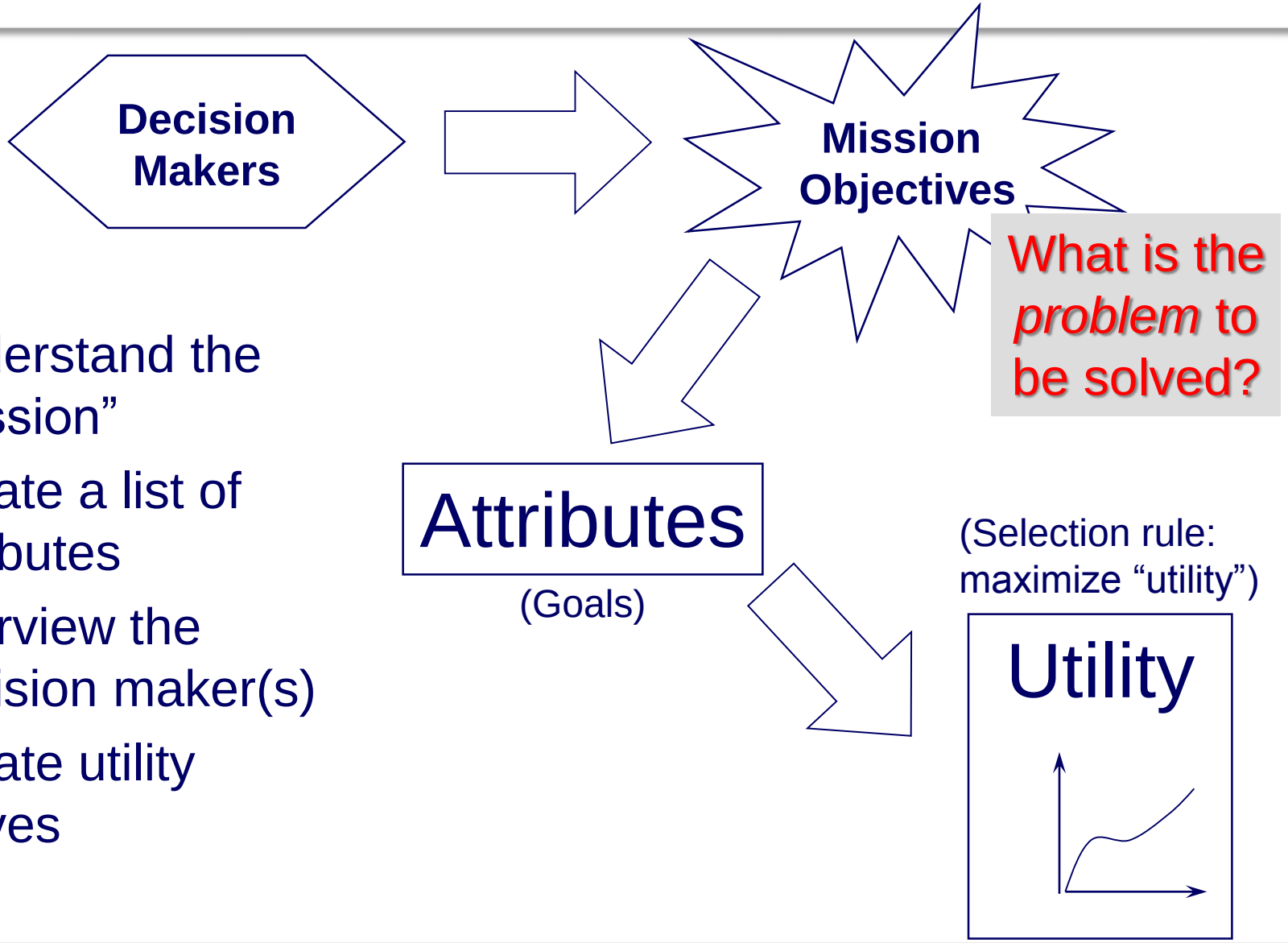


There may be many stakeholders, but…

Decision makers are a subset that have significant influence/control over the driving need and/or resources

… so focus on satisfying decision makers

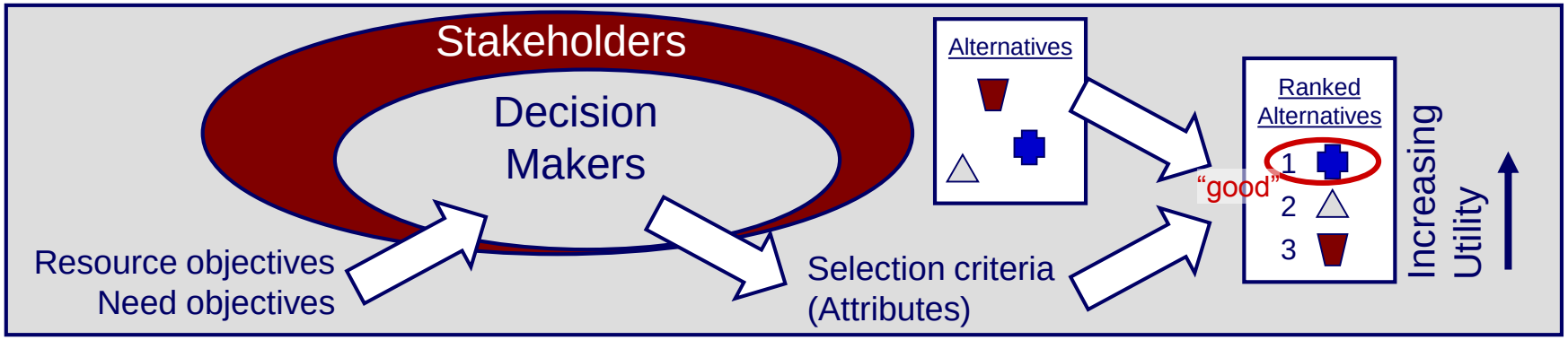
Define the Mission



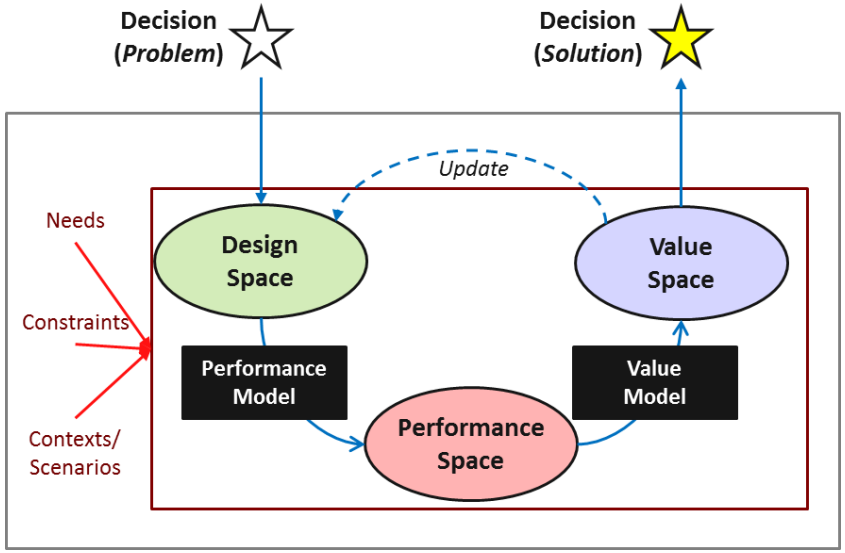
- Understand the "mission"
- Create a list of attributes
- Interview the decision maker(s)
- Create utility curves

Stakeholders-Attributes-Utilities

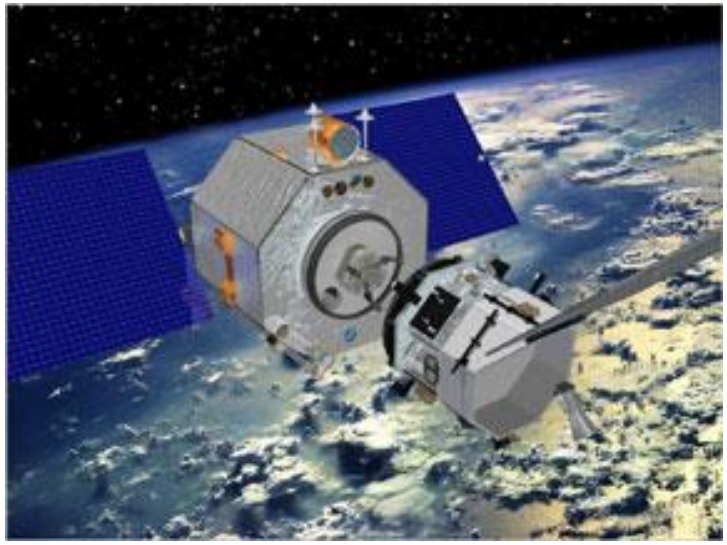
- In order to ensure a successful mission, the implied value proposition must be fulfilled
- Each system **stakeholder** has a value proposition—what they want to "get out" of the mission
- Decision makers are stakeholders with influence over the mission objectives for needs and/or resources
- Meeting the objectives for each decision maker can be assessed in terms of "**attributes**"
- An alternative that scores well in a set of attributes gives a decision maker value, or "**utility**"
- The goal for the selection of a good alternative is to maximize the utility for individuals and groups



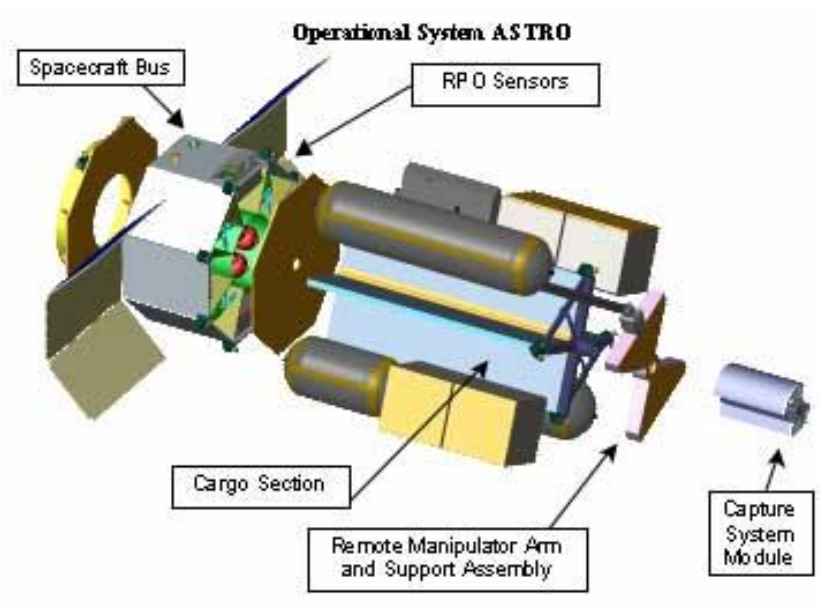
MATE Method for Tradespace Exploration



Example: Space Tug



General purpose vehicle to intercept, interact with, and accelerate other vehicles: General question - what would be a useful design for such a vehicle?



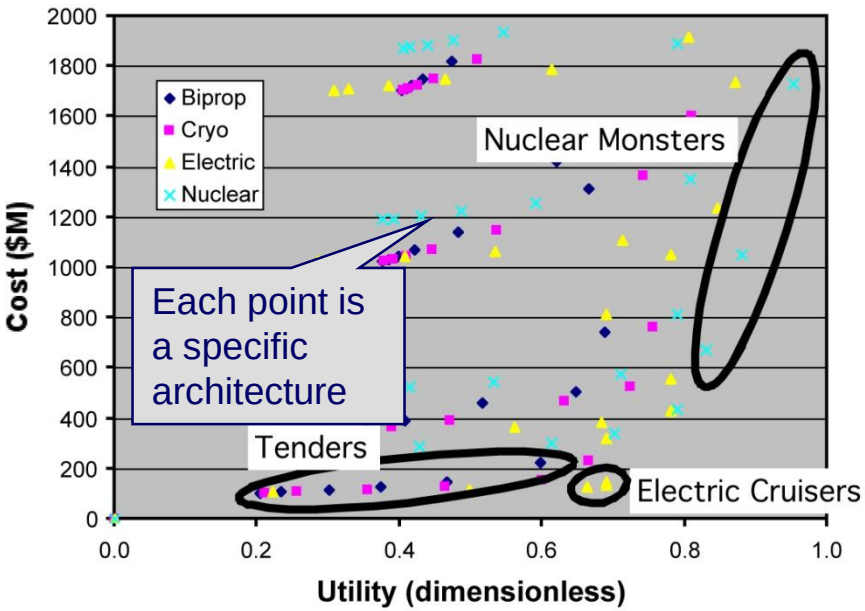
Recently flown Astro/NextSat mission:

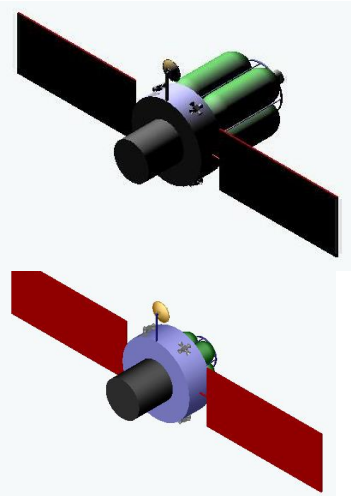
Robotic, autonomous on-orbit refueling and reconfiguration test program-

Proof of concept!

What is a Tradespace?

Attributes
- Delta-V
- Capability
- Response time





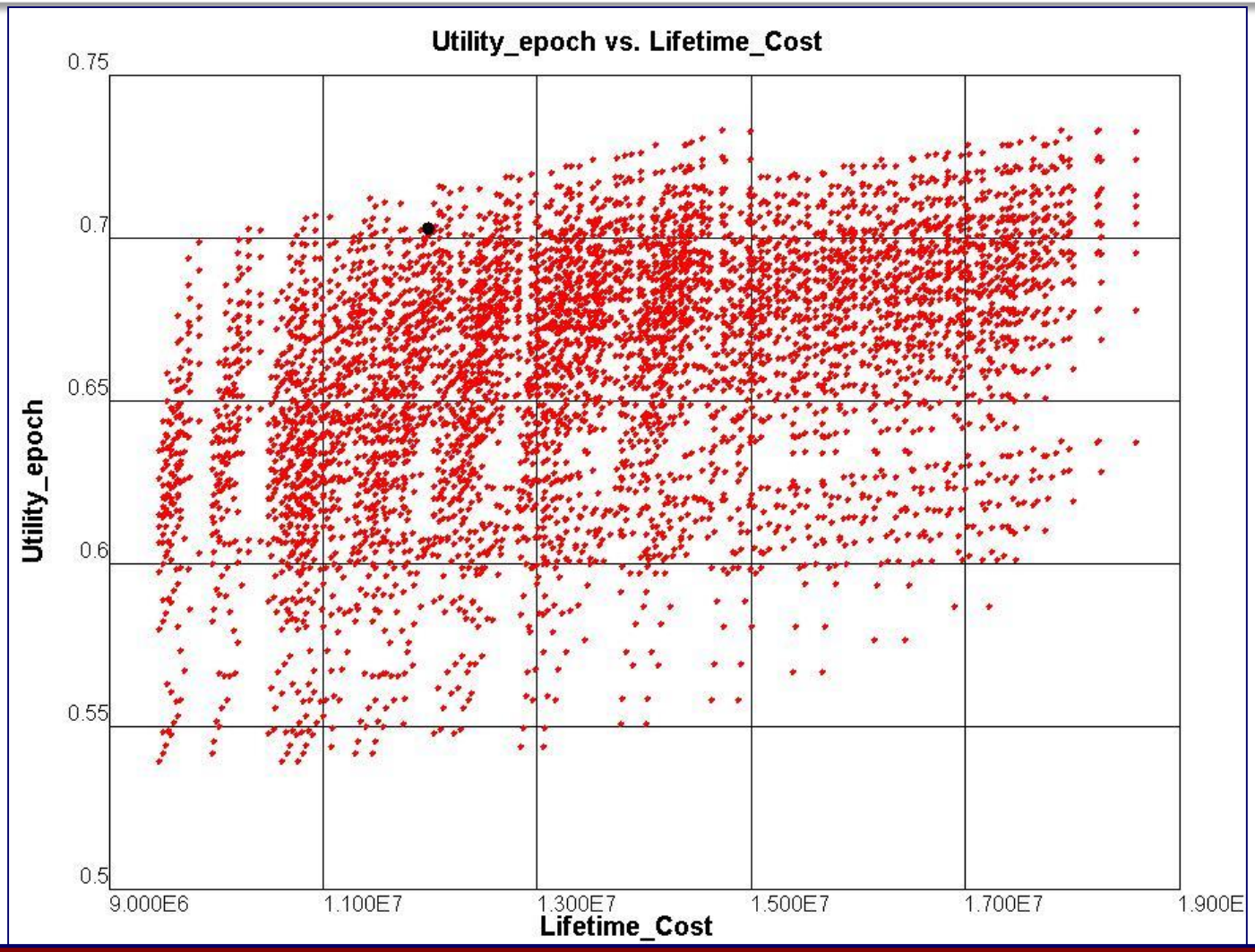
Design Space
- >Manipulator Mass
  - Low (300kg)
  - Medium (1000kg)
  - High (3000 kg)
  - Extreme (5000 kg)
- >Propulsion Type
  - Storable bi-prop
  - Cryogenic bi-prop
  - Electric (NSTAR)
  - Nuclear Thermal
- >Fuel Load - 8 levels

>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 benefit (e.g. utility) and cost of a large space of possible system designs

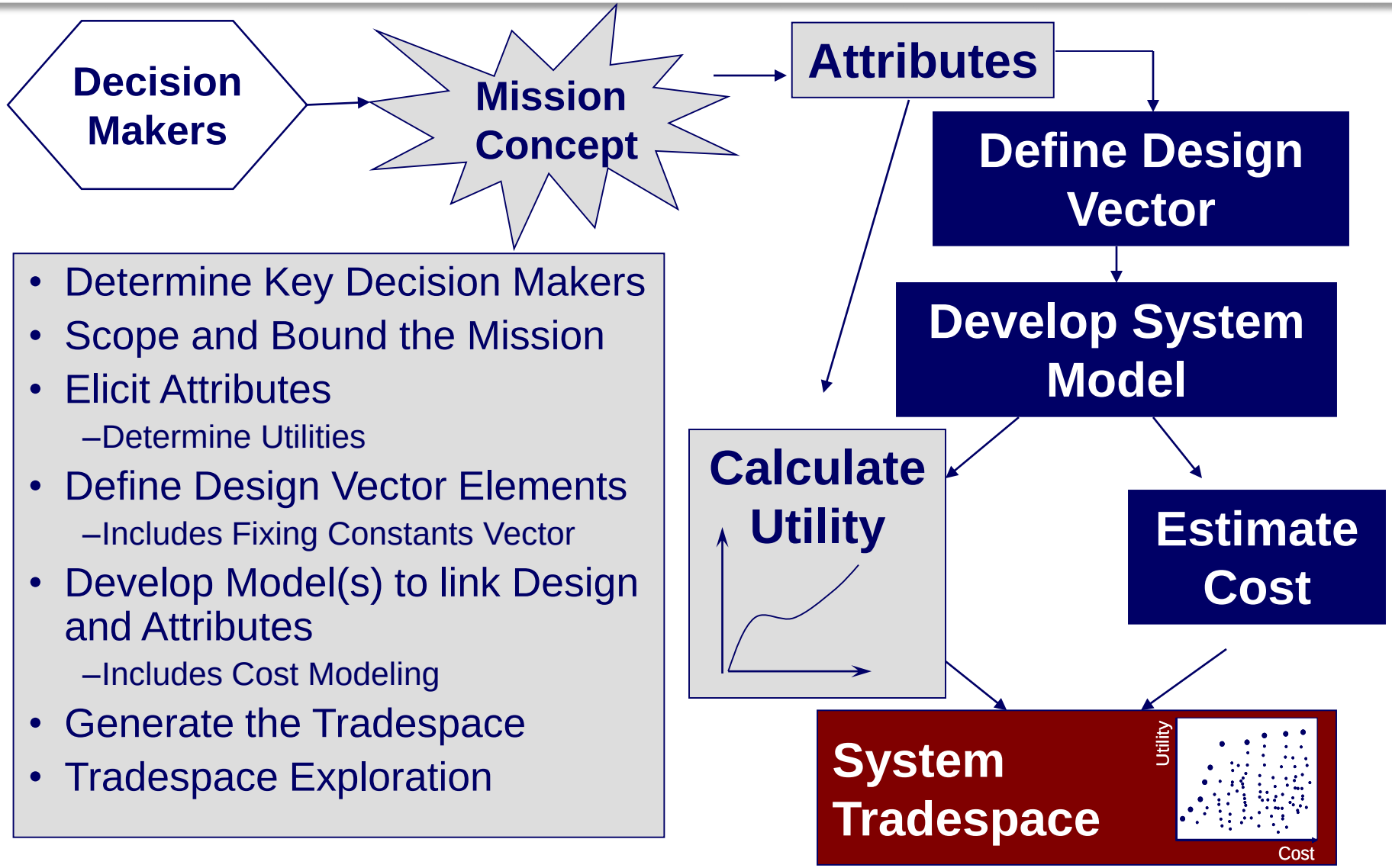
Tradespace Data Representation

Rich data sets can be explored to reveal complex relationships between design-space and value-space for generating intuition into problem—a multi-dimensional analogy to graphing y=f(x)



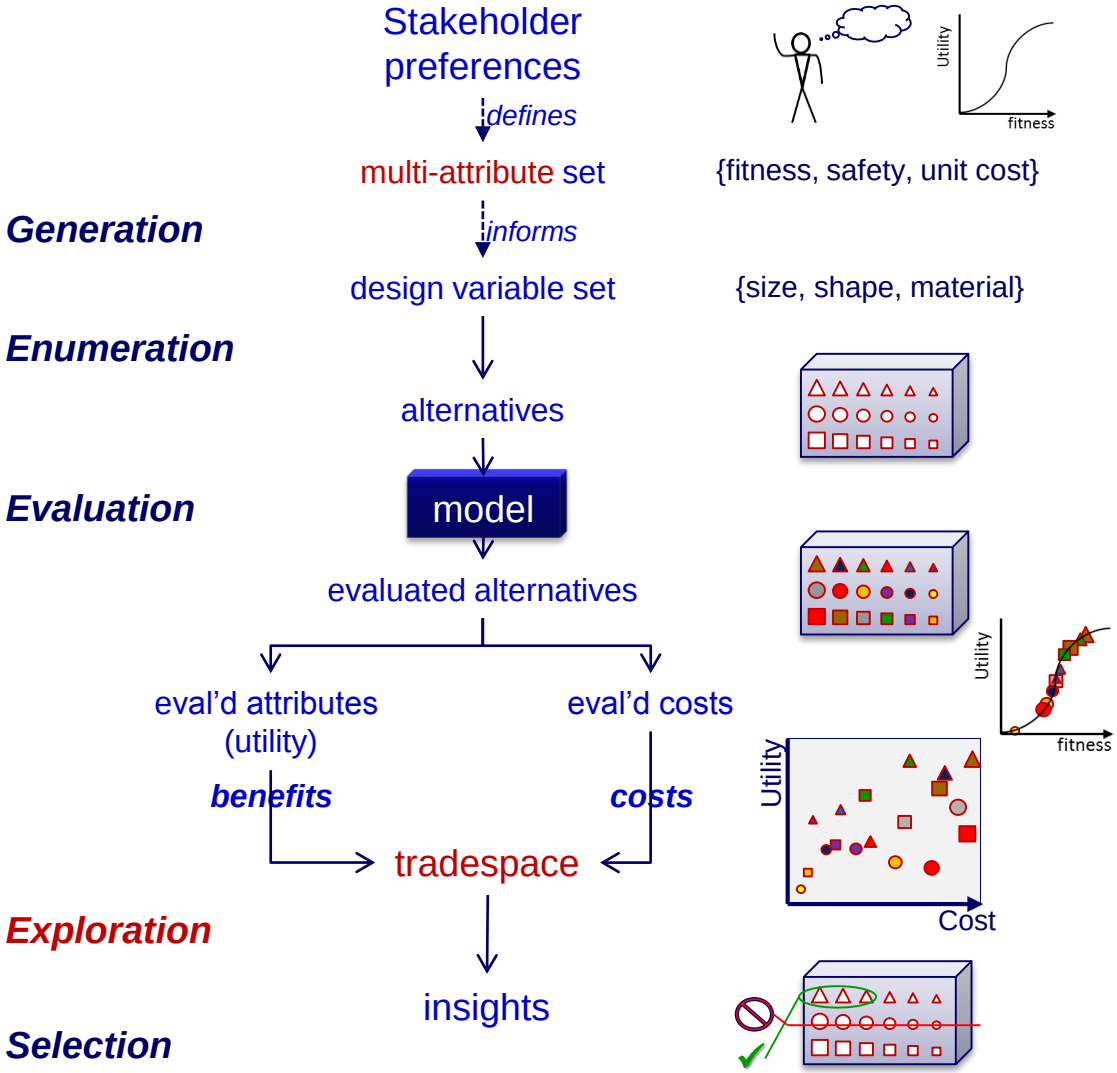
"Explore" tradespace data to develop intuition into complex design-value relationships

Steps for Multi-Attribute Tradespace Exploration (MATE)



- 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

Key Concepts in MATE



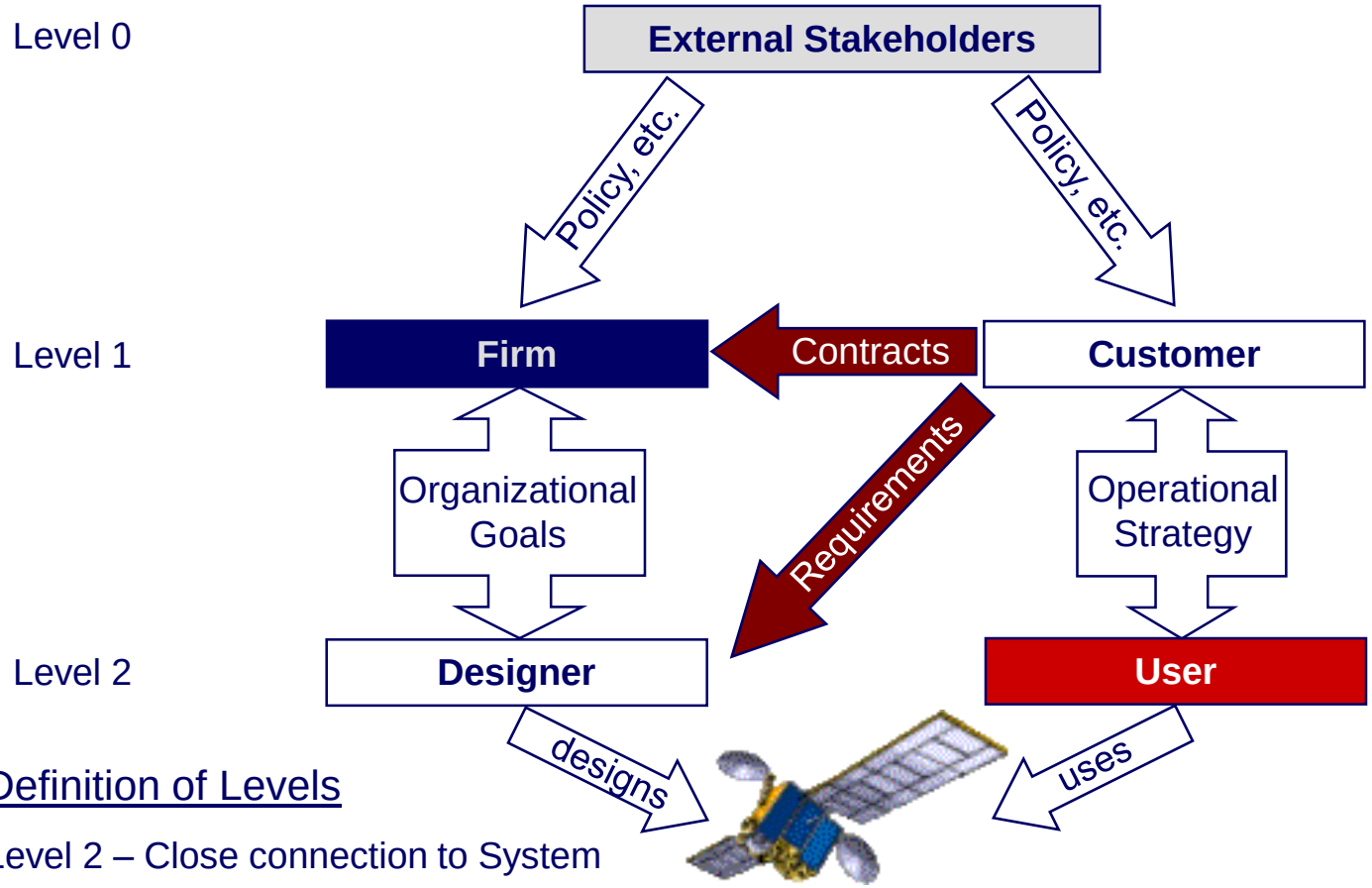
Decision Makers and Mission Concept

- 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

Framework for Identifying Key Decision Makers



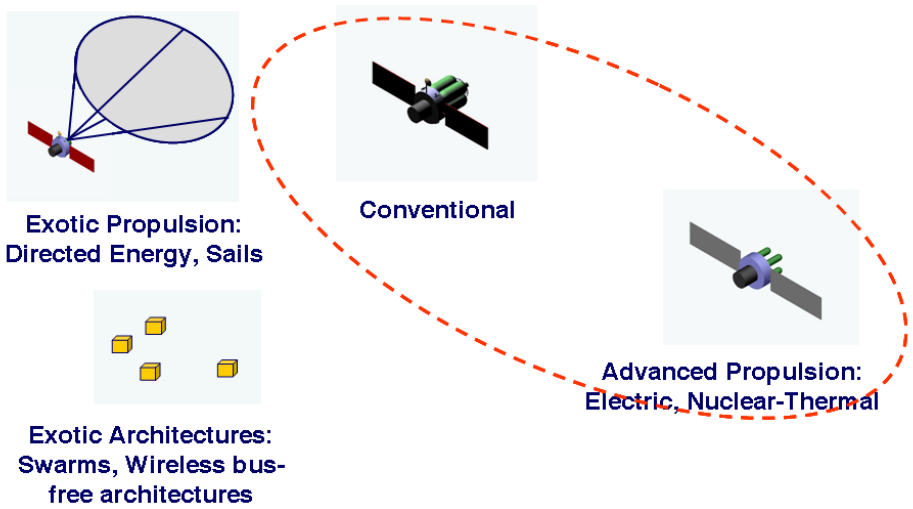
Definition of Levels

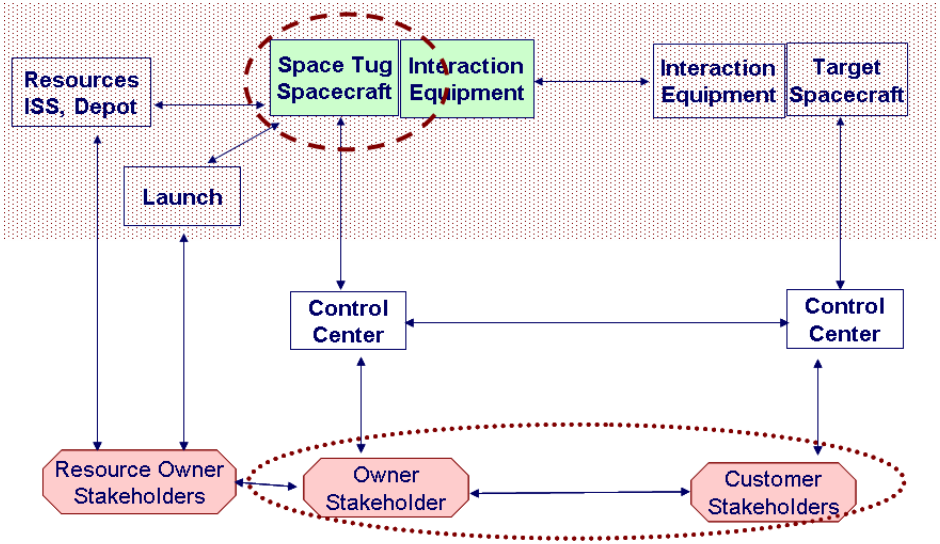
Level 2 – Close connection to System

Level 1 – Distant connection to System

Level 0 – Little or no connection to System

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

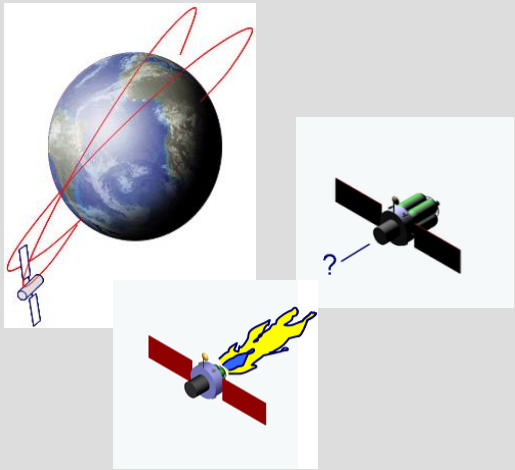
You will probably have to iterate

Space Tug Example:

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

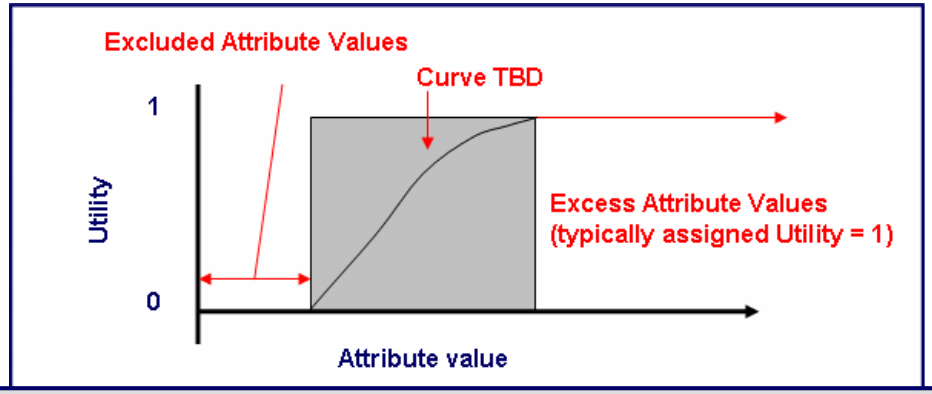
2) **Interaction Capability**: What can the vehicle do to the target? (kg of equipment carried) [>0→5000]

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

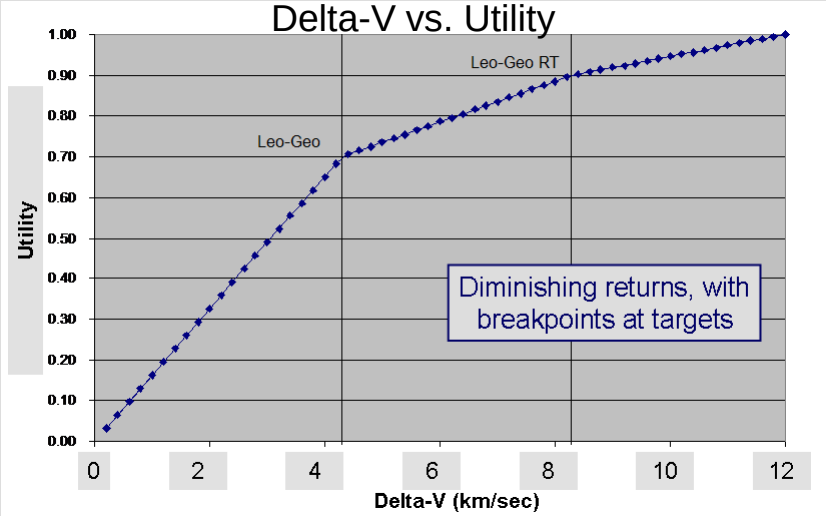


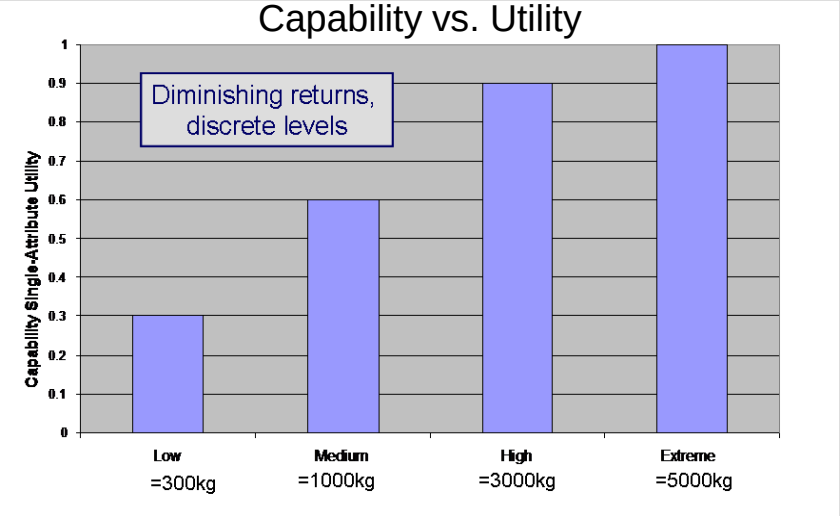
Defining Utilities

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

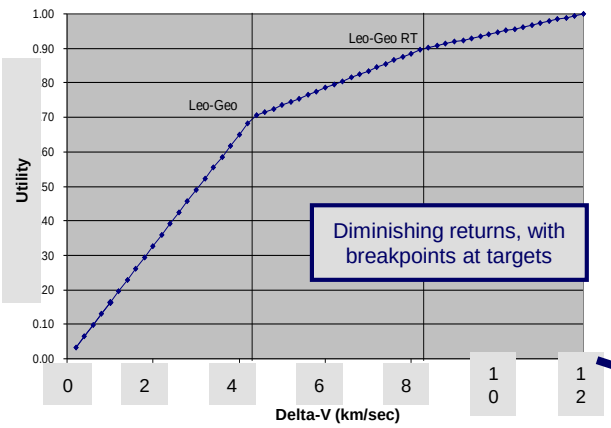


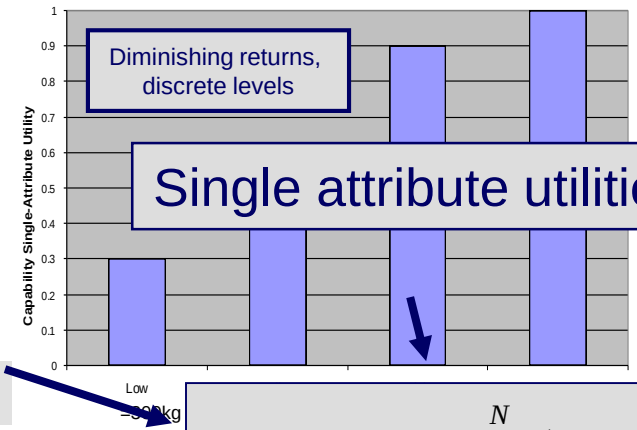
Space Tug Example:

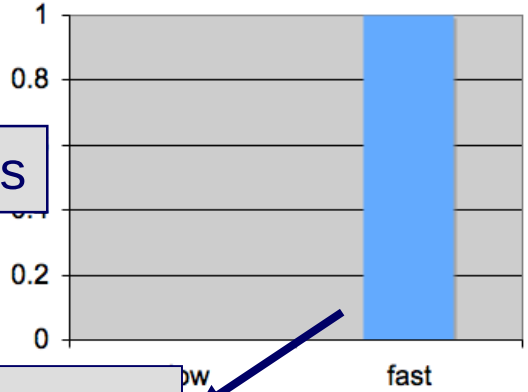




Aggregating Utilities



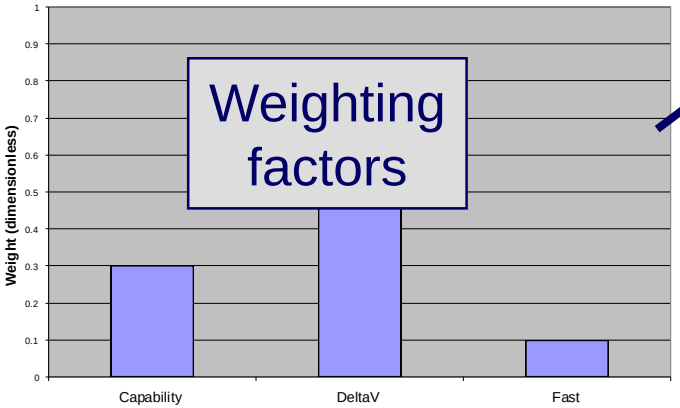




Single attribute utilities

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

Aggregating Function



Weighting factors

- *If possible*, define an aggregating function
  - Weighted sum often used (iff $\Sigma k_i=1$!)
  - MAUT Keeney-Raiffa function better
  - 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:

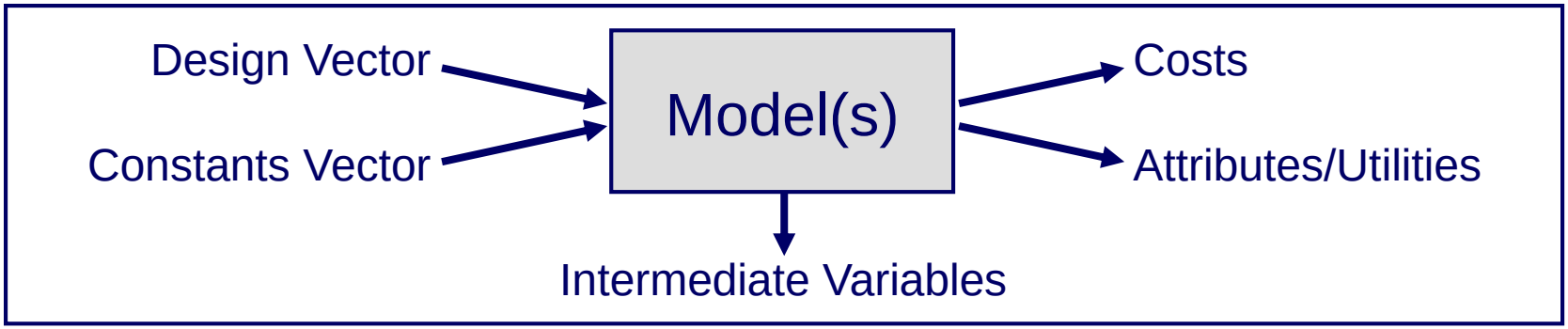
Design Var. Associated Quantities

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	

Design-Value Mapping (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)

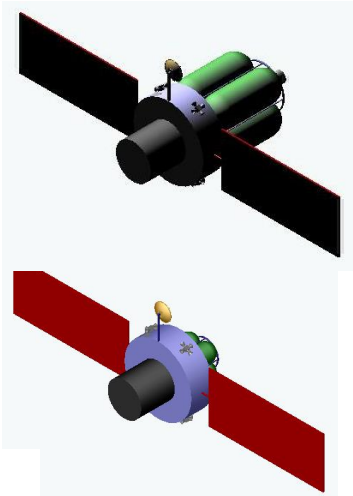
Space Tug Example:

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

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

Baseline Study: Space Tug

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



Design Space

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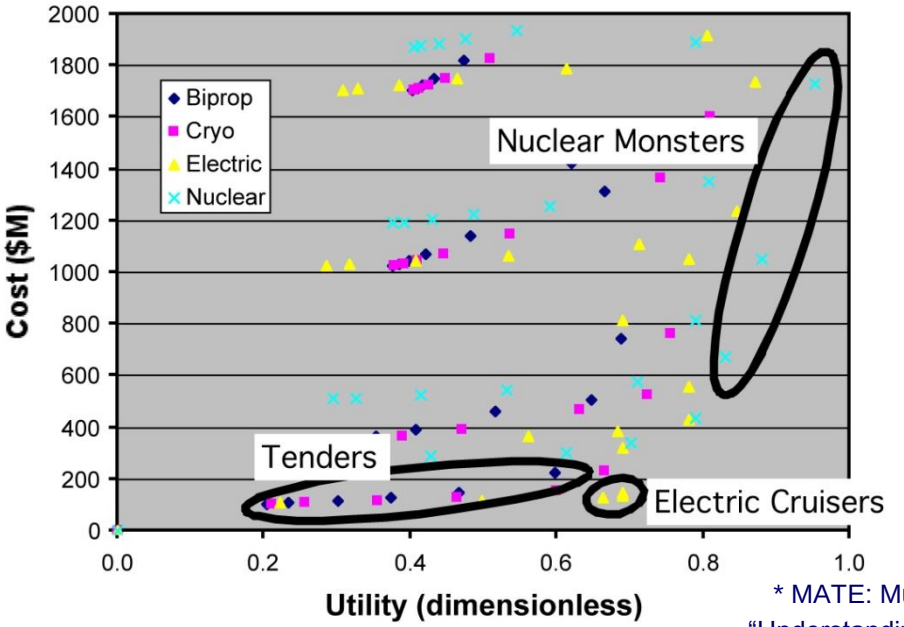
>Fuel Load - 8 levels



>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.

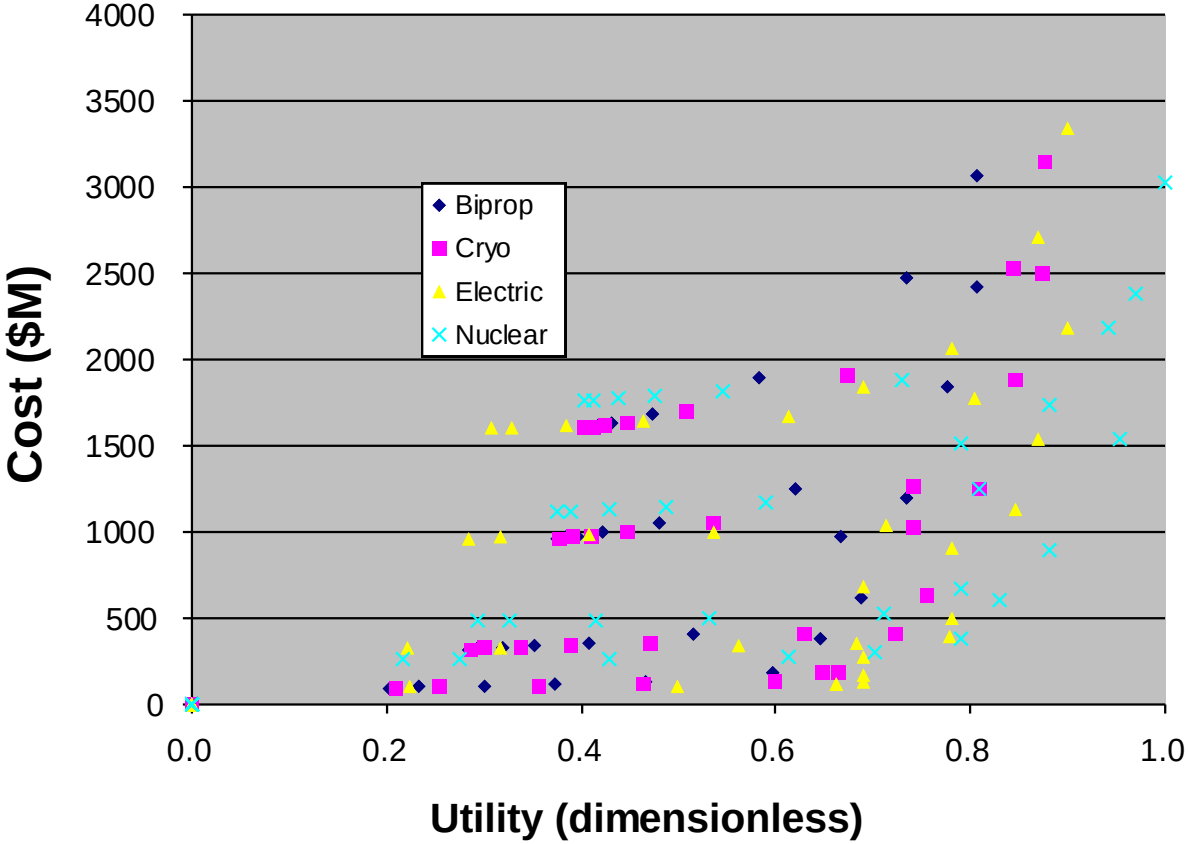
The Tradespace

- 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*

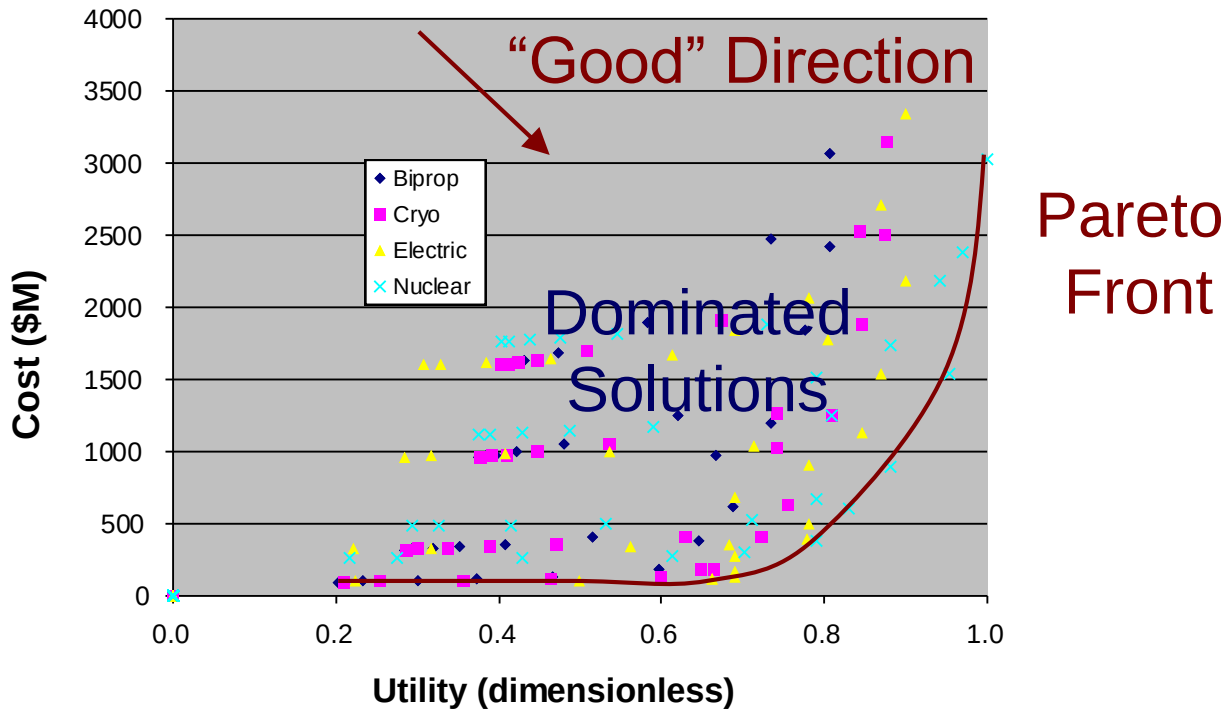
Need to distill this *information* into *knowledge* useful to decision makers

Space Tug Tradespace Aggregated Utility vs. Cost



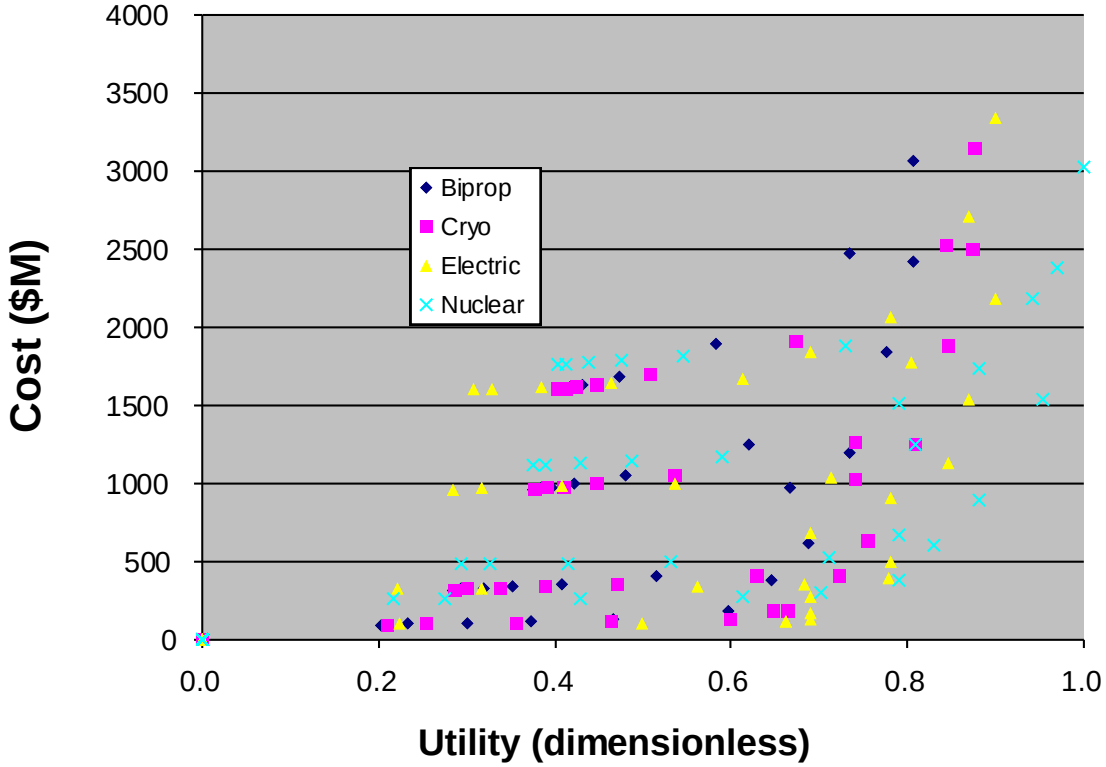
Each point is a complete design

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

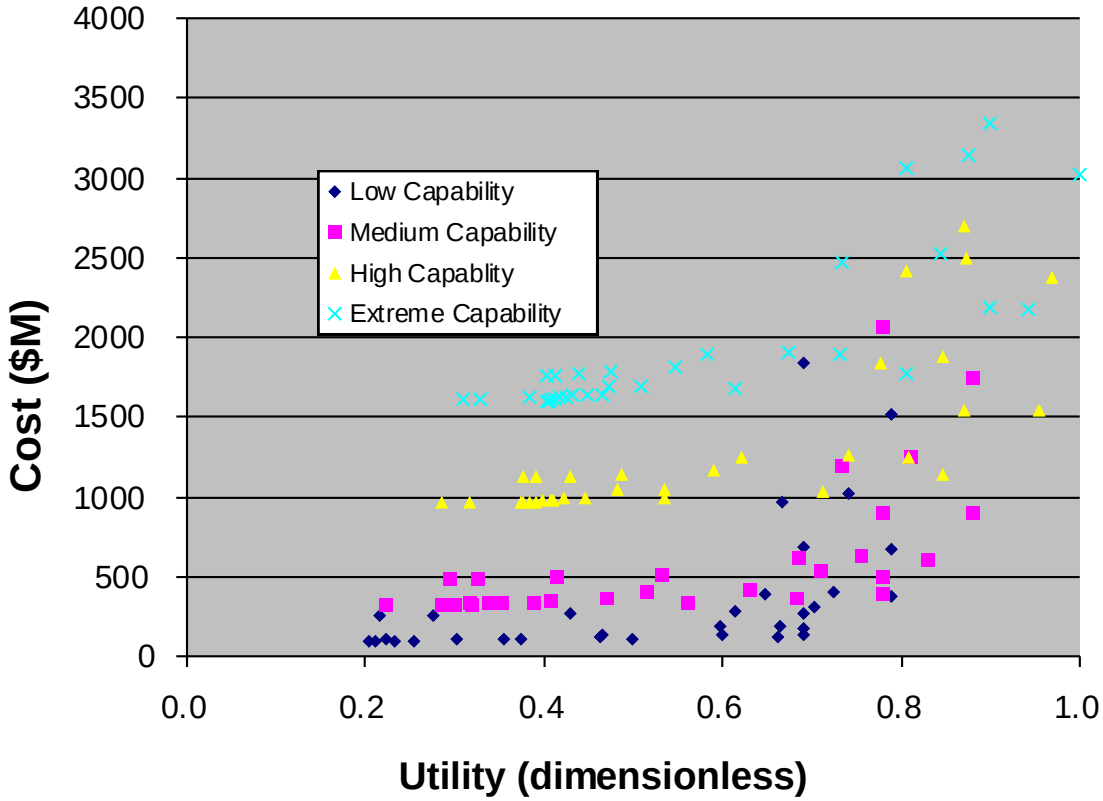
Understanding Design Choices



- 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

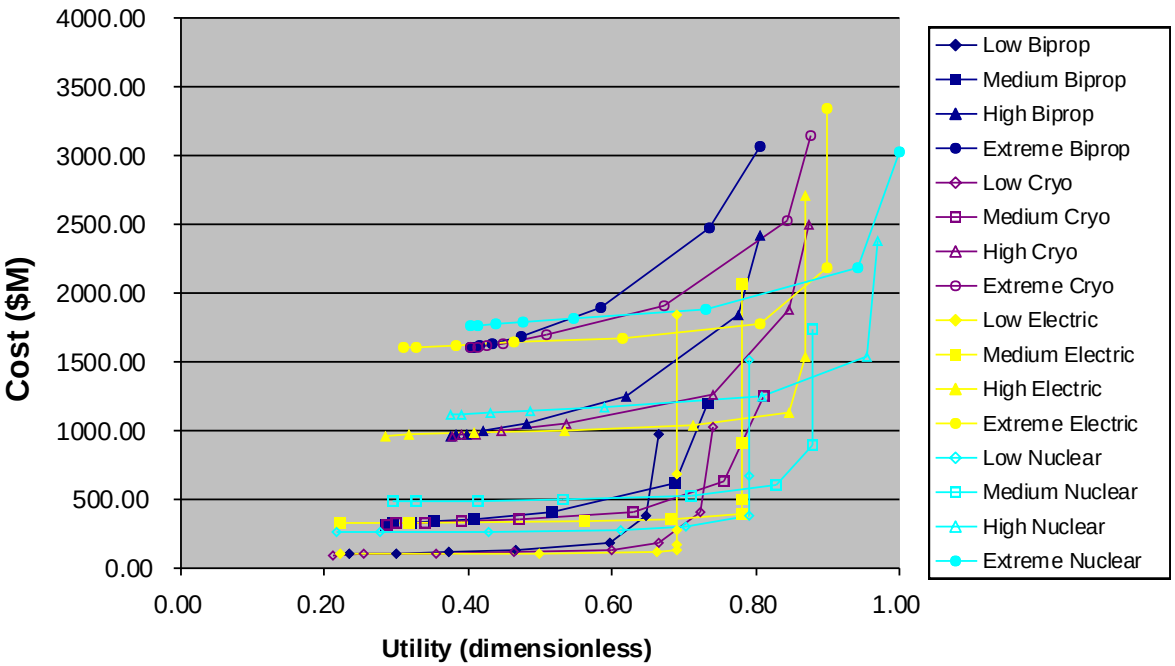
Understanding Design Choices: Example II



- 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

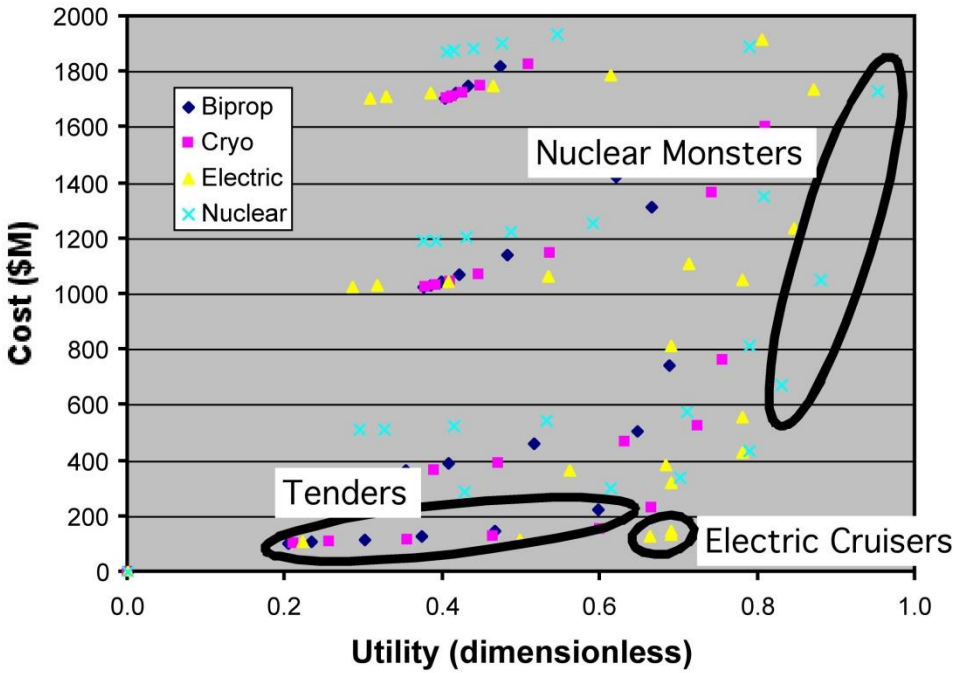
Understanding Design Choices: Example III



- 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 ΔV capability (tenders)
- Small, slow, high-ΔV 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

Structuring Exploration: Question-Guided Approach

- Decade of tradespace research encapsulated in papers and theses, but "art" of exploration resided in experts
- Need for codifying exploration in order to mature the method and aid in deployment
- Proposed series of case study explorations guided by inquiry (i.e., "questions") in order to codify expertise (through hypothetical "user" sessions)
  - Activity uses VisLab* software and pre-populated database
  - During a TSE session, users will seek to answer the following questions:

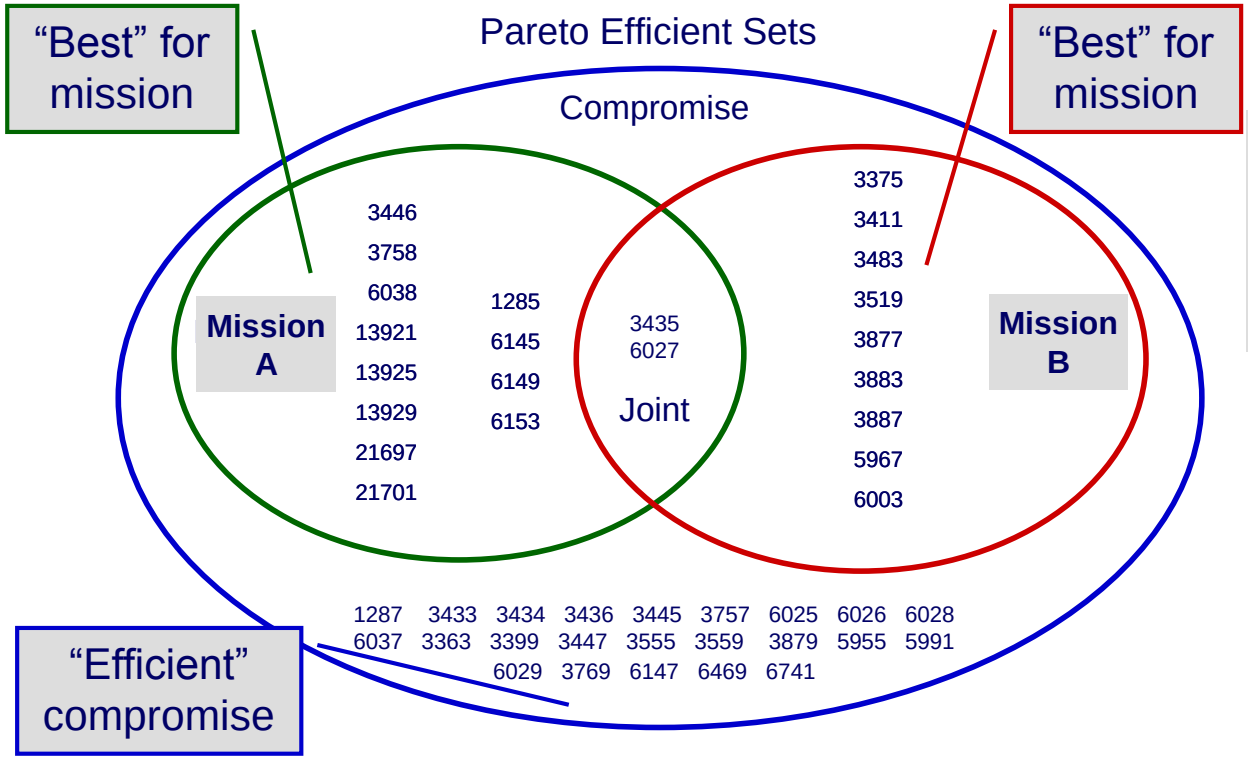
1. Can we find "good value" designs?
2. What are strengths and weakness of selected designs?
3. Are lower cost designs feasible?
4. What about time and change?
5. What about uncertainty
6. How can detailed design development be initiated to have increased chance of program success?

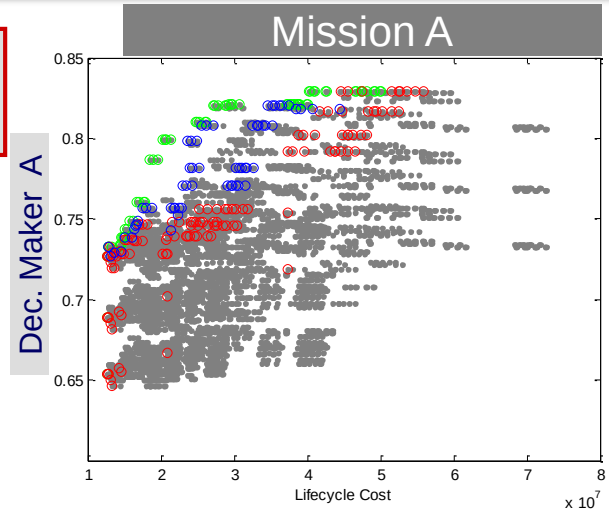
Questions guide the exploration of the datasets, helping to select the proper tools and representations for knowledge-generation

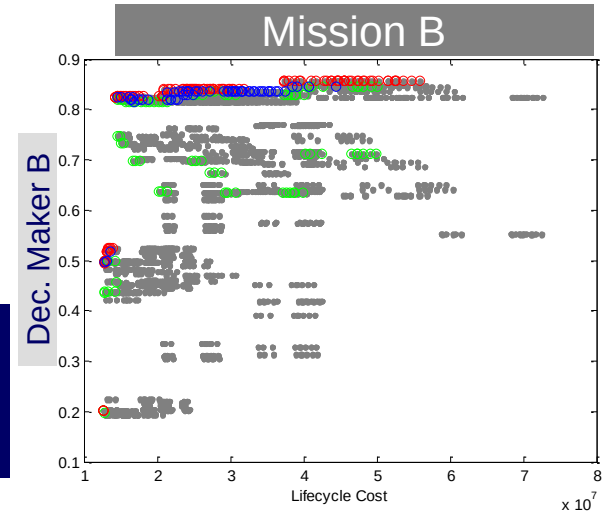
*VisLab software is MATLAB®-based, in-house analysis and visualization program for interactive TSE, but any suite of applications that can perform the necessary functions can be used

Find details in: Ross, A.M., McManus, H.L., Rhodes, D.H., and Hastings, D.E., "Revisiting the Tradespace Exploration Paradigm: Structuring the Exploration Process," AIAA Space 2010, Anaheim, CA, September 2010.

Finding "Compromises" Across Missions and Decision Makers







Method provides quantitative approach for discovering "best" mission-specific designs, as well as "efficient" (benefit at cost) compromises across missions and decision makers

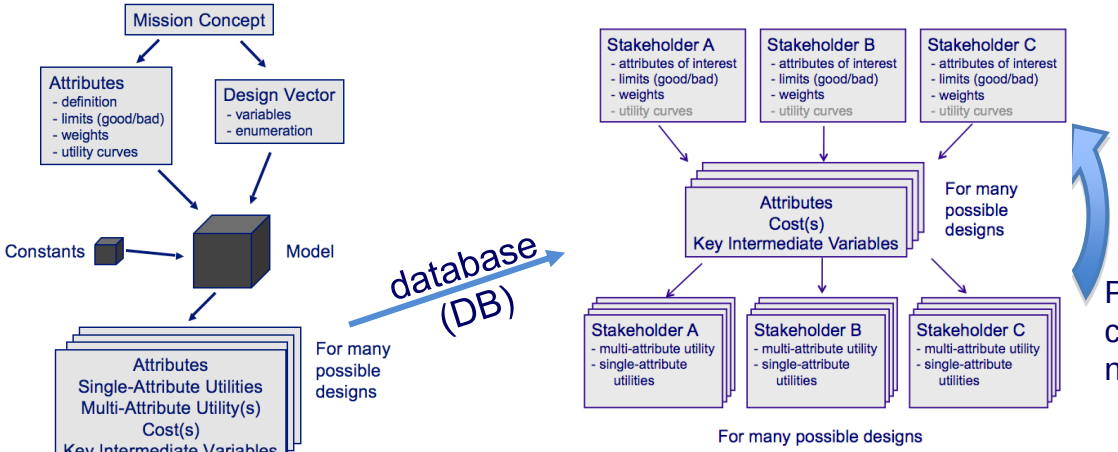
Discover "best" alternatives for individual missions, as well as "efficient" compromises

Role-Playing Session

Motivation: Wanted to test proposed methods using decision makers, not analysts

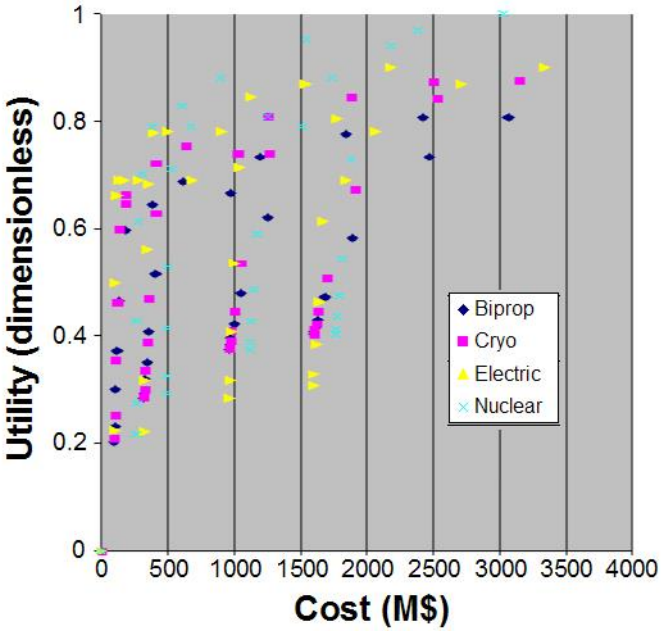
- Decision makers filled out preferences in advance using a provided worksheet that constrained preferences to derive from existing model data set
- 2 hour role-playing session using VisLab 1.0 with the following tasks:
  - Find "best" designs per mission
  - Seek "compromise" solutions across missions
  - Vary mission priorities (weights) and repeat
  - Vary mission acceptance ranges (time permitting)
  - Vary mission contexts (time, capability permitting)

Hypothesis: real-time database interaction with multiple simultaneous decision makers will allow for feedback between preference updating and "favorite" solutions, allowing for better compromises

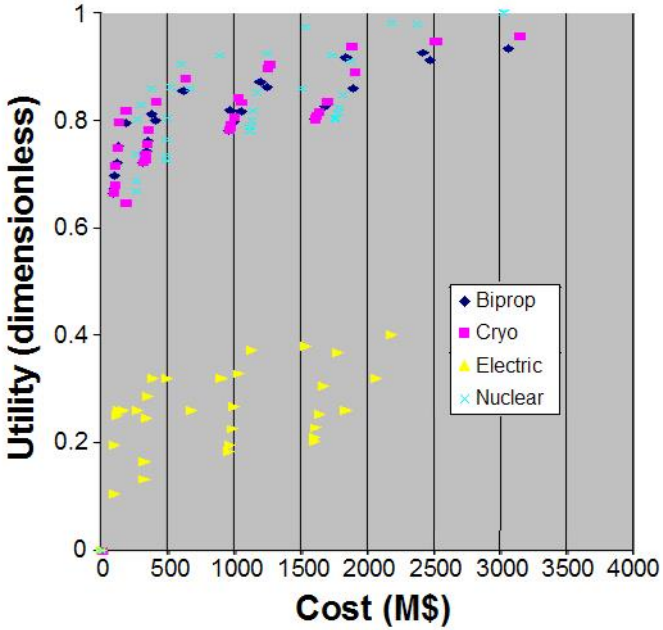


For details see: Ross, A.M., McManus, H.L., Rhodes, D.H., and Hastings, D.E., "A Role for Interactive Tradespace Exploration in Multi-Stakeholder Negotiations," AIAA Space 2010, Anaheim, CA, September 2010.

Typical Benefits: Assessing Changing Requirements



User needs change, so Utilities recalculated



Space Tug example:
added requirement for rapid response drastically lowers utility of electric propulsion designs

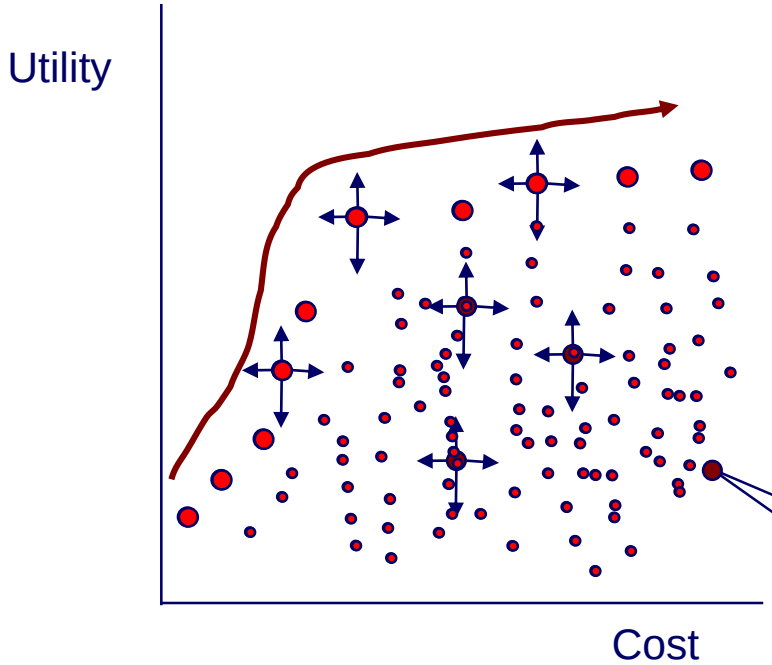
Example MATE Benefits

The following strengths of MATE were identified by a user of the method

- Forces alignment of solutions to needs
- Reveals structure of design-value spaces not apparent with few point designs
  - Akin to graphing calculator showing function shapes, tradespace gives insight/intuition into complex design-value space relationships
- Facilitates cross-domain socio-technical conversation
- Ability to discover compromise solutions
  - Beyond “optimized” per stakeholder solutions
  - Experts often unable to find “suboptimal” solution that may be better compromise across stakeholders
- Structured means for considering large array of possible futures for discovering robust systems and strategies

MATE highlights and helps to focus attention on important trades, possibly overlooked by traditional methods

Tradespace Exploration Paradigm: Avoiding Point Designs



Differing types of "trades"

0. Choose a solution
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

Value-Driven Conceptual Design Through Tradespace Exploration

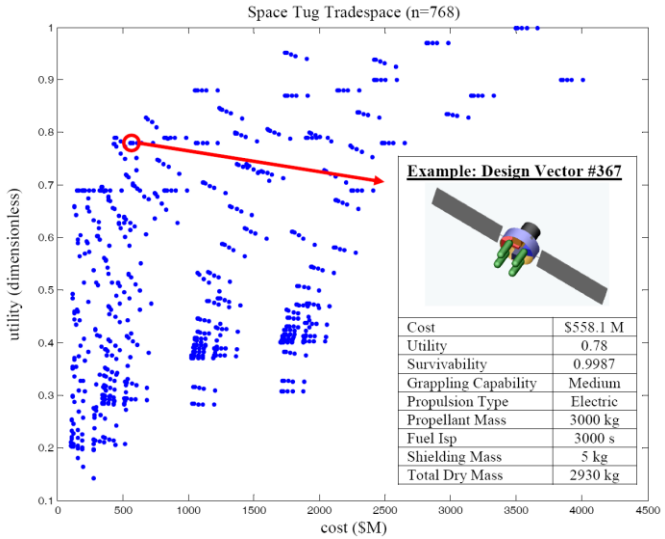
Value is a measure of net benefit specified by a stakeholder

Value-centric perspective enables unified evaluation of technically diverse system concepts

Operationalized through the application of decision theory to engineering design -- quantifies benefits, costs, and risks

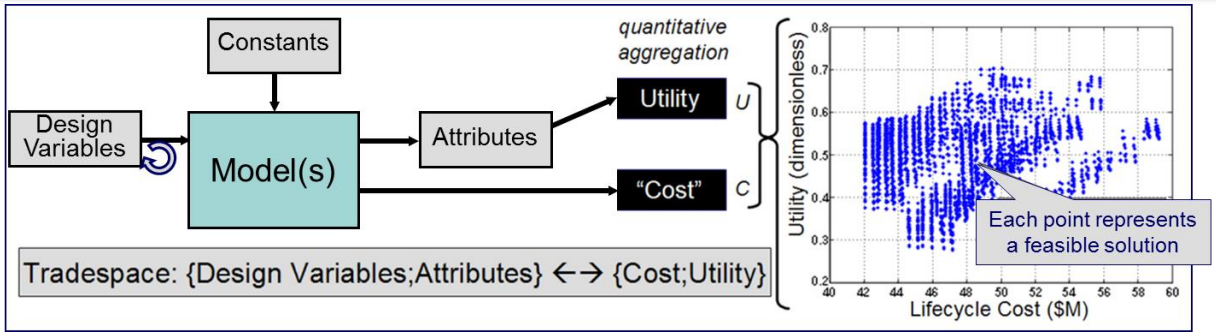
Tradespace exploration uses computer-based models to compare many alternatives on a common basis

- Avoids limits imposed by myopic local point solutions
- Maps decision maker preference structure to potential designs
- Reveals conflicts and confluence in delivering value to stakeholders

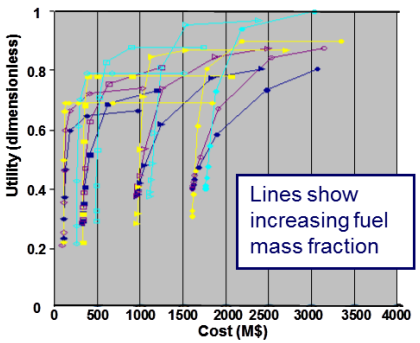


A MATE study can be conducted at different levels of effort and should be scaled appropriately

Summary



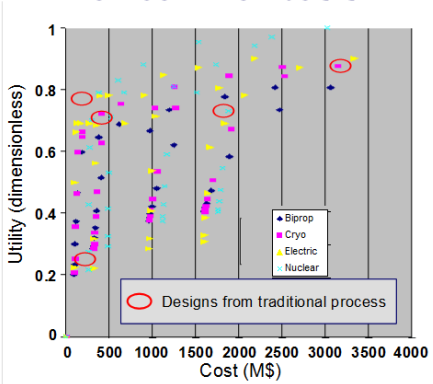
Understanding limiting physical or mission constraints



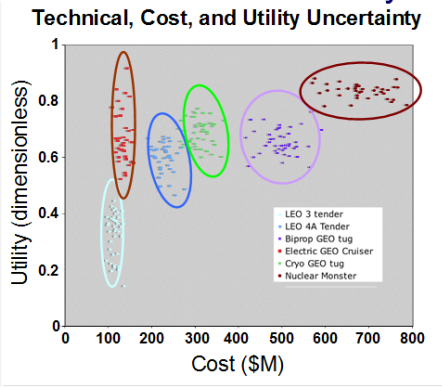
MATE includes an ordered set of steps for creating an information-rich tradespace:

1. Scoping and bounding the mission
2. Choosing attributes
3. Choosing design variables
4. Modeling and evaluating concepts
5. Creating the tradespace
6. Conducting tradespace exploration

Comparing alternatives on common basis



Understanding differential uncertainty



The goals of concept design and tradespace exploration are the extraction of knowledge and the identification of potentially valuable solutions

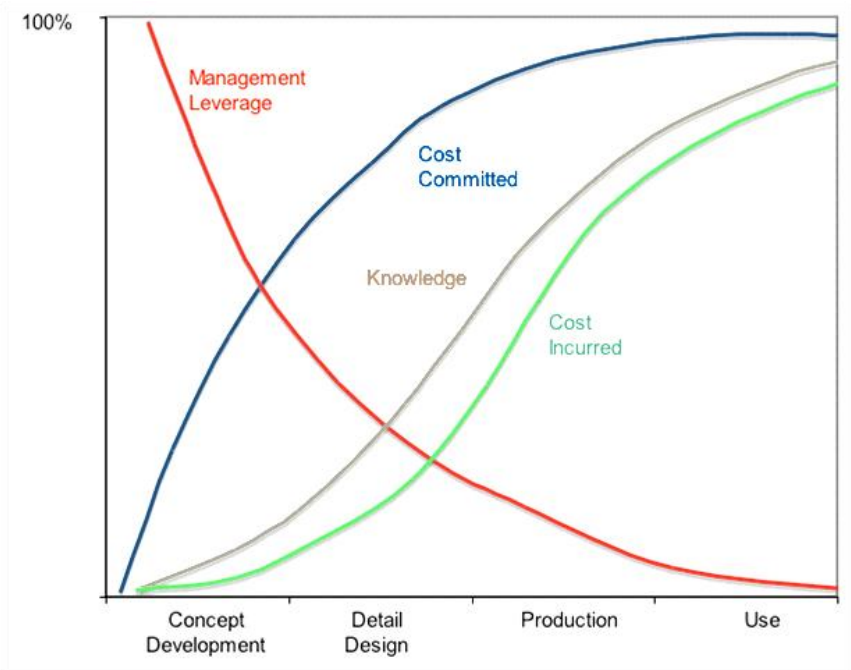
Decade of Foundational Research in Tradespace Exploration (TSE)

A method for understanding complex solutions to complex problems
Better informs "upfront" decisions and planning
Evolved through 14 multi-faceted case studies using method

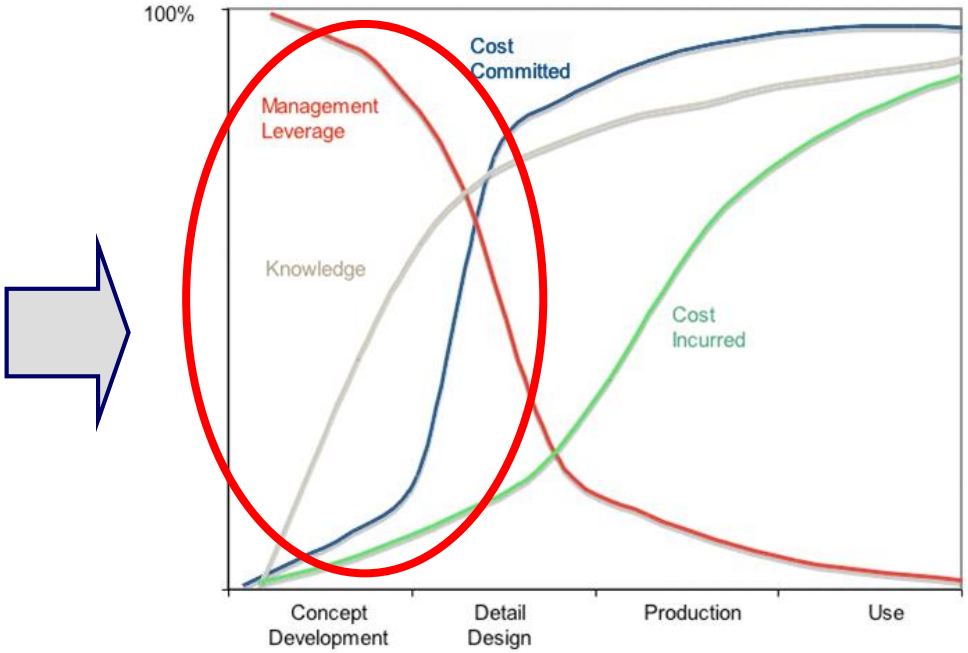
- Model-based, high-level assessment of system capabilities
- Ideally, *many* designs assessed
- Avoids optimized *point solutions* that will not support evolution in environment or user needs
- Provides basis to explore technical and policy *uncertainties*
- Provides a way to assess the value of *potential*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

Importance lies in power to generate knowledge and to engage senior decision makers in effective dialogue and negotiations

Changing the Picture



Classic decision impacts



New paradigm decision impacts

Increased knowledge (including understanding of uncertainties) and value-focused thinking allows for better up front decisions

APPENDIX

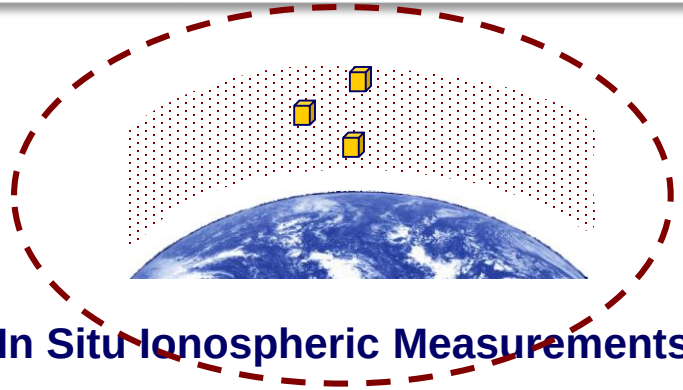
MATE Applications

Name	Num DV	Num Att	Size Tradespace
A-TOS	7	2	1380
B-TOS	6	5	4033
C-TOS	NA	5	1
X-TOS	9	5	50488
SDB	5	2-4	8700+8700+35000
SBR	5	7	1872
Space Tug	3-5	3	256
TPF	8-10	4-6, 2-3	10611
JDAM	8-11	5-8, 1-3	7151
ORDSS	5,7	10	2340+8640
SRS	10	5,5,5	23328x245
ORS	6	6	1100+1100+1100
Chicago Exp	10	3,3,5	$3.6x10^9$
MarSec	12-14	6, 6, 4	$16x10^6x11520$

There have been 14 case studies as of June 2012

A-TOS

Swarm making in-situ ionosphere measurements



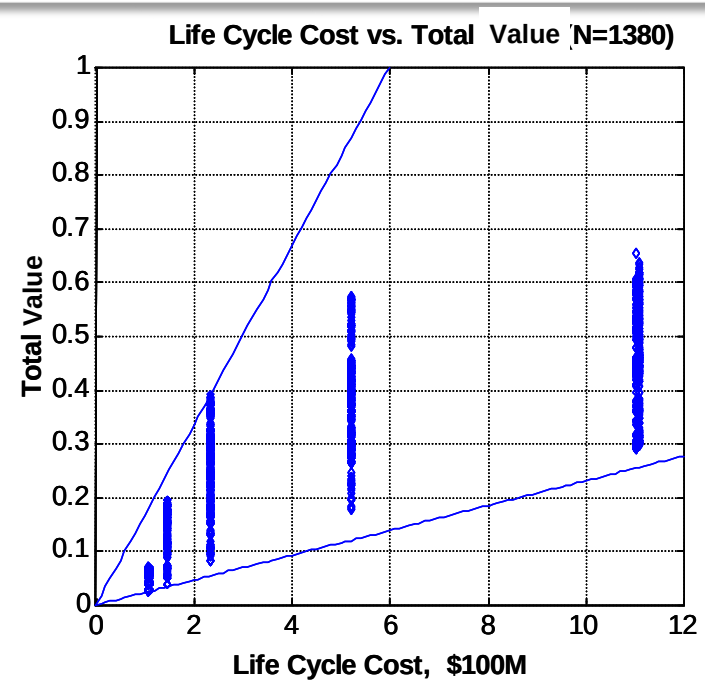
DESIGN VARIABLES (7)

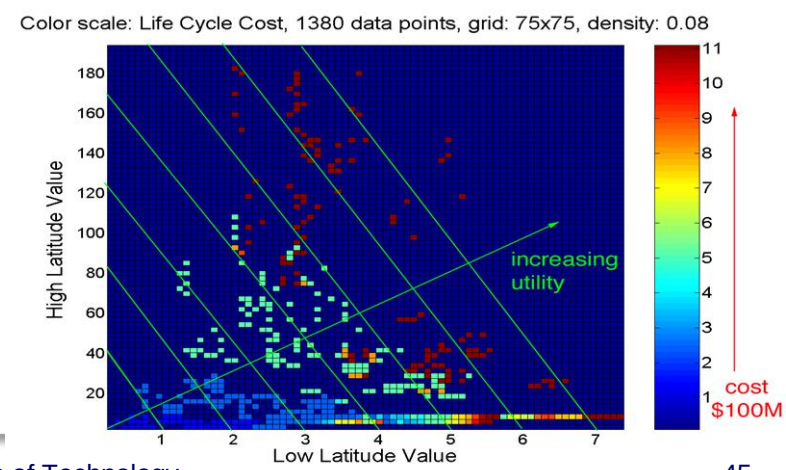
- Bulk Orbit Variables
  - Swarm inclination (deg) — 63.4
  - Swarm perigee altitude (km) — 200 – 800
  - Swarm apogee altitude (km) — 200 – 800
  - Swarm argument of perigee (deg) — 0
  - Number of orbit planes — 1
  - Swarms per plane — 1
- Swarm Orbit Variables
  - Subsats per swarm — 1 – 26
  - Number of subplanes in each swarm — 1 – 2
  - Number of suborbits in each subplane — 1 – 4
  - Yaw angle of subplanes (deg: vector) — ±60
  - Maximum satellite separation (km) — 0.001 – 200
- Non-orbit Variables
  - Mothership — (yes/no)

ATTRIBUTES (2)

- "Value" in Low latitude mission, "Value" in High latitude mission

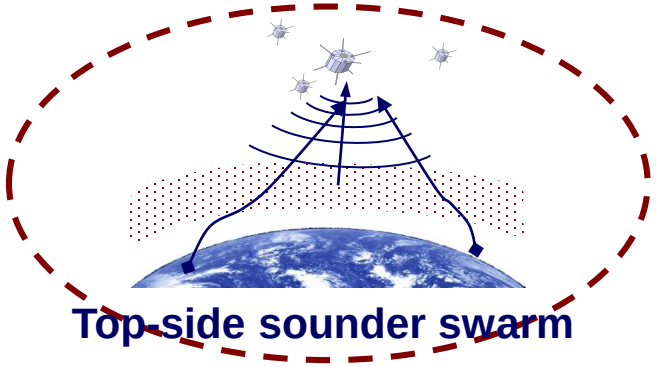
Number of Designs Explored: 1380

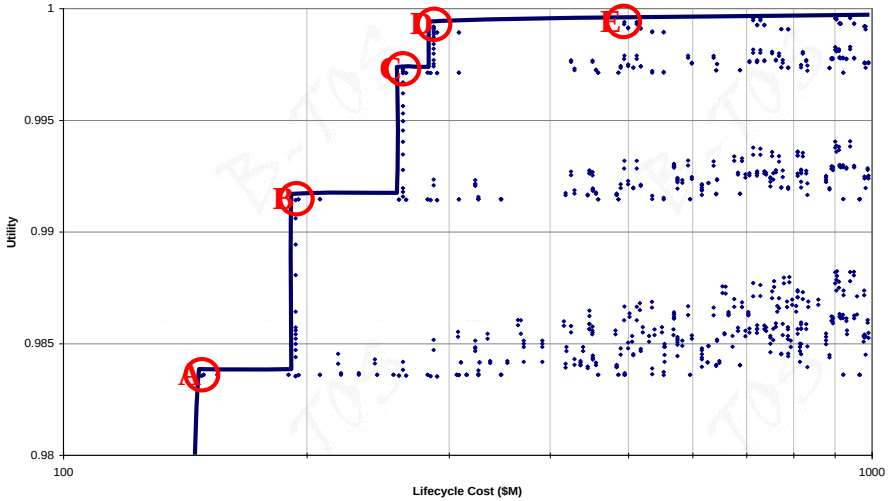




B-TOS

Hills swarm making ionosphere soundings



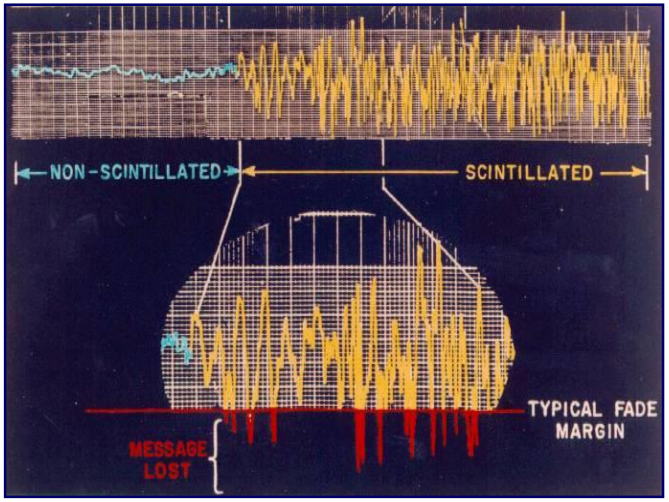


DESIGN VARIABLES (6)

- Large Scale Arch
  - Circular orbit altitude (km) — 1100, 1300
  - Number of Planes — 1, 2, 3, 4, 5
- Swarm Arch
  - Number of Swarms/Plane — 1, 2, 3, 4, 5
  - Number of Satellites/Swarm — 4, 7, 10, 13
  - Radius of Swarm (km) — 0.18, 1.5, 8.75, 50
- Vehicle Arch
  - 5 Configuration Studies — Trades payload, communication, and processing capability

ATTRIBUTES (5)

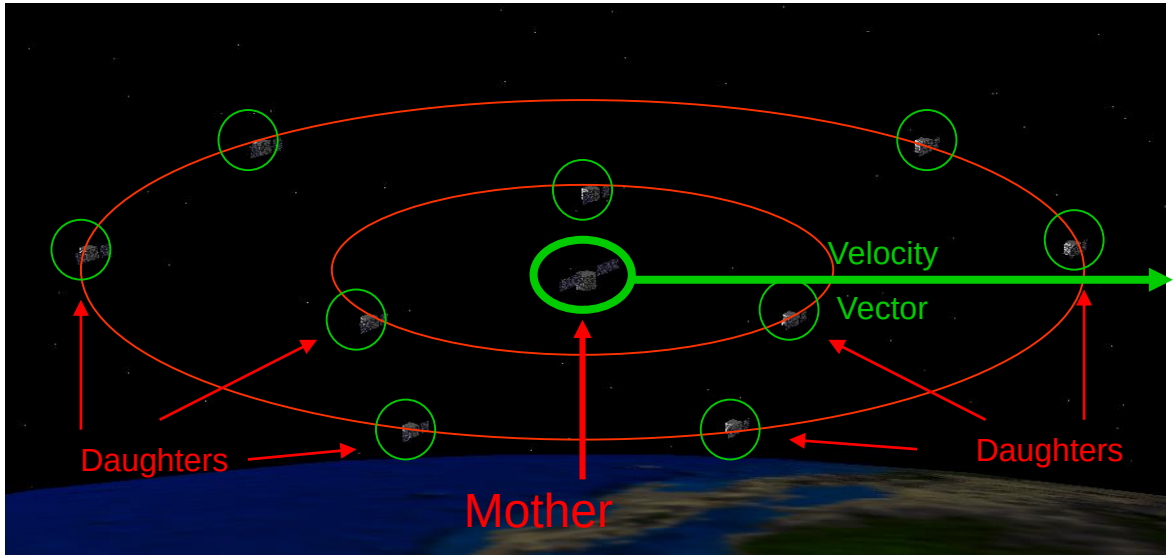
- Spatial Resolution (deg^2), Revisit Time (min), Latency (min), Accuracy (deg), Inst. Global Coverage (%),

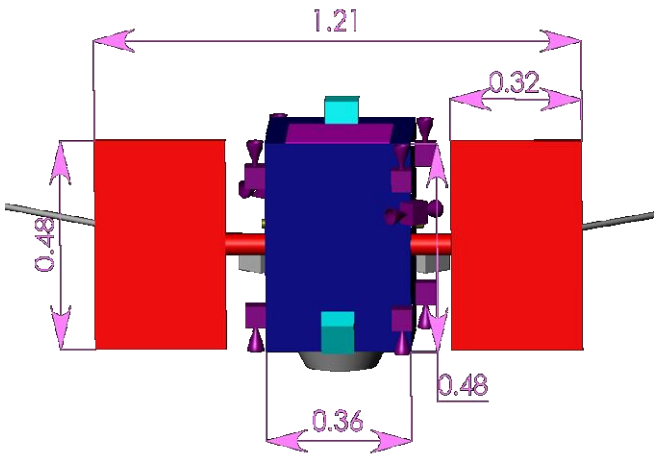


Number of Designs Explored: 4033

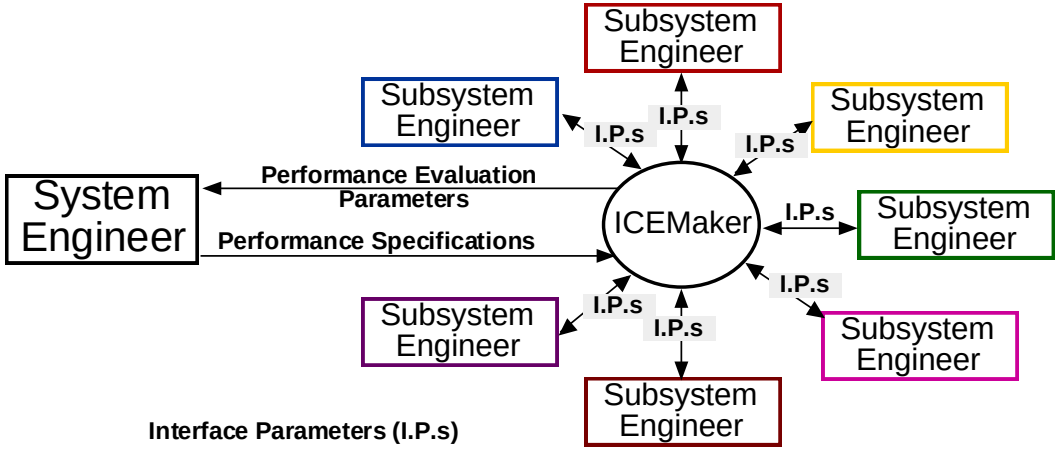
C-TOS

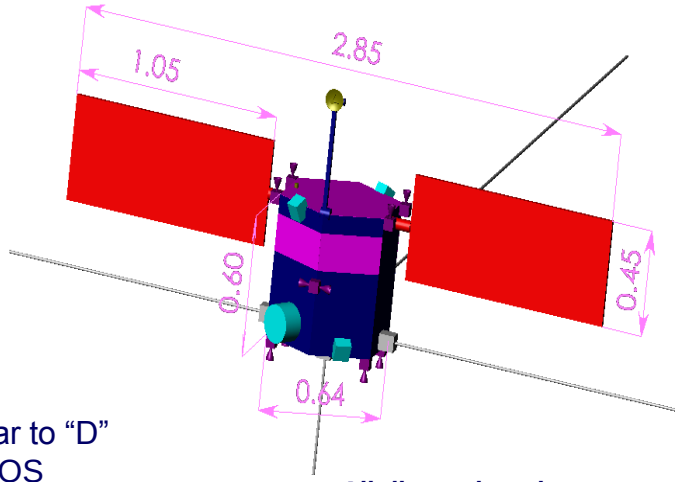
ICE design of B-TOS like vehicles*





All dimensions in meters





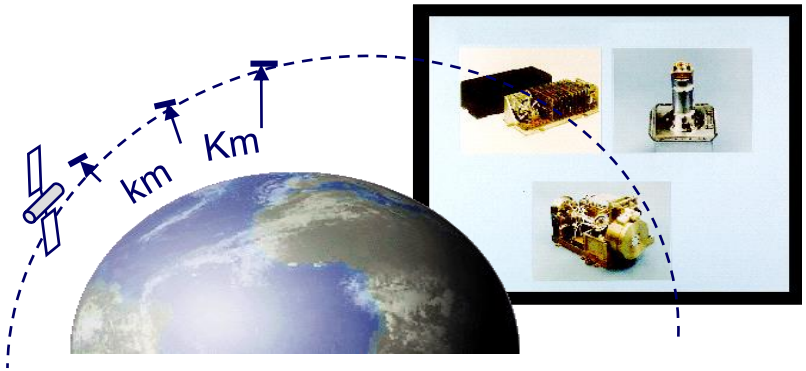
All dimensions in meters

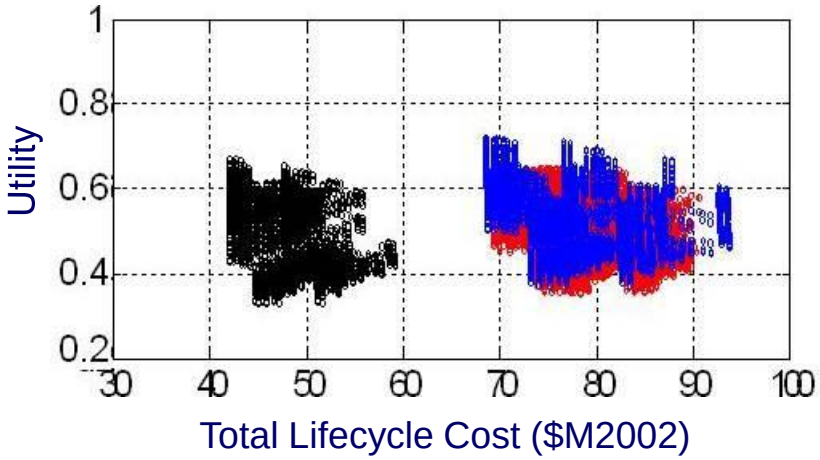
Number of Designs Explored: 1

*Design similar to "D" from B-TOS

X-TOS

Single-Vehicle *in-situ* density measurements



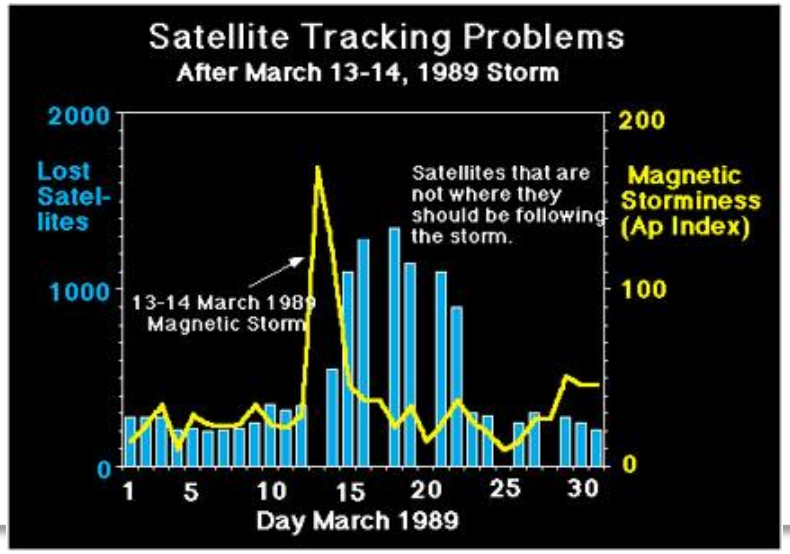


DESIGN VARIABLES (9)

- Mission Design
  - Scenario — 1 sat, single launch; 2 sats, sequential launch; 2 sats, parallel launch
- Orbital Parameters
  - Apogee altitude (km) — 200-2000
  - Perigee altitude (km) — 150-350
  - Orbit inclination (deg) — 0, 30, 60, 90
- Physical Spacecraft Parameters
  - Antenna gain — low, high
  - Communication architecture — TDRSS, AFSCN
  - Propulsion type — electric, chemical
  - Power type — solar, fuel cell
  - Delta_v (m/s) — 200-1000

ATTRIBUTES (5)

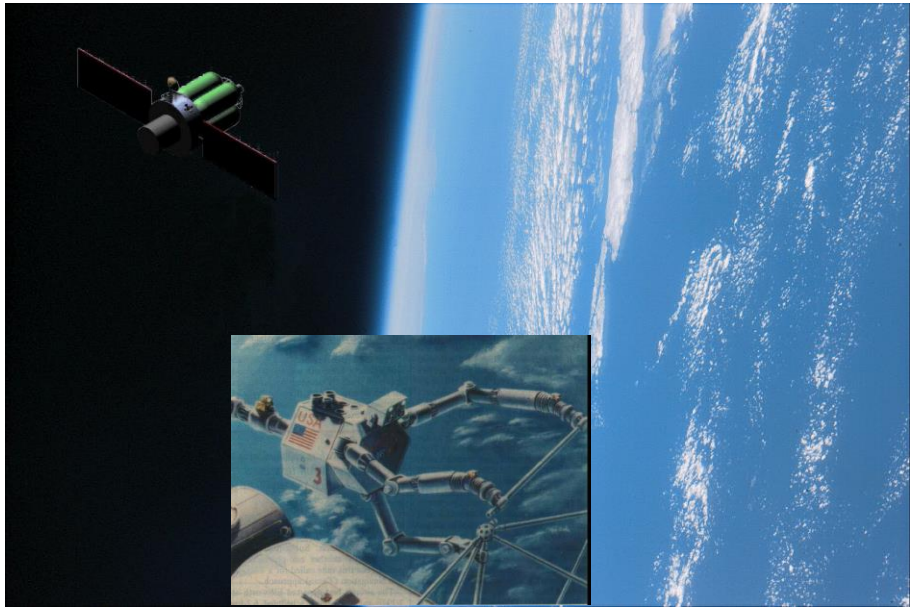
- Data lifespan (mos), Sample altitude (km), Latitude diversity (deg), Equatorial time (hr/day), Latency (hrs)

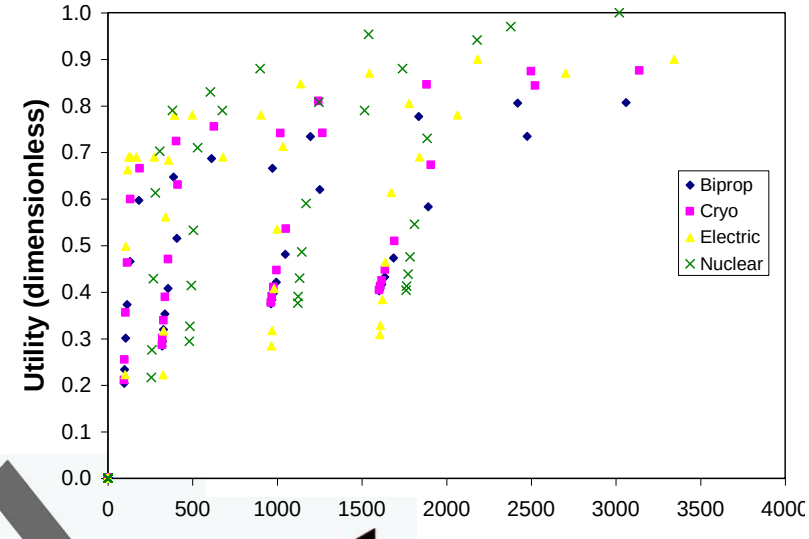


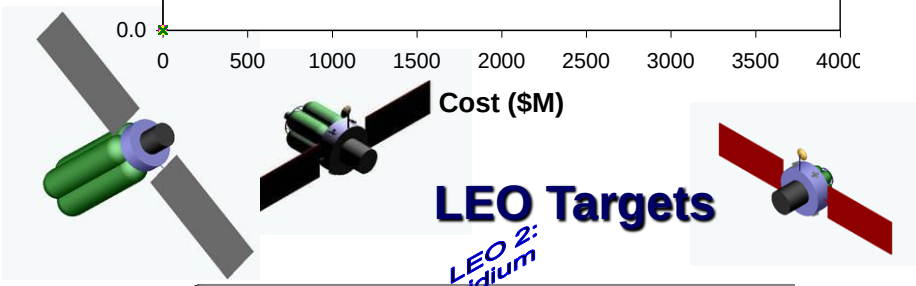
Number of Designs Explored: 50488

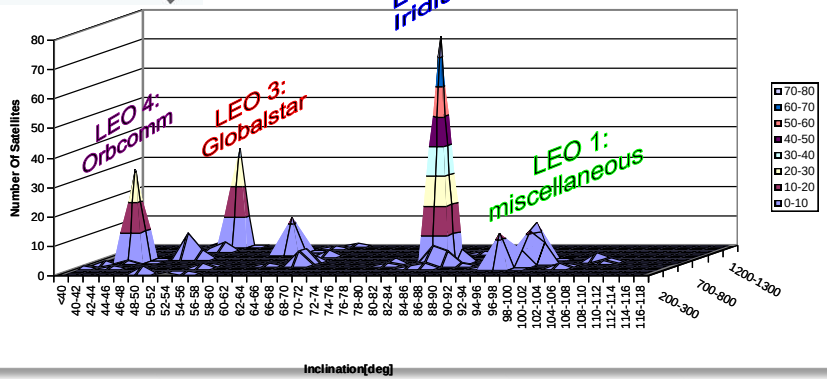
Space Tug

General purpose orbital service vehicle









DESIGN VARIABLES (3)

- Physical Spacecraft Parameters
  - Tugging Capability — low, med, high, extreme
  - Propulsion Type — storable-bi, cryogenic, electric, nuclear
  - Propellant Mass (kg) — 0-50000

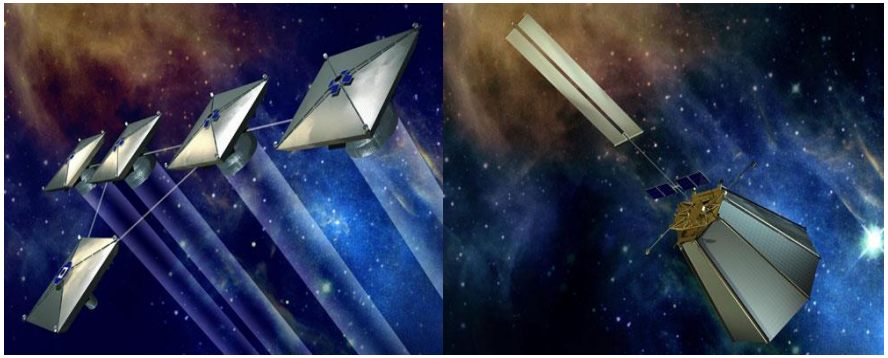
ATTRIBUTES (3)

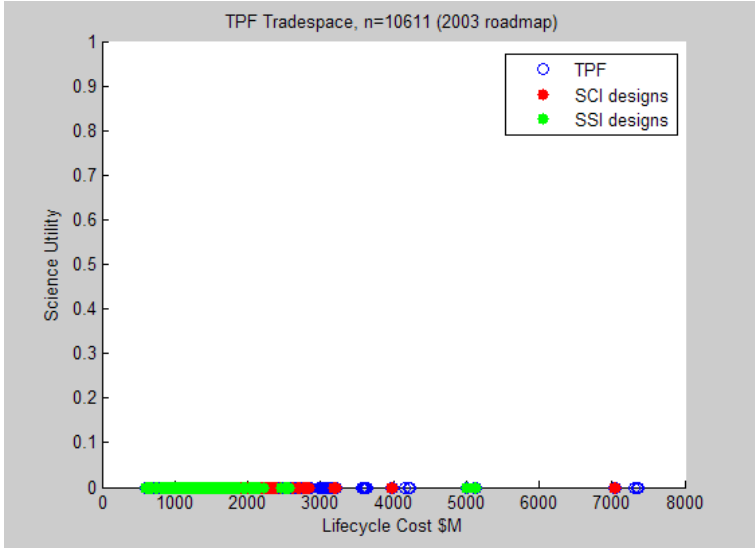
- Capability (kg), DeltaV (m/s), Fast (y/n)

Number of Designs Explored: 137

Terrestrial Planet Finder (TPF)

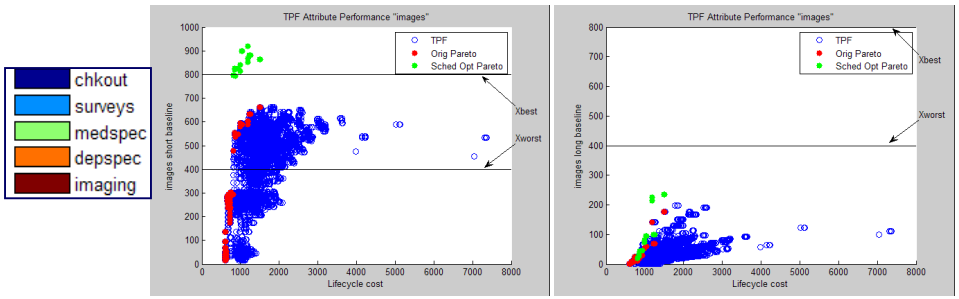
A “Big Science” Project





DESIGN VARIABLES (8+2)

- Orbit Type — {L2, LO, DA}
- Num Apertures — 4,6,8,10
- Wavelength — 7,10,20 microns
- Interferometer Type — {sci, ssi, tsi}
- Aperture type — {circular optics, strip optics}
- Aspect Ratio — {multi, const}
- Aperture Size — Variable
- Interferometer Baseline — Variable
- [Schedule] — [0-1 for each obs type]
- [Design Lifetime] — 5 or 10

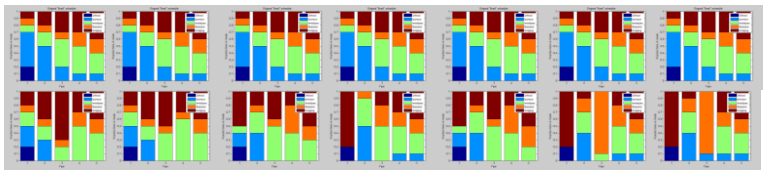


ATTRIBUTES (4+2, 2+1)

- Science
  - Num of Surveys (num), Num Medium Spectroscopies (num), Num Deep Spectroscopies (num), Number of Images (um) [Num Long Baseline Images (num), Num Short Baseline Images (num),
- Agency
  - Lifecycle Cost ($M), Operational Lifetime (years), [Annual Ops Cost $M)]

“Fixed” Schedule

“Optimal” Schedule

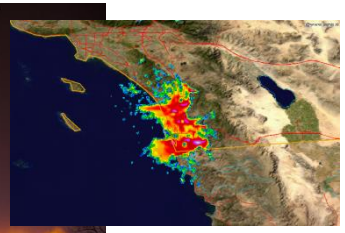


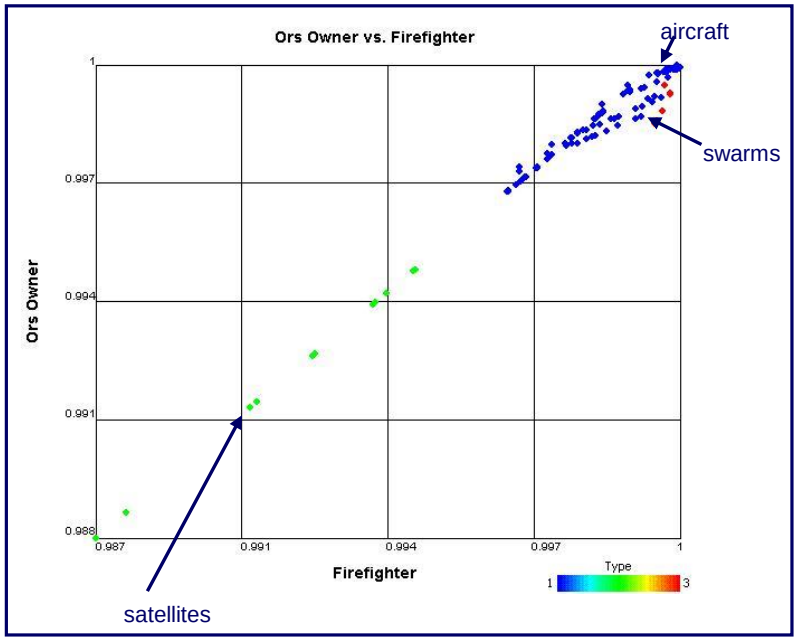
Number of Designs Explored: 10611

From Ross, 2006

Operationally Responsive Disaster Surveillance System

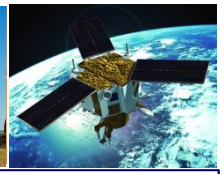
A Multi-Concept Responsive System

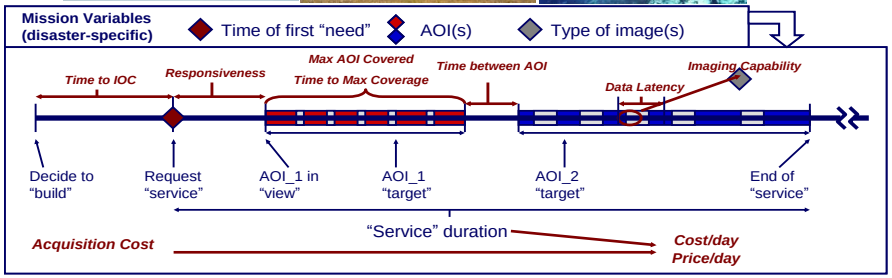




DESIGN VARIABLES (5+7)

- Aircraft DV
  - Configuration Flag — 1-13 (3x jet, 2x small prop, 2x med UAV, small UAV, existing Cessna, Orion, Predator, ScanEagle, Global Hawk)
  - Gross Weight Flag — low, medium, high
  - Number of Assets — 1-6
  - Payload Type — visible, infrared
  - Aperture Size — 0.01, 0.02, 0.04, 0.07, 0.08 m
- Spacecraft DV
  - Deployment Strategy — 1-4 (on-orbit, launch-ready, pre-fab parts, classic design)
  - Altitude — 120-1100 km
  - Inclination — 0,23,90,sun-synch
  - Number of assets — 1-5
  - Payload Type — visible, infrared
  - Excess Delta-V — 600-1200 m/s
  - Ops Lifetime — 5-10 yrs





ATTRIBUTES (10): Firefighter/Owner

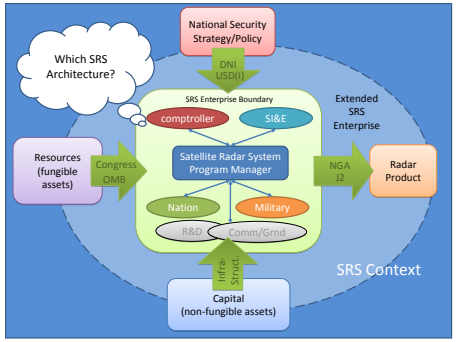
- Acquisition Cost ($M), Price/day ($K/day), Cost/day ($K/day), Responsiveness Time to IOC (days), Max % of AOI (%), Time to Max Coverage (min), Time between AOI (min), Imaging Capability (NIIRS level), Data Latency (min)

Number of Designs Explored: 2340+8640

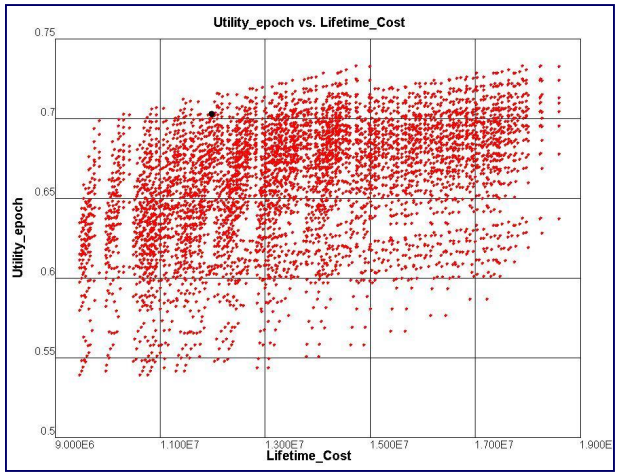
Image * from http://www.boeing.com/companyoffices/gallery/images/scaneagle/dvd-1390-1.html

Satellite Radar System

Satellite-based radar multi-mission system of system



			ATTRIBUTES															
			Mission										Programmatics					
			Tracking						Imaging					Cost		Schedule		
	Variable Name	Definition Range	Minimum Target RCS	Min. Discernable Velocity	Number of Target Boxes	Target ID Time	Target Track Life	Tracking Latency	Resolution (Proxy)	Targets per Pass	Field of Regard	Revisit Frequency	Imaging Latency	Baseline Cost	Actual Costs (Era)	Baseline Schedule	Actual Schedule (Era)	Total Impact
DESIGN VARIABLES	Peak Transmit Power	1.5 10 20 [KW]	9	9	9	3	1	1	9	9	9	0	1	9	9	9	9	96
	Radar Bandwidth	.5 1 2 [GHz]	9	9	3	3	1	1	9	9	9	0	1	3	3	3	3	66
	Physical Antenna Area	10 40 100 200 [m^2]	9	9	9	3	1	1	9	9	9	1	1	9	9	9	9	97
	Antenna Type	Mechanical vs. AESA	9	9	9	3	3	1	9	9	9	1	1	9	9	9	9	99
	Satellite Altitude	800 1200 1500 [km]	9	9	3	9	9	3	9	9	9	9	3	1	1	1	1	85
	Constellation Type	8 Walker IDs	0	0	1	9	9	3	0	0	3	9	3	9	9	9	9	73
	Comm. Downlink	Relay vs. Downlink	0	0	0	0	0	9	0	0	0	0	9	9	9	3	9	48
	Tactical Downlink	Yes vs. No	0	0	0	0	3	9	0	0	0	0	9	9	9	3	9	51
	Maneuver Package	1x, 2x, 4x	1	1	1	1	1	0	1	1	1	1	0	9	3	3	3	27
	Constellation Option	none, long-lead, spare	0	0	0	0	0	0	0	0	0	0	0	9	9	9	9	36



DESIGN VARIABLES (10)

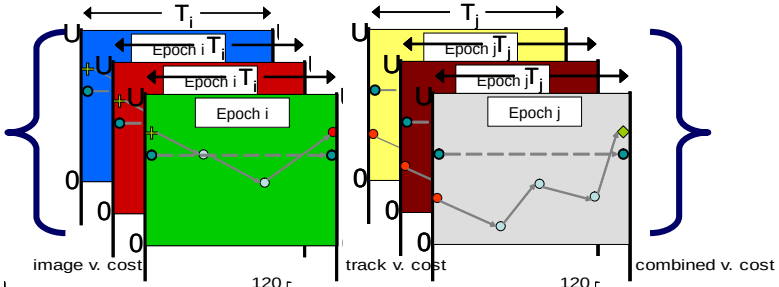
- Orbit DV
  - Orbit Altitude — 800, 1200, 1500 km
  - Constellation design — 8 Walker IDs
- Spacecraft DV
  - Antenna Size — 40, 80, 100 m^2
  - Peak power — 1.5, 10, 20 kW
  - Radar bandwidth — 0.5, 1, 2 GHz
  - Comm Arch — relay, downlink
  - Tactical Downlink — yes/no
  - Path enablers — (Extra sats, fuel)

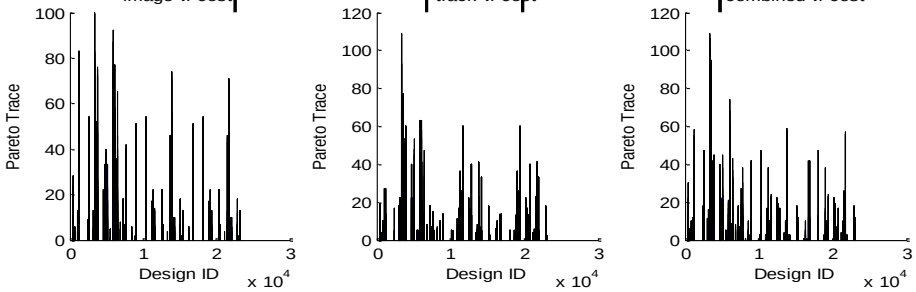
EPOCH VARIABLES (6)

- Technology avail, Comm infrastructure, Target list, AISR avail, Environment, Mission priorities

ATTRIBUTES (3 “missions”, 15 total)

- Tracking, Imaging, Programmatic





Number of Designs Explored: 23328; Number of Epochs Explored: 245