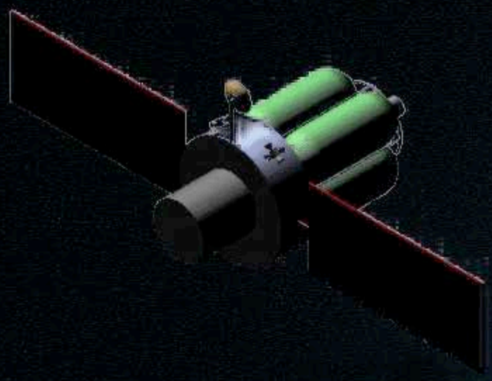


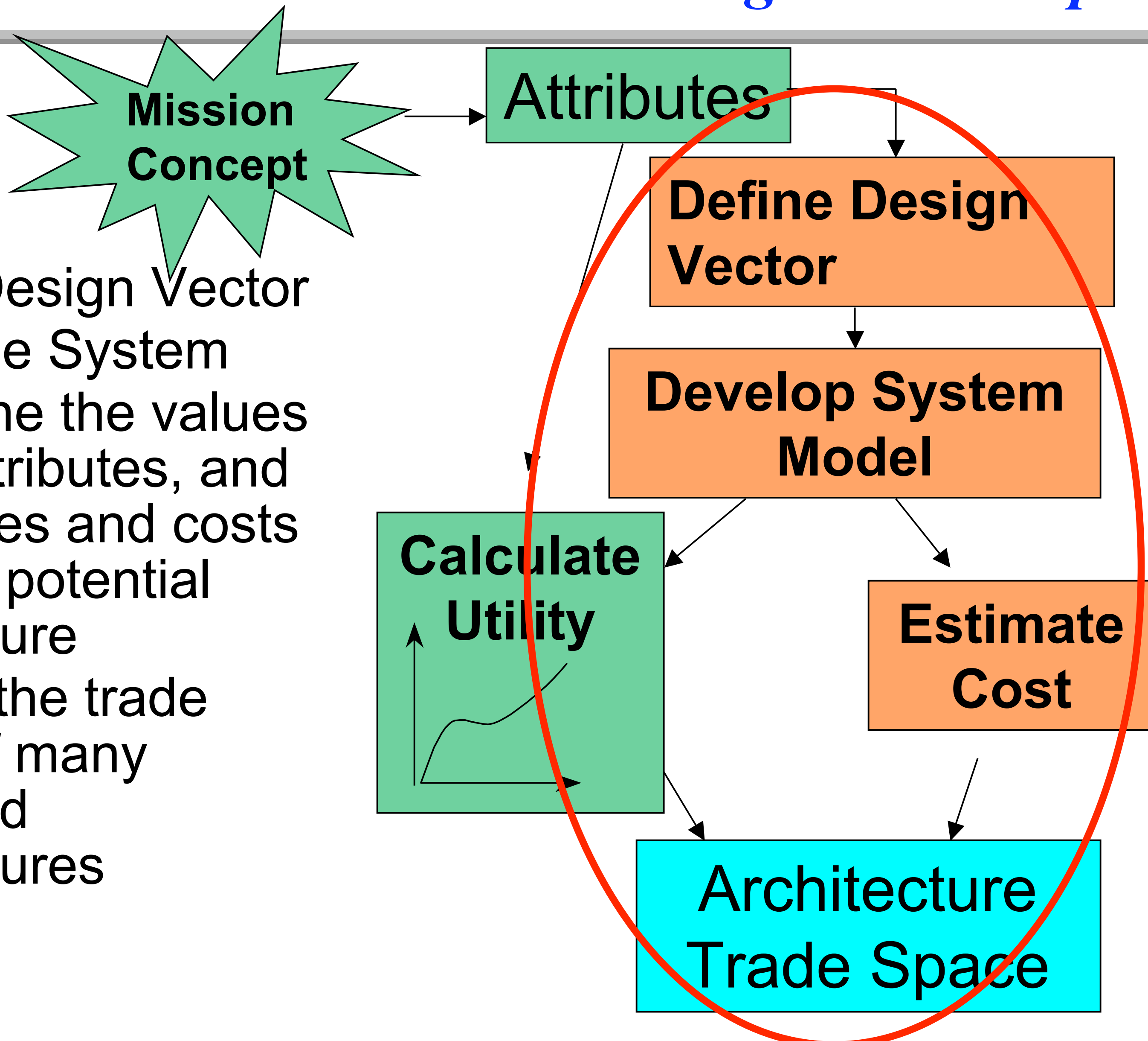
Space Systems Architecture

Prof. Daniel Hastings
Dr. Hugh McManus

Lecture 5: Modeling and Exploring the Tradespace

Simulating the Tradespace

- Define Design Vector
- Model the System
- Determine the values of the attributes, and the utilities and costs for each potential architecture
- Explore the trade space of many evaluated architectures



Design Vector

- Set of physical characteristics of the proposed architectures
- Enumerated - values to be evaluated are selected
- Strongly effect attributes
  - Typical elements include orbit parameters, characteristics of spacecraft, mission profiles
- Other "design" variables may go in the *constants vector*
  - During study, may elevate "constants" to design vector, or demote non-discriminating design variables to constants

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Design Vectors

- X-TOS
  - Altitude of Apogee (km)
  - Altitude of Perigee (km)
  - Inclination (deg)
  - Total Delta-V (m/s)
  - Comm. Sys Type
  - Antenna Gain
  - Propulsion Type
  - Power Sys Type
  - Mission Scenario
- Space Tug
  - Mass of on-board equipment (grapplers, observation equipment, etc)
  - Propulsion system
  - Fuel load
- Space Based Radar
  - Scan Angle
  - Technology Level
  - Aperture Area
  - Orbit Altitude
  - Constellation type
- B-TOS
  - Circular orbit altitude (km)
  - Number of Planes
  - Number of Swarms/Plane
  - Number of Satellites/Swarm
  - Radius of Swarm (km)
  - 5 Configuration Studies

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Enumeration of X-TOS Design Vector

Design Variable	Levels	Justification
Altitude of Apogee (km)	200:50:350; 650:300:2000*	Emphasis on low altitude in utility function, therefore sample at a higher rate at low altitudes
Altitude of Perigee (km)	150:50:350*	Utility curve declines quite steeply between 150 and 350 km; will take a significant utility hit if spacecraft never flies below 350
Inclination (deg)	0; 30; 70; 90	Covers the possible range of inclinations
Total Delta-V (m/s)	200:100:1000*	The low end of the range is a high average value for low earth orbit satellites. The high end is an estimate of the optimistic (on the large side) estimate delta V allowed before the spacecraft mass will no longer accommodate small and medium sized US launch vehicles.
Comm. Sys Type	AFSCN; TDRSS	Discrete choice of systems available
Antenna Gain	High; Low	Discrete choice of systems available
Propulsion Type	Chemical; Hall	high-thrust at low efficiency vs. low-thrust at high efficiency
Power Sys Type	Solar; Fuel cells	Only body mounted solar considered due to prohibitive drag penalty of wings
Mission Scenario	Single; 2 Series; 2 Parallel	More than two satellites is computationally prohibitive since the number of possible multi-spacecraft mission grows as N^k where *k* is number of spacecraft in the mission scenario and N is number of combinations of the other (spacecraft and orbit related) design variables.

*The notation *low* : *inc* : *high* means from *low* to *high* in steps of *inc*.

QFD mapping of Design Vector to Attributes

Attributes \ Design Vars	Perigee	Apogee	Delta-V	Propulsion	Inclination	Comm System	Ant. Gain	Power system	Mission Scenario	Total Impact
Data Lifespan	9	9	9	6	0	0	0	6	9	48
Sample Altitude	9	9	0	0	0	0	0	0	9	27
Diversity of Latitudes	0	0	0	0	9	0	0	0	9	18
Time at Equator	0	6	0	0	9	0	0	0	9	24
Latency	3	3	0	0	3	9	9	6	3	36
Total	21	27	9	6	21	9	9	12	39	
Cost	9	9	3	6	6	3	6	6	9	
Total w/Cost	30	36	12	12	27	12	15	18	48	

- *Assess* (by quick calcs, experience, etc.) effects
- Rate on 9-6-3 or 9-3-1 scale
- Check impacts (low impact attributes or variables should be rethought) and areas to model

Modeling

Attributes	Perigee	Apogee	Delta-V	Propulsion	Inclination	Comm System	Ant. Gain	Power system	Mission Scenario	Total Impact
Data Lifespan	9	9	9	6	0	0	0	6	9	48
Sample Altitude	9	9	0	0	0	0	0	0	9	27
Diversity of Latitudes	0	0	0	0	9	0	0	0	9	18
Time at Equator	0	6	0	0	9	0	0	0	9	24
Latency	3	3	0	0	3	9	9	6	3	36
Total	21	27	9	6	21	9	9	12	39	
Cost	9	9	3	6	6	3	6	6	9	
Total w/Cost	30	36	12	12	27	12	15	18	48	

Number of Sats, etc.

Easy orbital mechanics

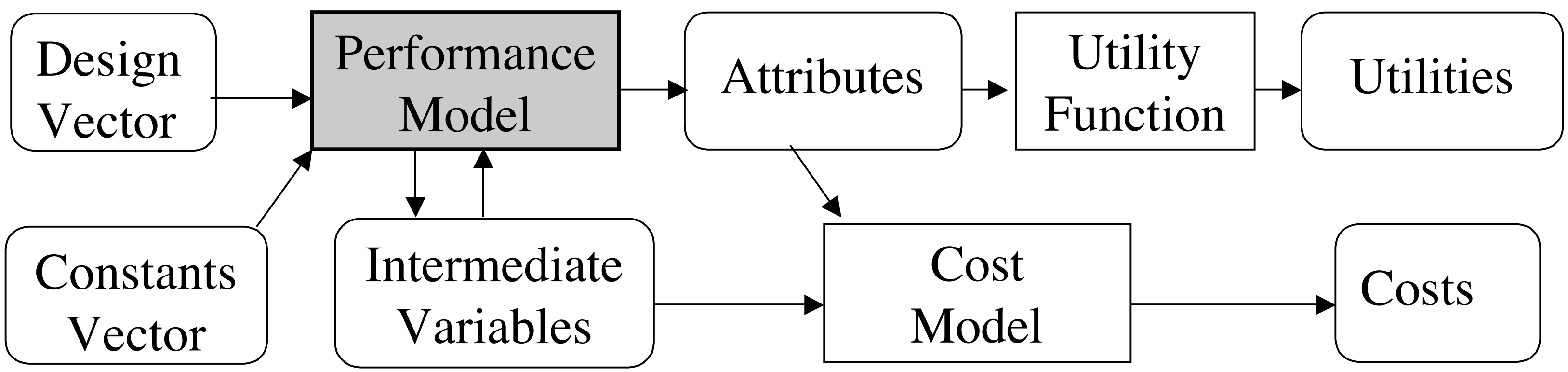
Hard orbital mechanics (drag)

Comm Sys Design

- Start with QFD

Modeling principles

- Right level of detail
- Modular, well organized code
- Identify key *intermediate variables*
- Simulate rather than optimize (most of the time)



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DSM principles

- Mapping model modules against each other to clarify interactions
- If all the interactions are one way (below the diagonal) iterations can be eliminated (or at least kept within the modules)

	Orbit	Spacecraft	Launch	Cost (TFU)	*SATDB*	Mission Scenarios	Cost (Lifecycle)	Calc Attributes	Utility
Orbit									
Spacecraft	X								
Launch	X	X							
Cost (TFU)		X	X						
Satellite Database	X	X	X	X					
Mission Scenarios	X	X		X	X				
Cost (Lifecycle)		X	X	X	X	X			
Calc Attributes	X	X			X	X			

DSM principles

- Mapping model modules against each other to clarify interactions
- If all the interactions are one way (below the diagonal) iterations can be eliminated (or at least kept within the modules)

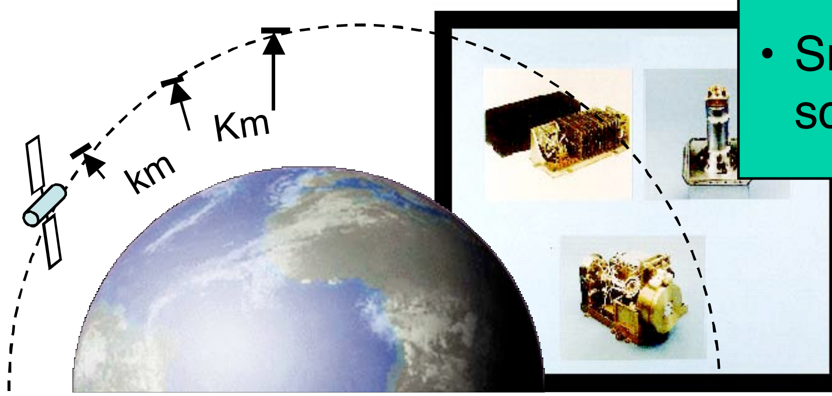
	Orbit	Spacecraft	Launch	Cost (TFU)	*SATDB*	Mission Scenarios	Cost (Lifecycle)	Calc Attributes	Utility
Orbit									
Spacecraft	X					x			
Launch	X	X							
Cost (TFU)		X	X						
Satellite Database	X	X	X	X					
Mission Scenarios	X	X		X	X				
Cost (Lifecycle)		X	X	X	X	X			
Calc Attributes	X	X			X	X			

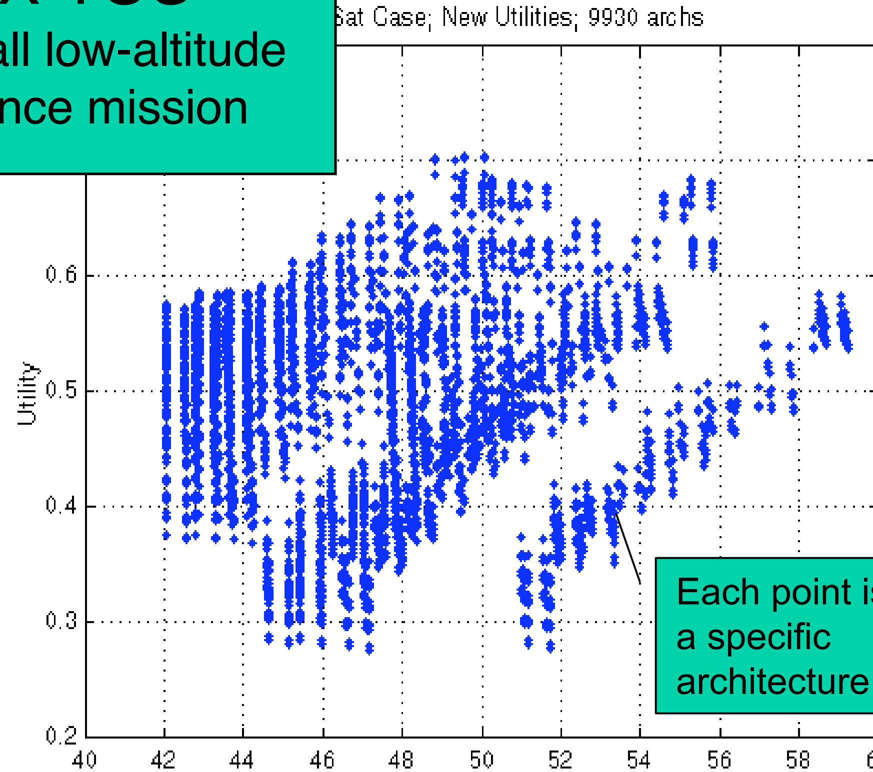
"above diagonal" interactions would require iteration of entire model (not good)

Exploring the Tradespace

X-TOS

- Small low-altitude science mission





DESIGN VARIABLES: The architectural trade parameters

- Orbital Parameters
  - Apogee altitude (km) 150-1100
  - Perigee altitude (km) 150-1100
  - Orbit inclination 0, 30, 60, 90
- Physical Spacecraft Parameters
  - Antenna gain
  - communication architecture
  - propulsion type
  - power type
  - delta_v

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

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Tradespace Exploration

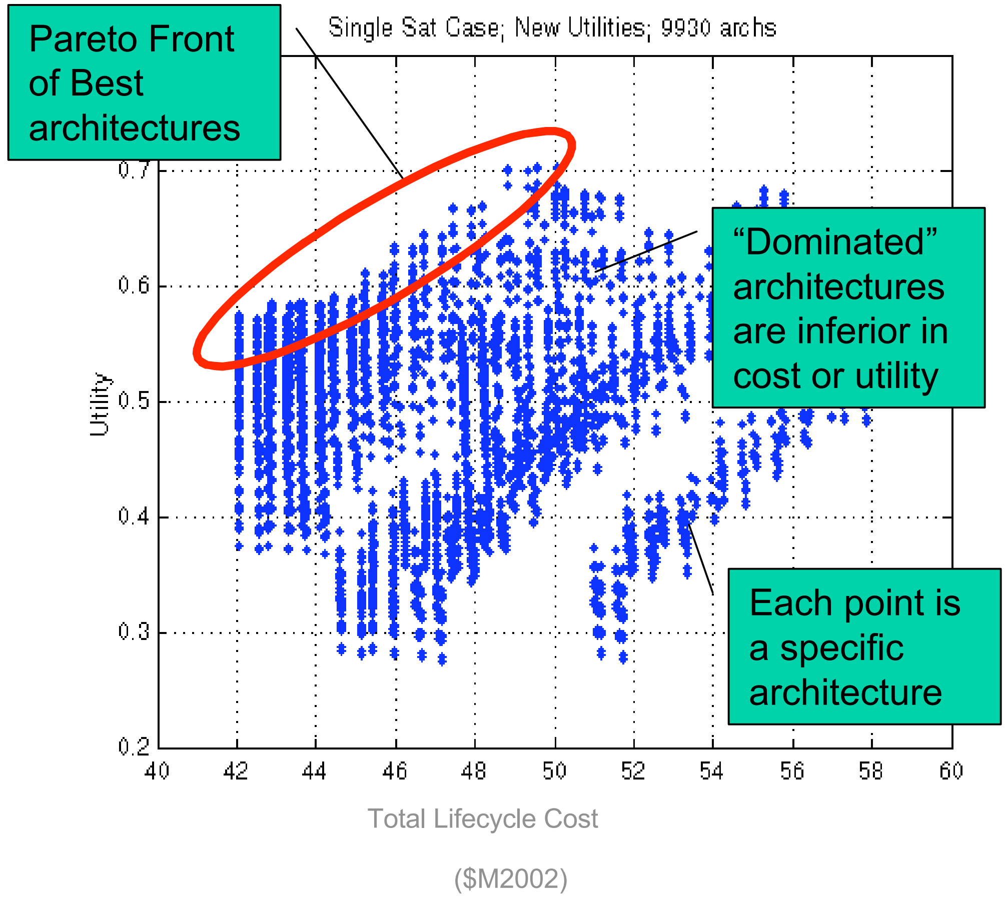
Point - turn data generated by model into knowledge

Techniques:

- Plot utility vs cost and determine Pareto Front
- Examine effects of design variables and attributes
- Parametrical (what if) explorations of uncertain elements
- Dive a little deeper into some designs
- Advanced explorations (to be revisited in coming weeks)

Pareto Front

- If an architecture is the best performance for a given cost, or the lowest cost for a given perfomance, it is on the *Pareto front*
- Other architectures are said to be *dominated*
- Moving along the Pareto front = making real trades (e.g. cost for utility)
- Focus (but not exclusive focus!) of exploration



Warning - Pareto front is not always in the upper left (read the axes!)

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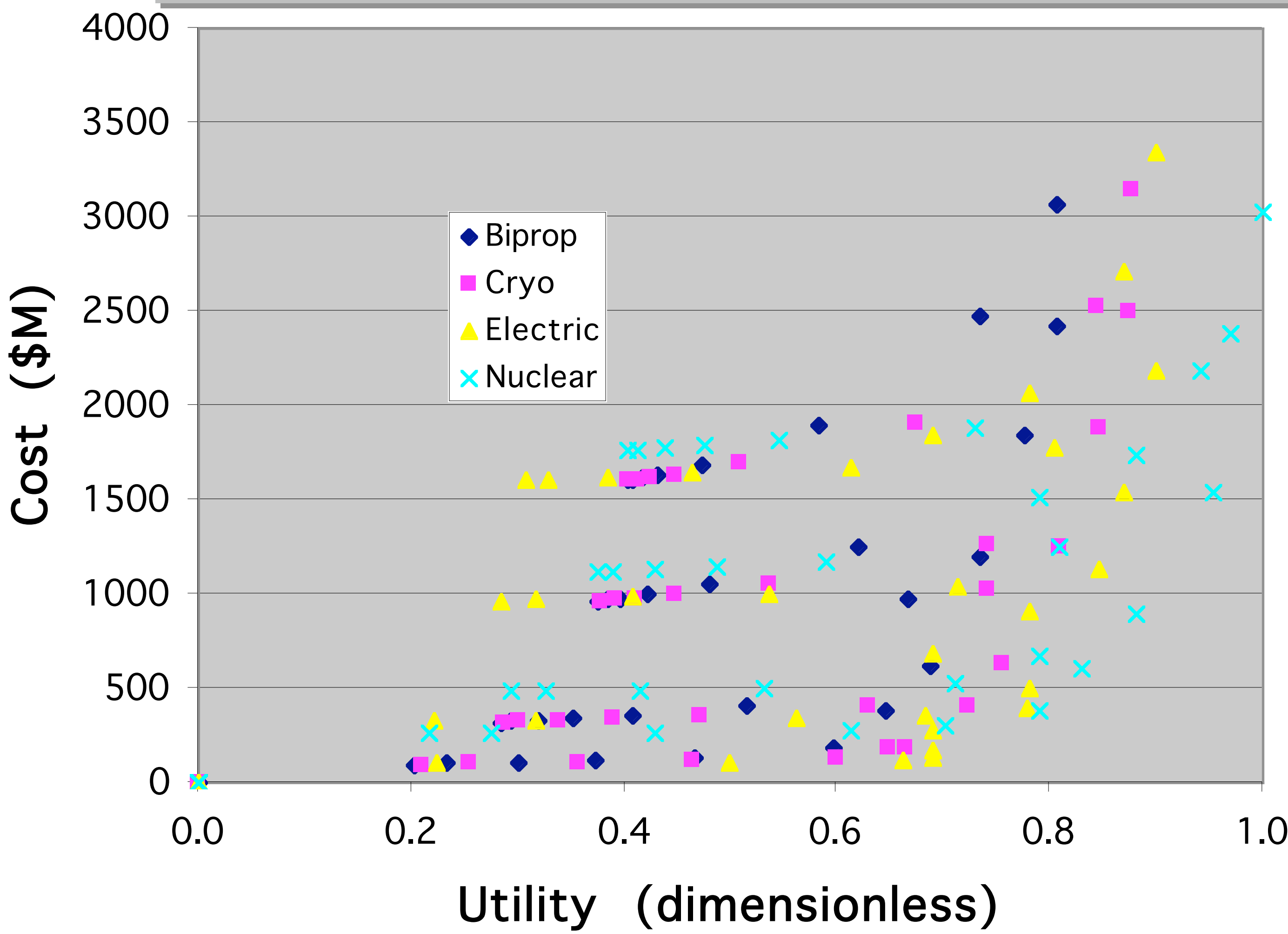
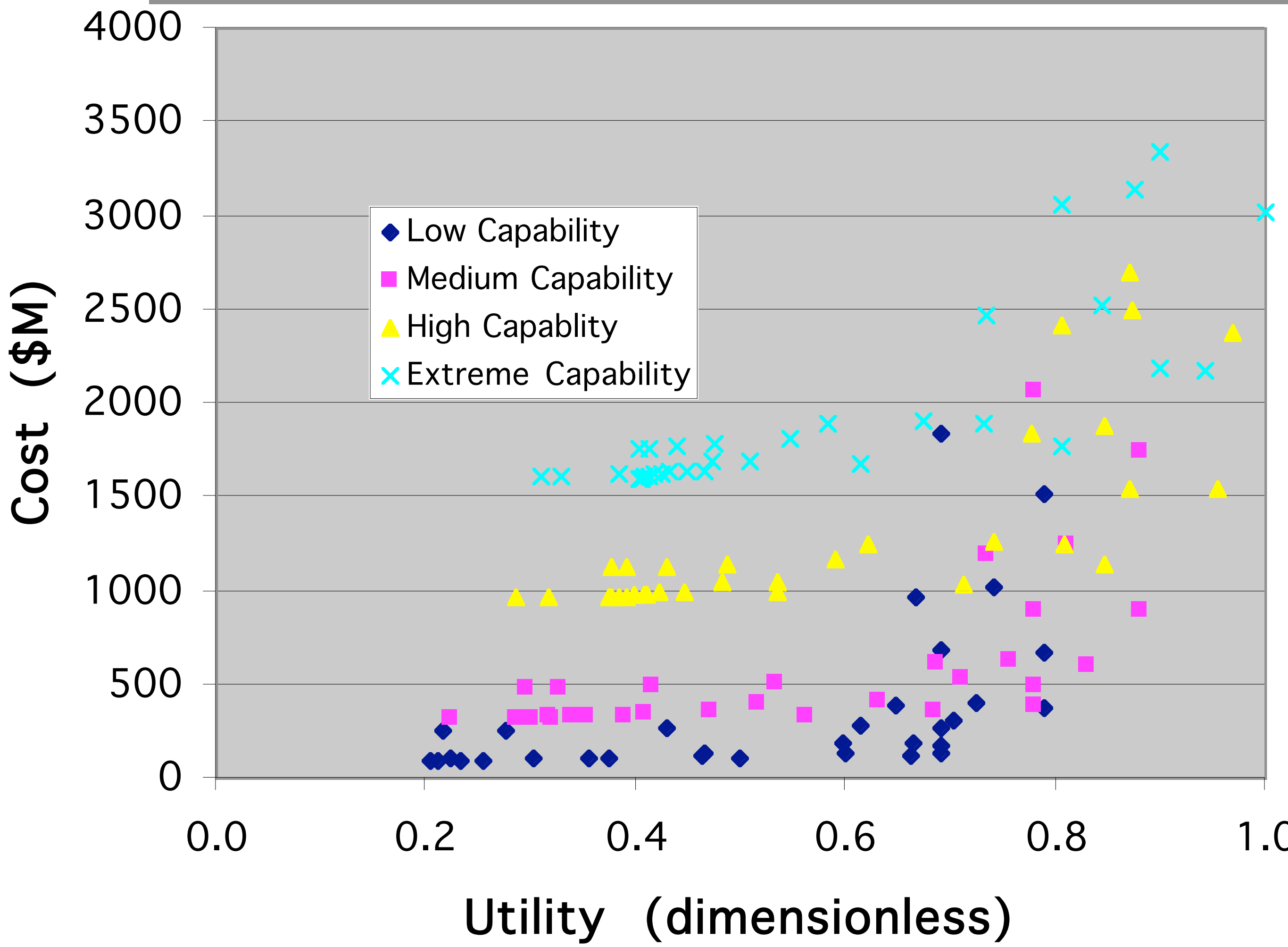
Spacetug Tradespace
Propulsion System as a Discriminator



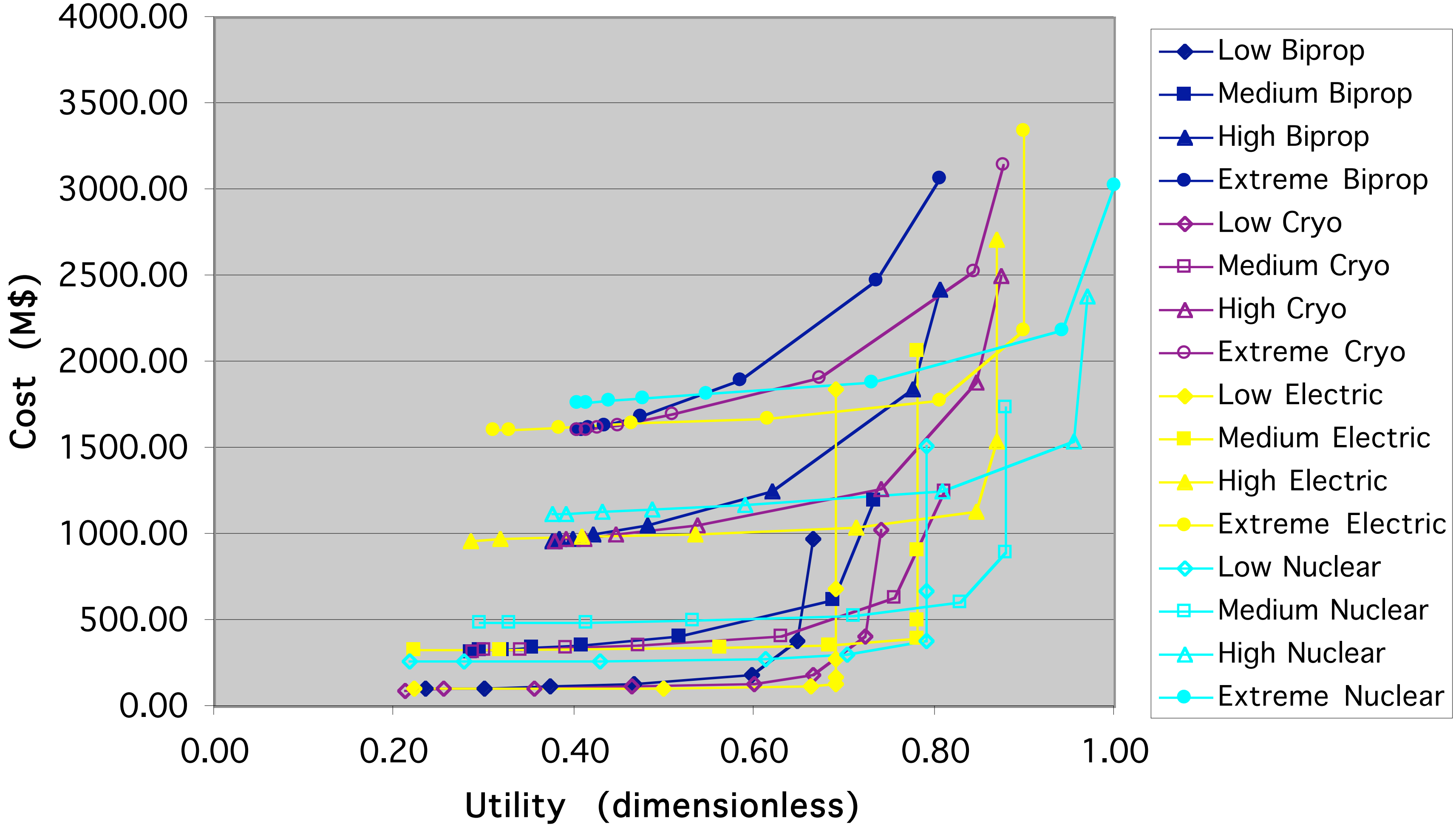
Highest performance systems require high ISP propulsion

Capability (mass of observation and grappler equipment) as Discriminator



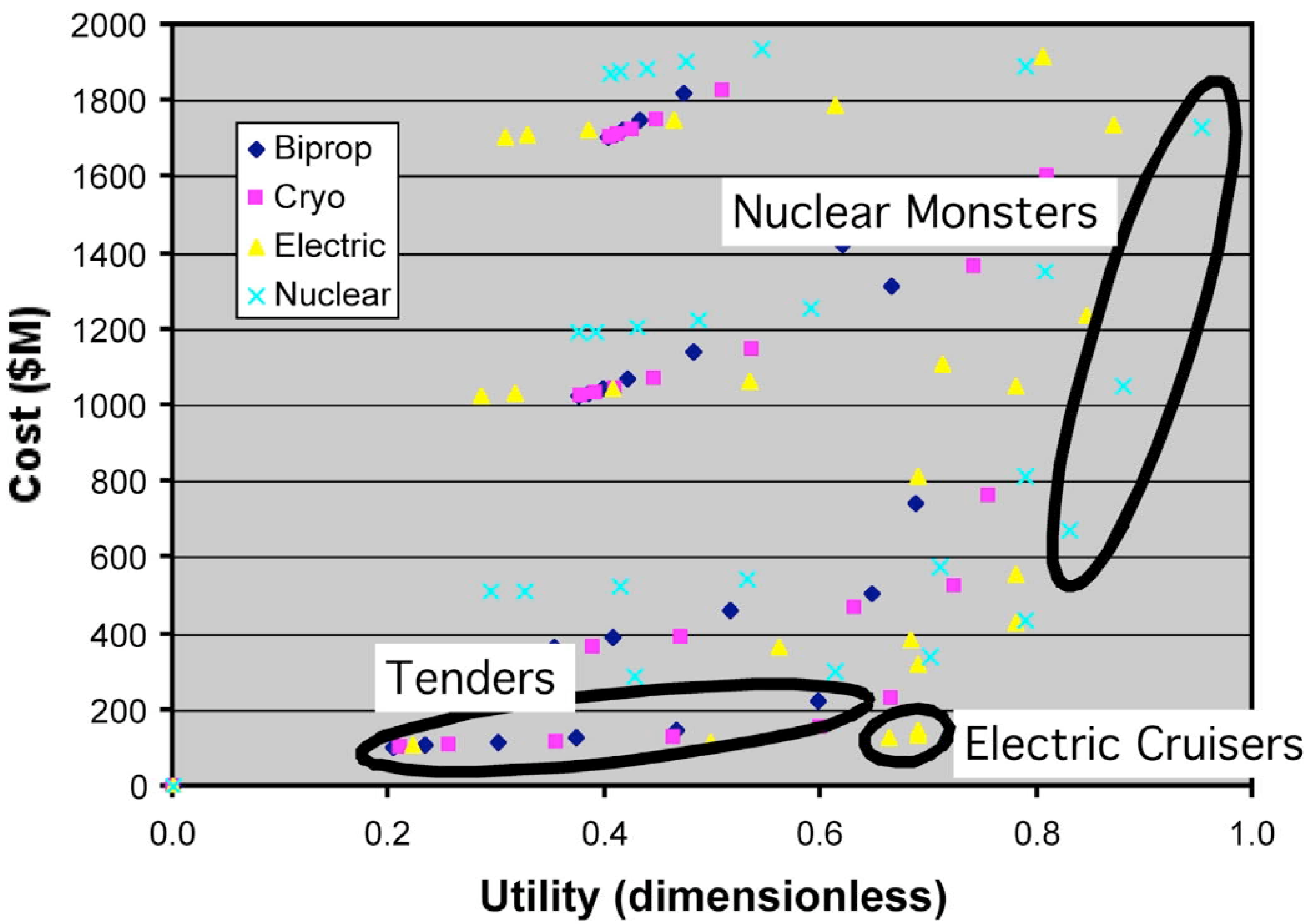
Low capability systems dominate lower cost systems

Key Physical Limits and Dangers



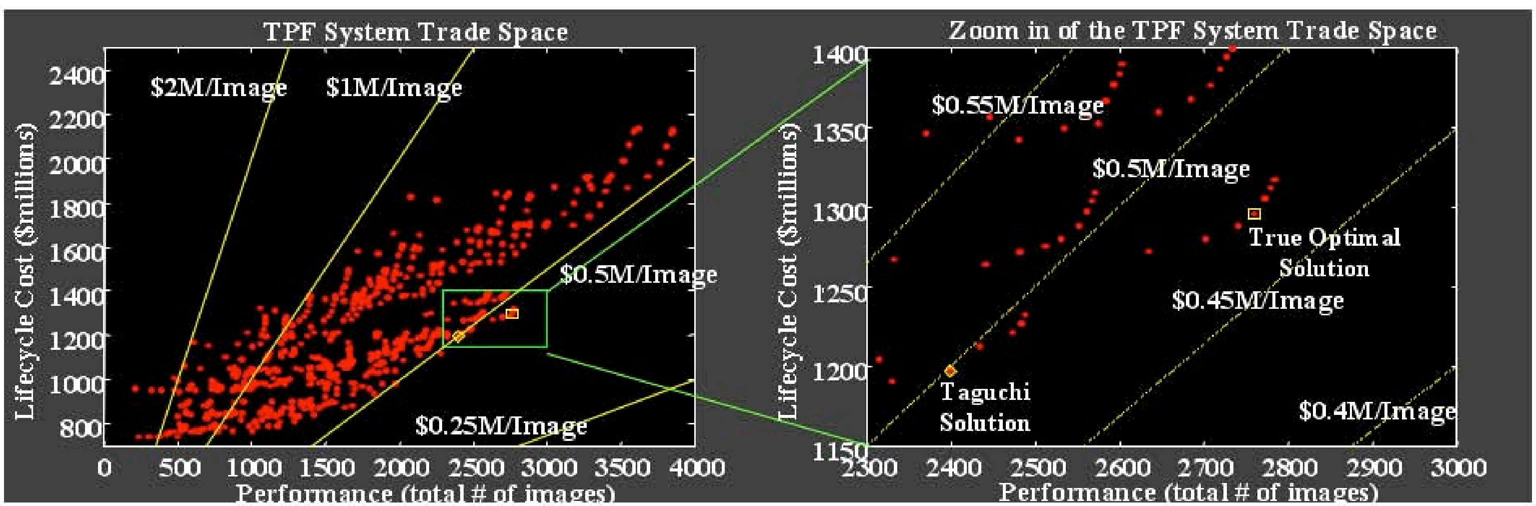
Hits a "wall" of either physics (can't change!) or utility (can)

Tradespace Reveals Promising Designs



Focus on Specific Designs

- TPF Pareto front looks good - many choices of cost/utility
- On the front, lots of little archs with local minima
- Individual (local optimal) designs are in differing architectural families - so once a choice is made, very difficult to change!



TPF Architectures on the Pareto Front

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Mission Cost & Performance: Low → Medium → High

# "Images"	LCC ($B)	Orbit (AU)	# Apert.'s	Architecture	Apert. Diam. (m)
502	0.743	1.5	4	SCI-1D	1
577	0.762	2.0	4	SCI-1D	1
651	0.767	2.5	4	SCI-1D	1
1005	0.768	1.5	4	SCI-1D	2
1114	0.788	2.0	4	SCI-1D	2
1171	0.790	2.5	4	SCI-1D	2
1195	0.807	1.5	6	SCI-1D	2
1292	0.811	1.5	6	SCI-2D	2
1317	0.830	1.5	8	SCI-1D	2
1424	0.836	2.0	4	SCI-1D	3
1426	0.838	1.5	8	SCI-2D	2
1464	0.867	2.5	6	SCI-2D	2
1631	0.877	1.5	6	SCI-1D	3
1684	0.881	1.5	6	SCI-2D	3
1687	0.932	2.0	6	SCI-1D	3
1828	0.936	2.0	6	SCI-2D	3
1881	0.980	1.5	8	SCI-2D	3
1978	0.982	1.5	6	SCI-1D	4
2035	1.086	2.0	8	SCI-2D	3
2132	1.112	1.5	8	SCI-1D	4
2285	1.120	1.5	8	SCI-2D	4
2328	1.190	2.5	6	SCI-2D	4
2398	1197	3.0	6	SCI-2D	4
2433	1.212	4.0	6	SCI-2D	4
2472	1.221	4.5	6	SCI-2D	4
2482	1.227	5.0	6	SCI-2D	4
2487	1.232	5.5	6	SCI-2D	4
2634	1.273	2.5	8	SCI-2D	4
2700	1.280	3.0	8	SCI-2D	4
2739	1.288	3.5	8	SCI-2D	4
2759	1.296	4.0	8	SCI-2D	4
2772	1.305	4.5	8	SCI-2D	4
2779	1.312	5.0	8	SCI-2D	4
2783	1.317	5.5	8	SCI-2D	4
2788	1.569	3.0	6	SSI-2D	4
2844	1.609	3.5	6	SSI-2D	4
2872	1.655	4.0	6	SSI-2D	4
2988	1.691	2.0	8	SSI-1D	4
3177	1.698	2.5	8	SSI-1D	4
3289	1.739	3.0	8	SSI-1D	4
3360	1790	3.5	8	SSI-1D	4
3395	1.850	4.0	8	SSI-1D	4
3551	1.868	2.5	10	SSI-1D	4
3690	1.919	3.0	10	SSI-1D	4

Family 4 ap. SCI-1D 2 m Diam.

Family 6 ap. SCI-2D 4 m Diam.

Family 6 ap. SSI-2D 4 m Diam.

Family 10 ap. SSI-1D 4 m Diam.

Family 4 ap. SCI-1D 1 m Diam.

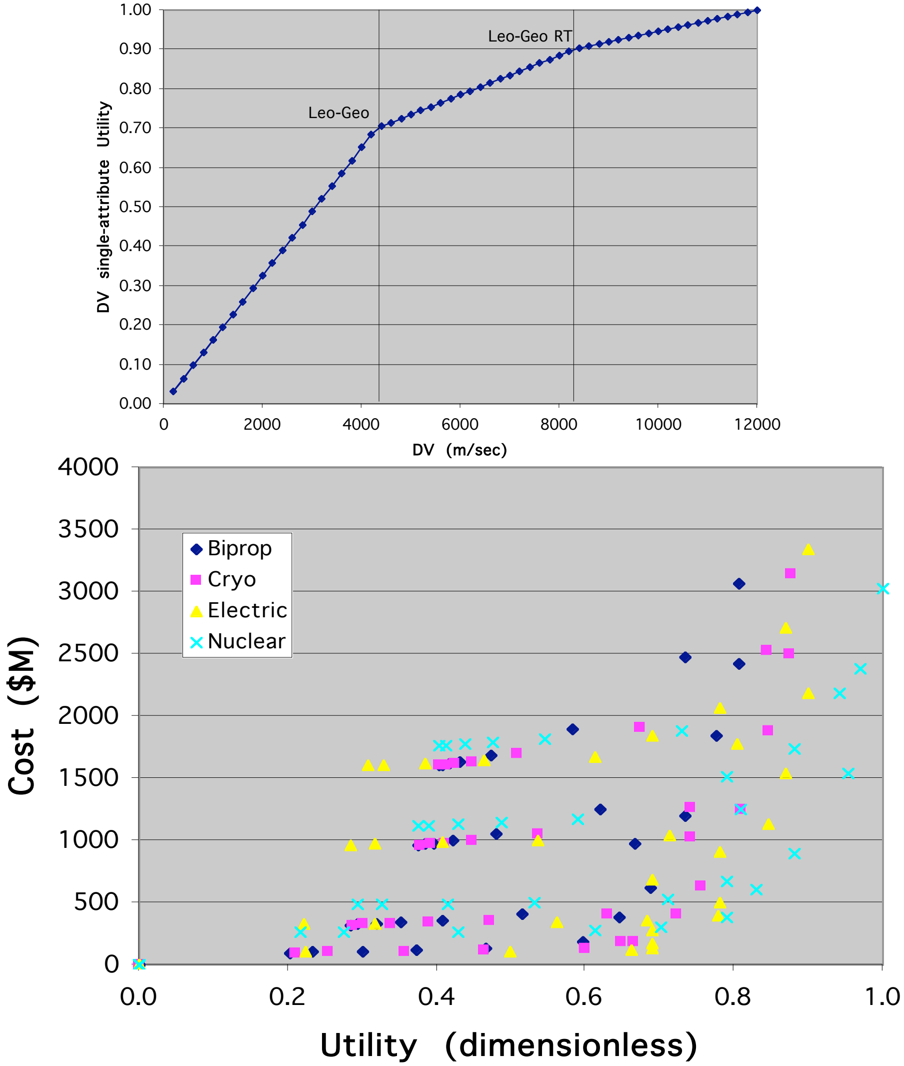
Intersection of Multiple Families

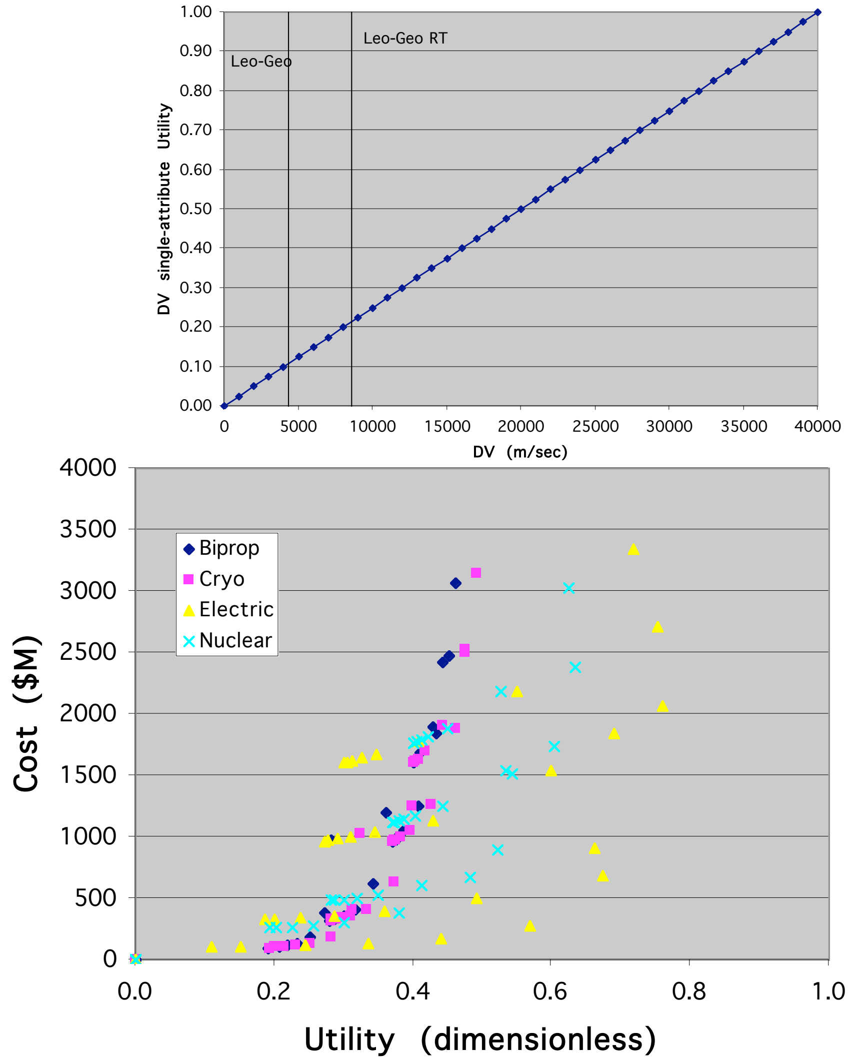
Family 8 ap. SCI-2D 4 m Diam.

Transition from SCI to SSI Designs

Family 8 ap. SSI-1D 4 m Diam.

Parametric Study: Sensitivities to shifts in user needs





Unlimited DV demand favors high ISP propulsion

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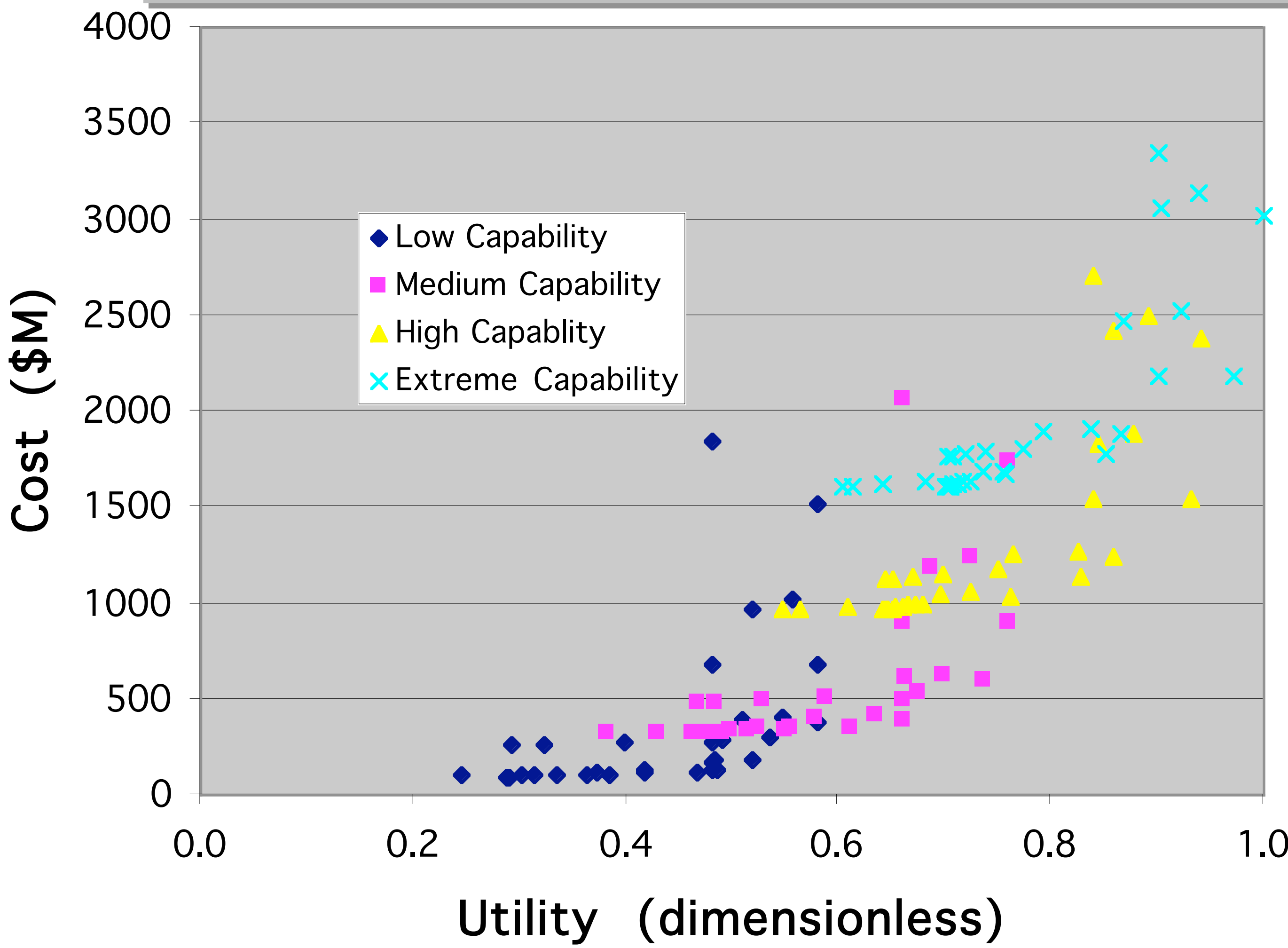
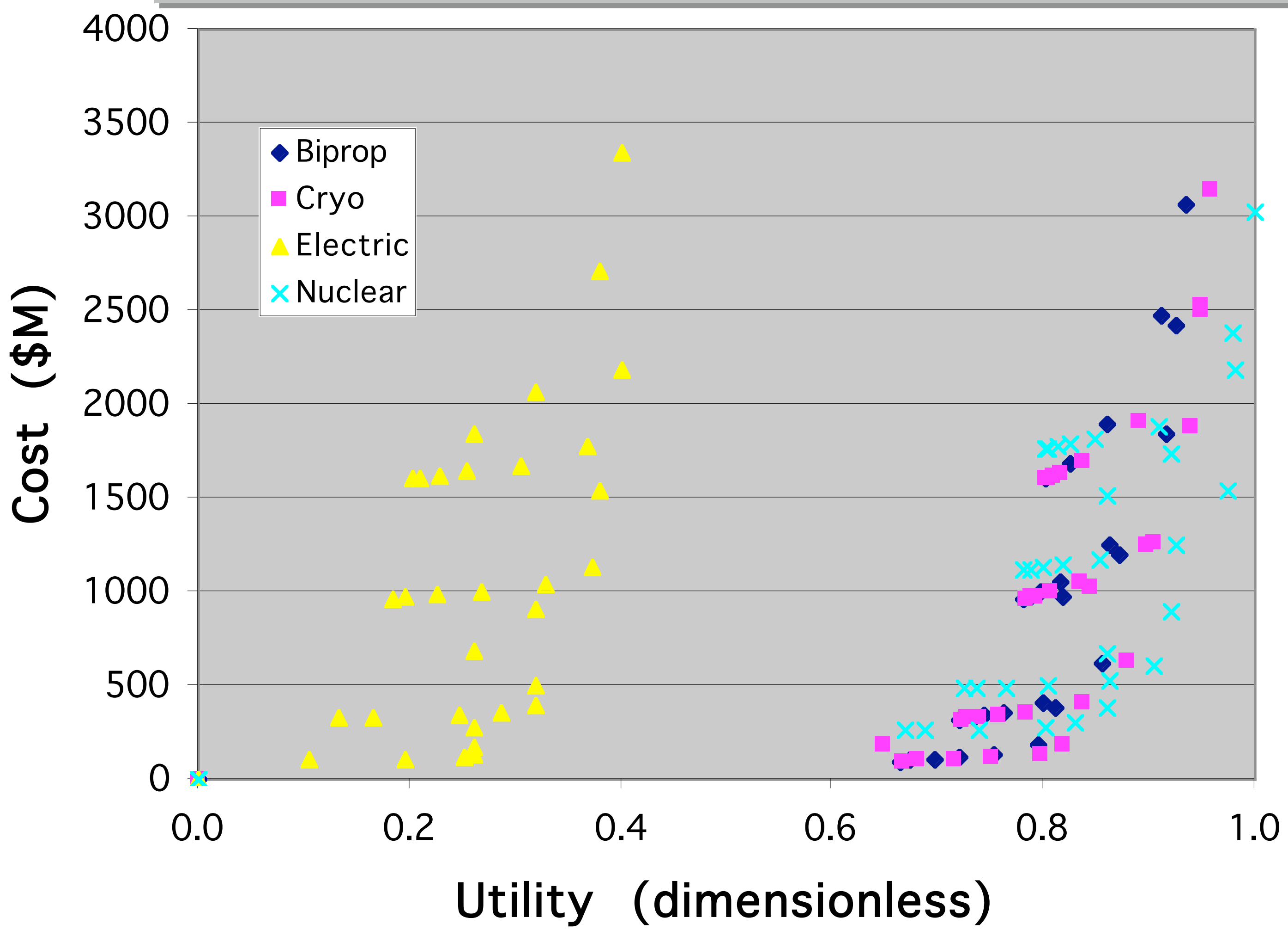
Changing Weightings - Capability stressed



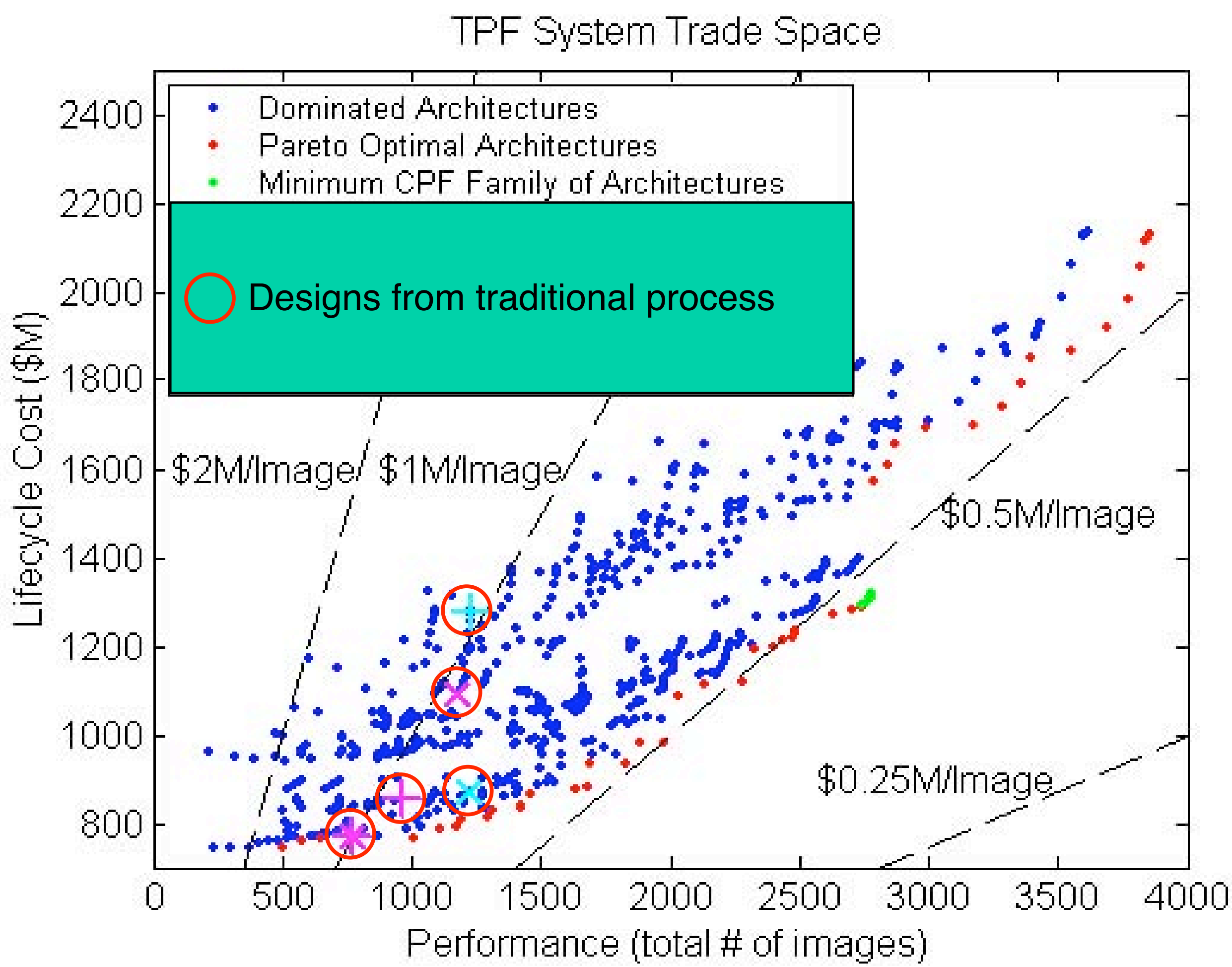
Spreads front at high-performance end

Changing Weightings - Response Time Stressed



Eliminates electric propulsion

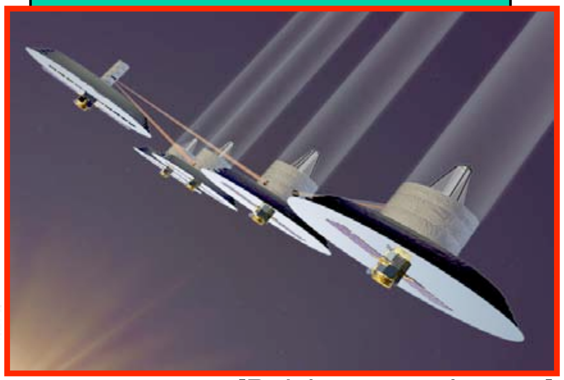
Using the Trade Space to Evaluate Point Designs



From Jilla, 2002

TPF

- Terrestrial Planet Finder - a large astronomy system
- Design space: Apertures separated or connected, 2-D/3-D, sizes, orbits
- Images vs. cost



[Beichman et al, 1999]

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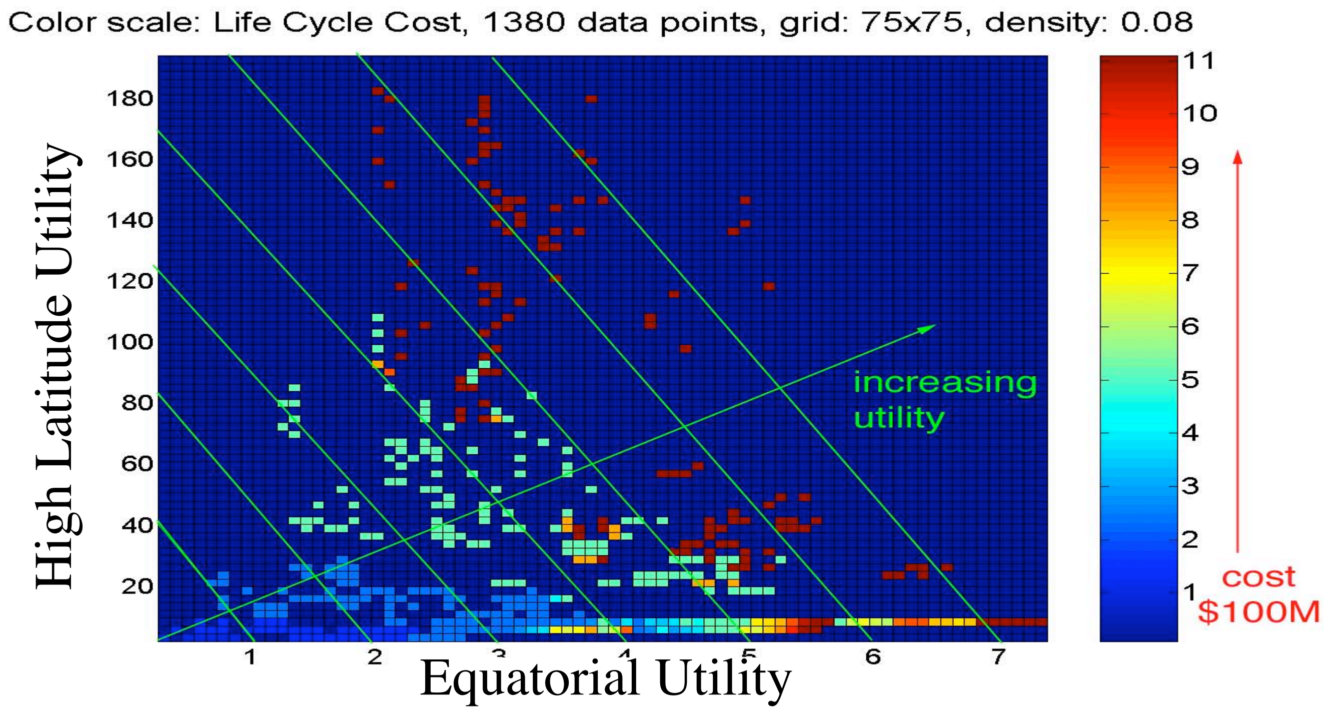
Questioning User Desires

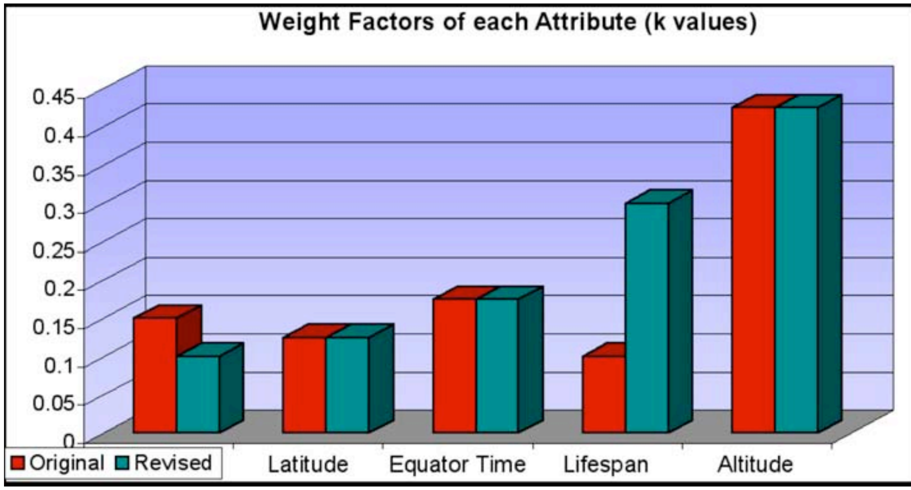
- Best low-cost mission do only one job well
- More expensive, higher performance missions require more vehicles
- Higher-cost systems can do multiple missions
- Is the multiple mission idea a good one?

A-TOS

- Swarm of very simple satellites taking ionospheric measurements
- Several different missions



Changes in User Preferences Can be Quickly Understood

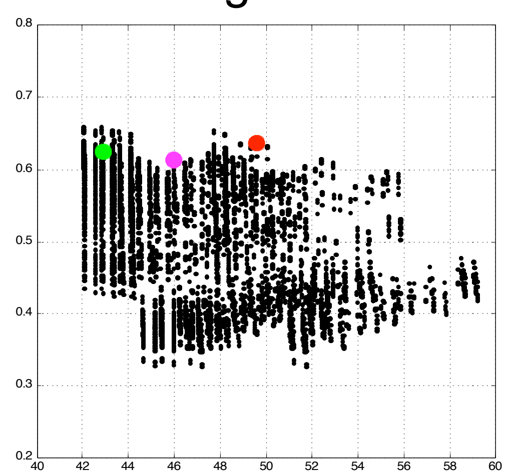


Architecture trade space reevaluated in less than one hour

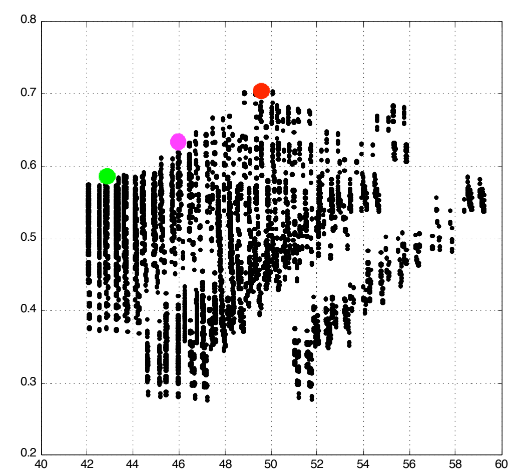
User changed preference weighting for lifespan

X-TOS

Original



Revised



Using Architecture Models to Consider Technical Uncertainty

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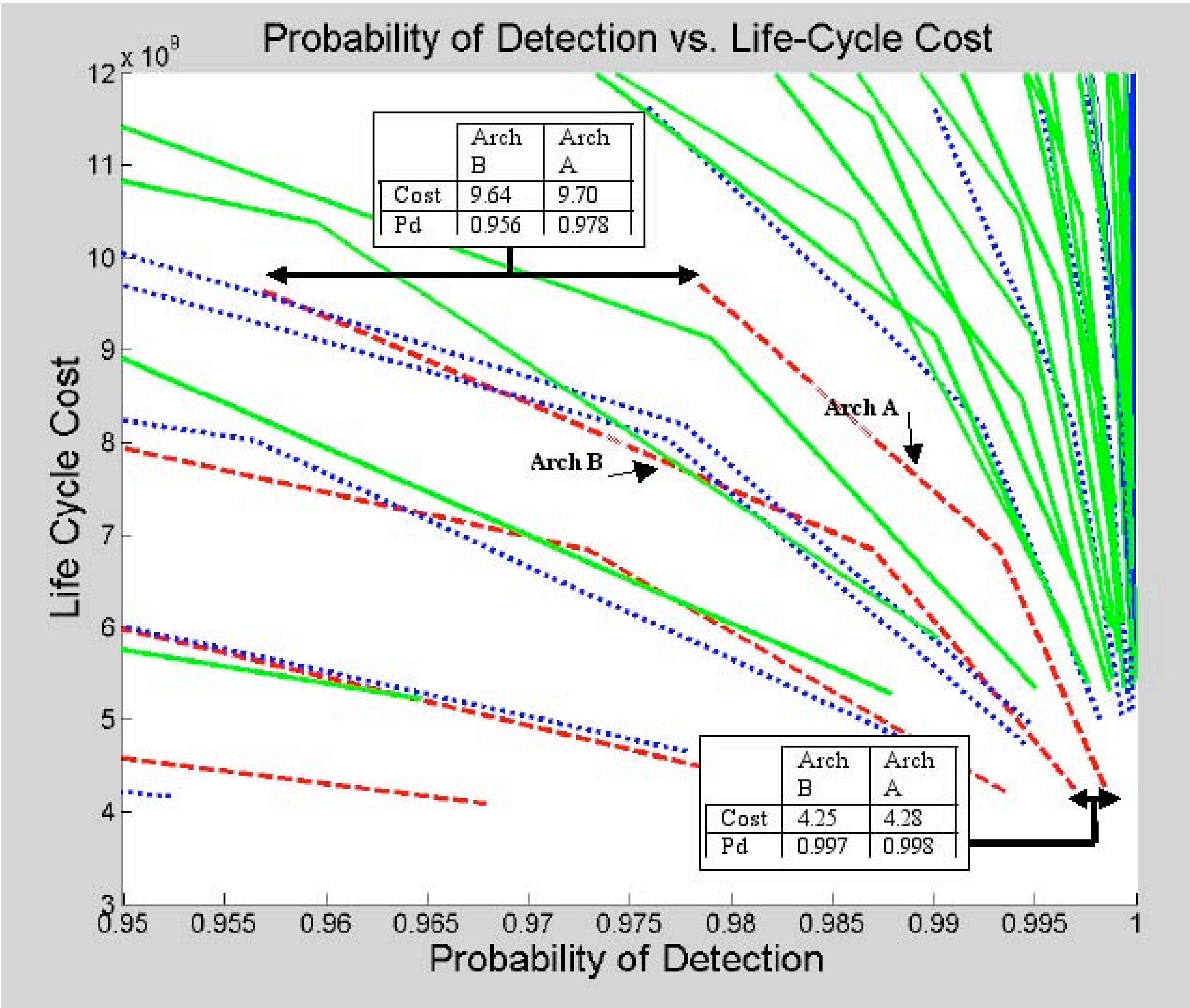


	Arch B	Arch A
Cost	9.64	9.70
Pd	0.956	0.978

	Arch B	Arch A
Cost	4.25	4.28
Pd	0.997	0.998

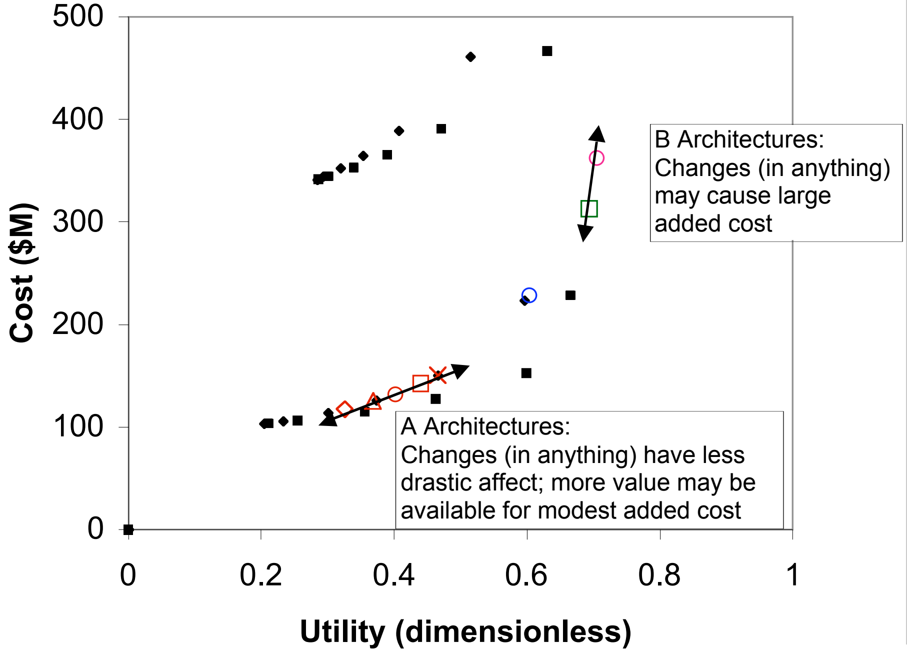
TechSat

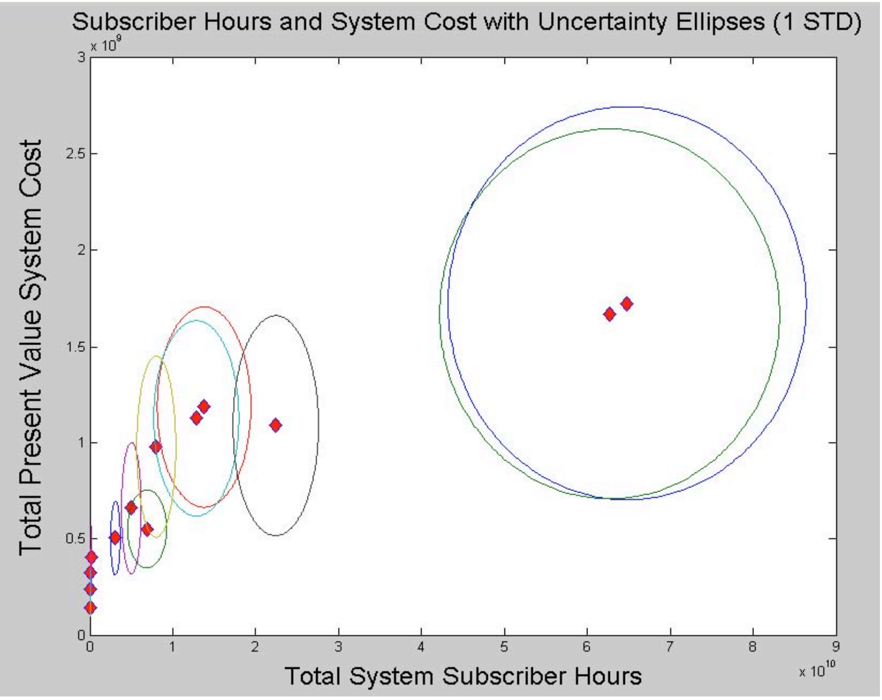
- Constellation of satellites doing observation of moving objects on the ground
- Uncertainties driven by instrument performance/cost

[Martin, 2000]

From Walton, 2002

Tradespace Exploration with Uncertainties

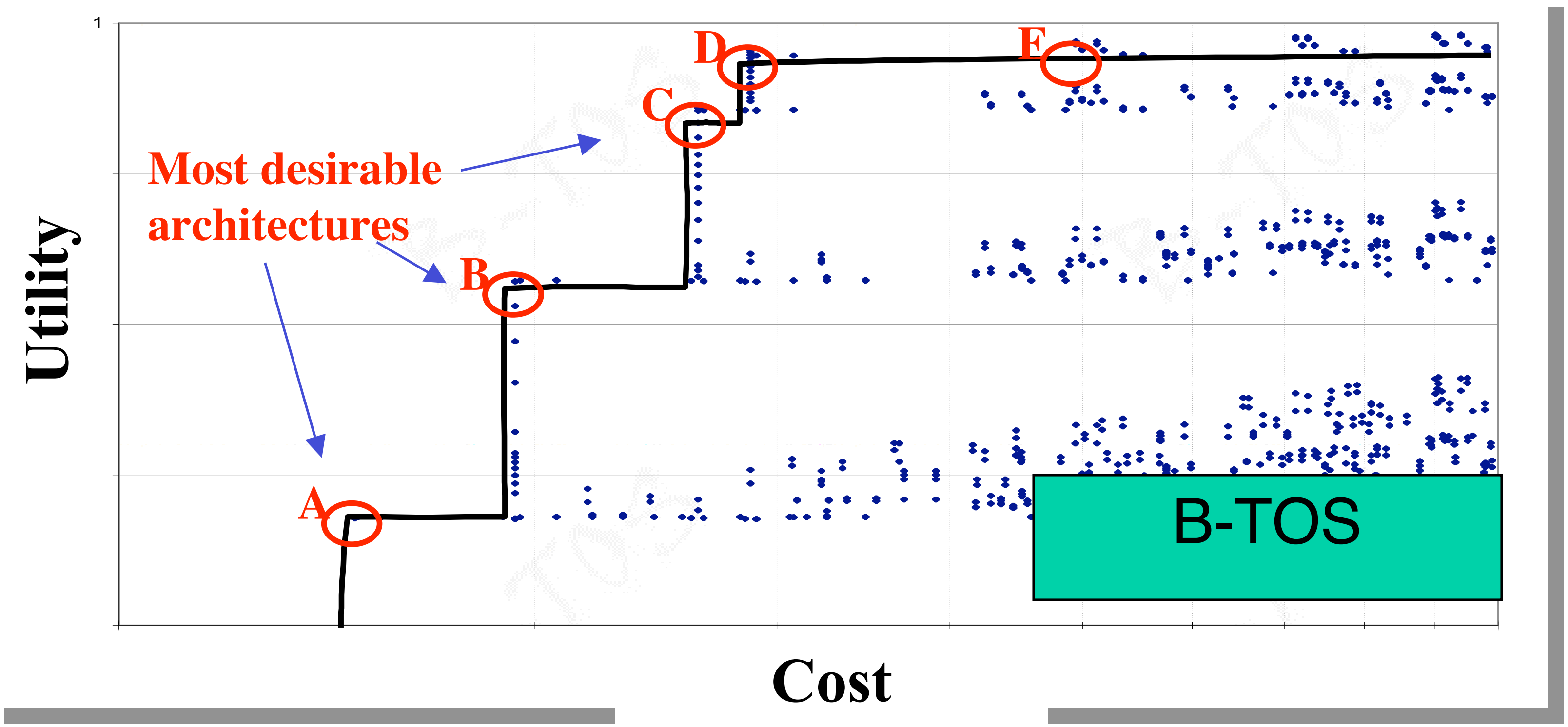




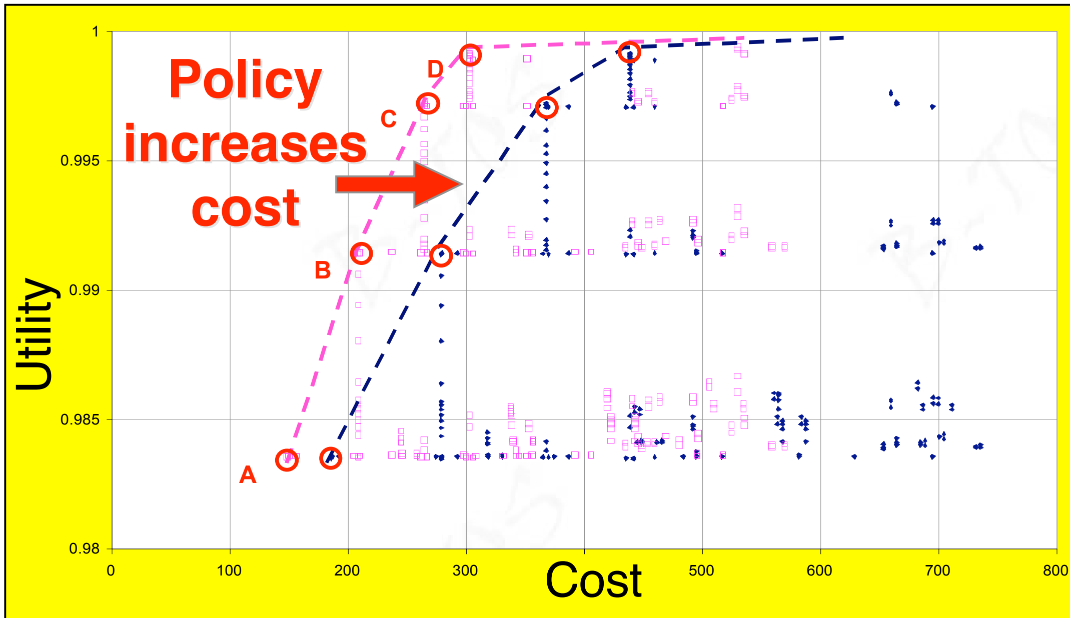
- Often learn a lot by simple examination
- Better: *Explicitly* look at sensitivity of models to uncertainties
- Uncertainties can be market (shown), policy, or technical
- Mitigate with portfolio, real options methods

Assessing Robustness and Adaptability

- Pareto front shows trade-off of accuracy and cost
- Determined by number of satellites in swarm
- Could add satellites to increase capability

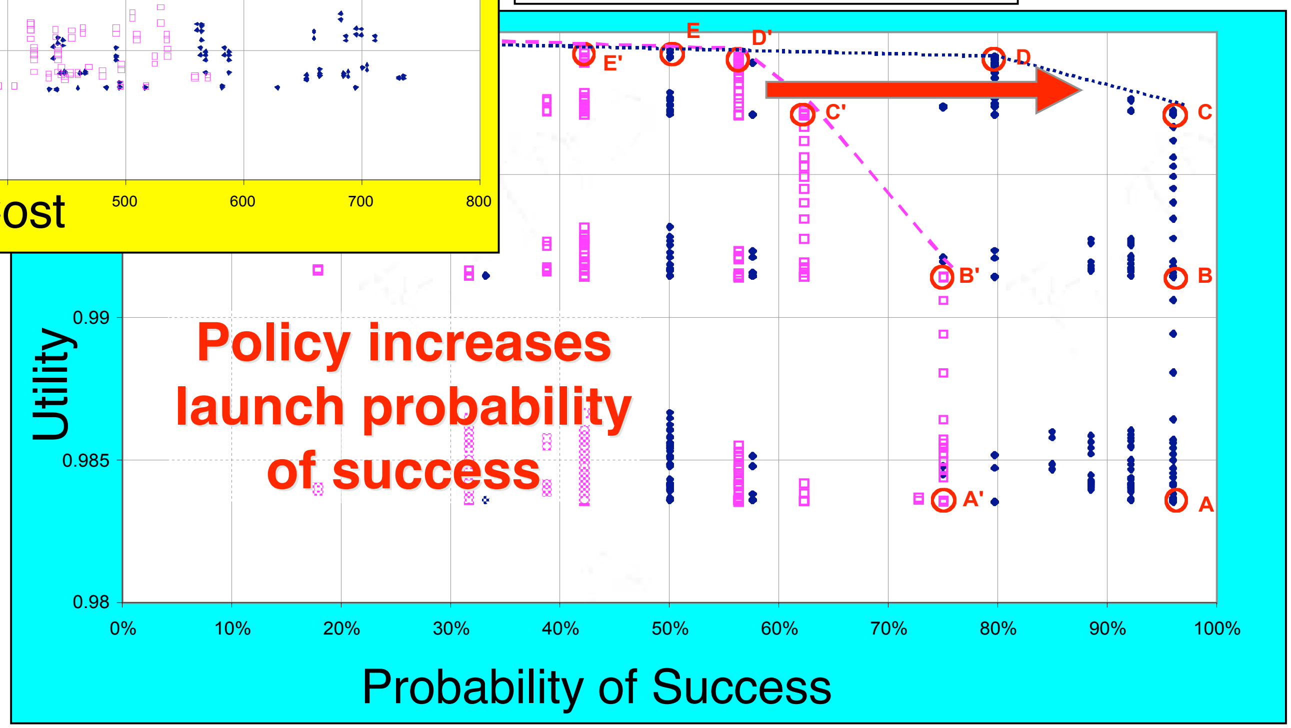


Using Architecture Models to Understand Policy Impacts



100% of B-TOS architectures have cost increase under restrictive launch policy for a minimum cost decision maker

◆ *Restrictive launch policy*
□ *Unrestrictive launch policy*



B-TOS

- Swarm of small sats. doing observation
- Utility for multiple missions

From Weigel, 2002