Using Pareto Trace to Determine System Passive Value Robustness

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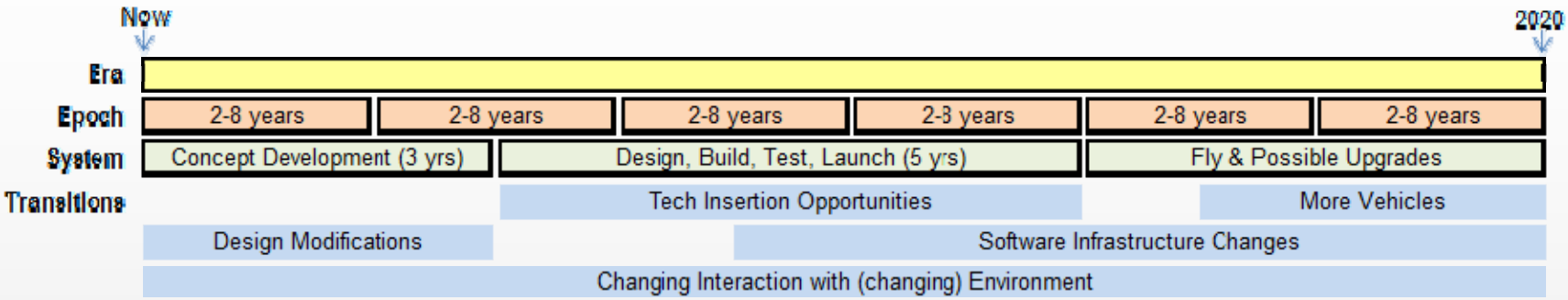
Managing System Cost, Schedule, and Performance in a Dynamic Reality



- Shift in contexts often occur more frequently than typical system development timelines (*e.g.,* budgets, administrations, near-term warfighter needs)
- Fluctuations feed back on programs, creating cost, schedule and performance risks (*e.g.,* reduced budgets, shifting priorities, change in adversary capabilities)
- By modeling tradespaces of system designs and the impact of context changes across the system's lifecycle, one can:
  - Gain insight into how context changes affect alternative system value delivery
  - Identify and develop system strategies that promote value robustness
  - Gain insight into possible future operational scenarios, informing affordability trades

Fact: Expectations and contexts for a given system will change over time

Goal: Develop *value robust* solutions

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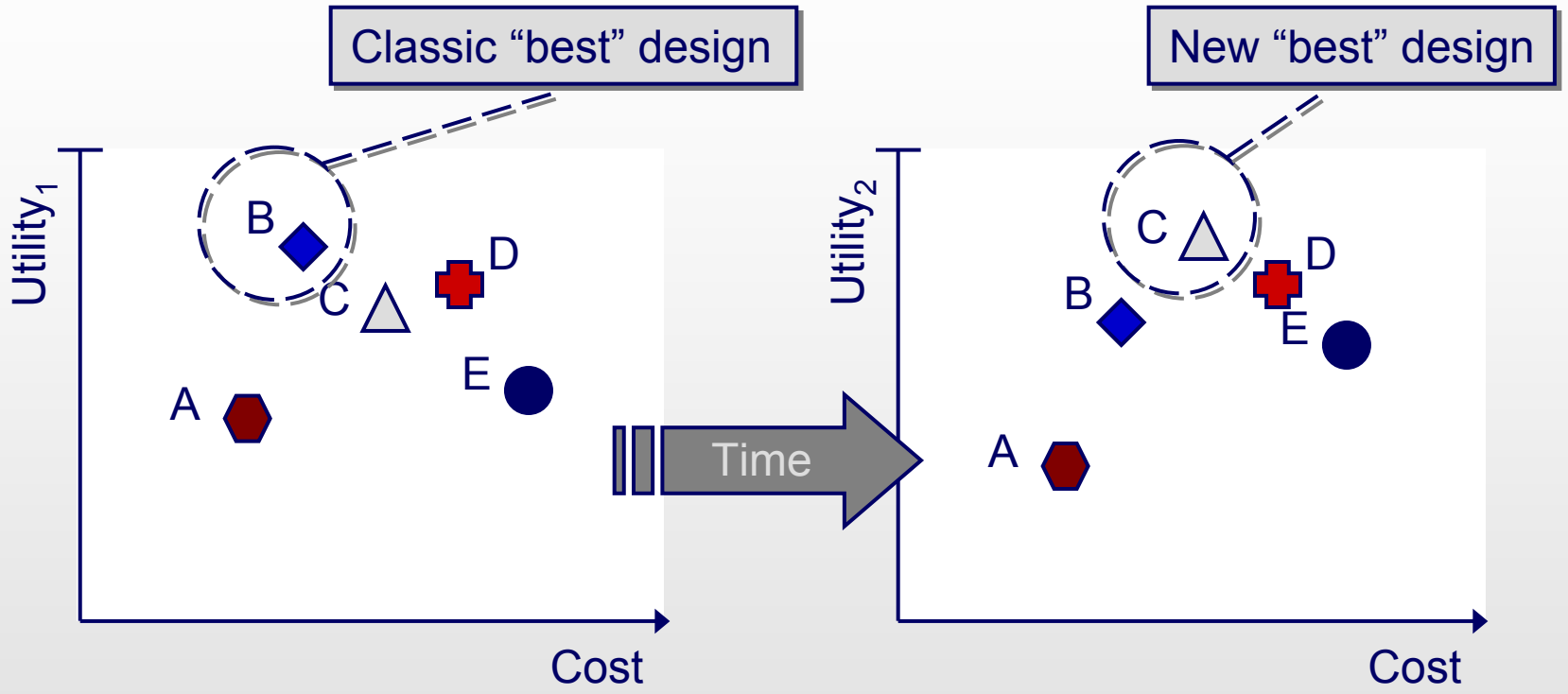
Tradespace Analysis: Selecting "Best" Designs



If the "best" design changes over time, how does one select the "best" design?

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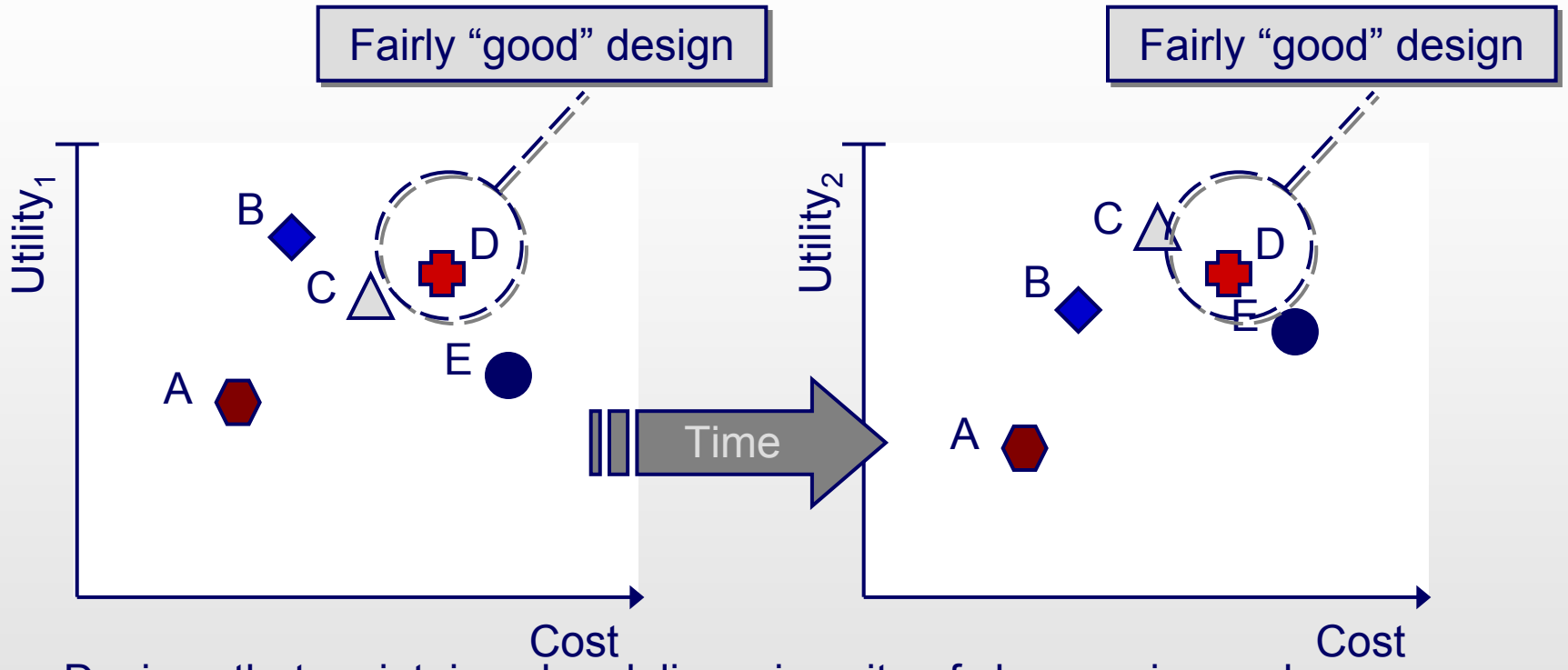
Tradespace Analysis: Identifying "Good" Designs



Designs that maintain value delivery in spite of changes in needs or contexts are called *value robust**

*if no system changes are required, then it is "passively value robust"

If the "best" design changes over time, how does one select the "best" design?

"Good", or "satisficing", designs can be identified across changing objectives

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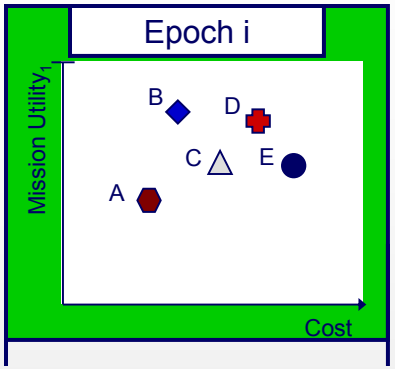
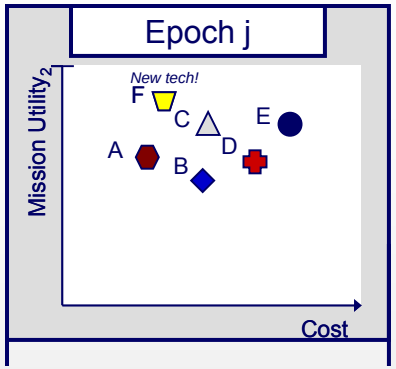
Epoch-Era Analysis for Generating Future Scenarios

Compare Alternatives

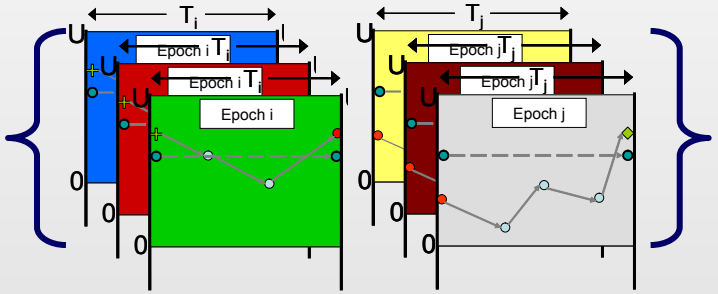
Static tradespaces compare alternatives for fixed context and needs (per Epoch)





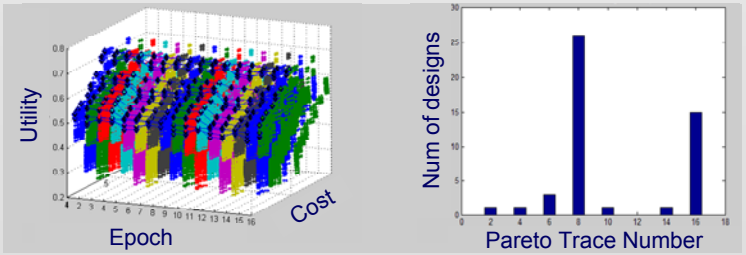
Define Epochs

Epoch set represents potential fixed contexts and needs



Multi-Epoch Analysis

Analysis across large number of epochs reveals “good” designs



Parameterizing future epochs allows for quantification of epoch effects on designs

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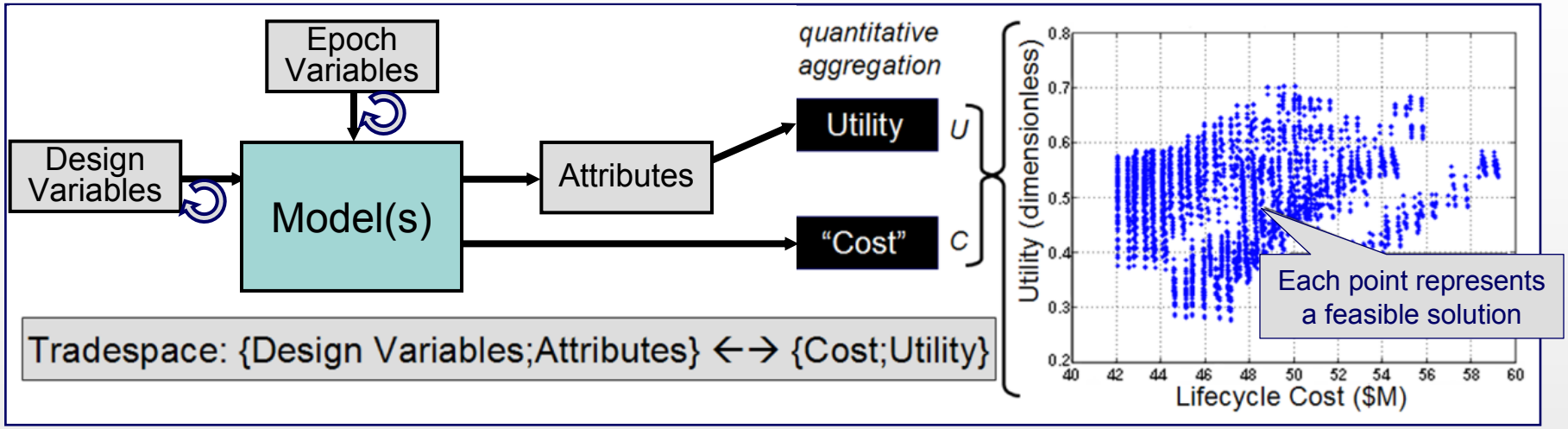
Tradespace Exploration



Compares many designs on a common, quantitative basis

- Maps structure of design space onto stakeholder value (attributes)
- Uses computer-based models to assess thousands of designs, avoiding limits of local point solutions
- Simulation can be used to account for design uncertainties (*e.g.*, cost, schedule, performance uncertainty)

Typical goal: maximize aggregate benefit (utility) and minimize aggregate cost (lifecycle cost)

Design tradespaces provide high-level insights into system-level trade-offs

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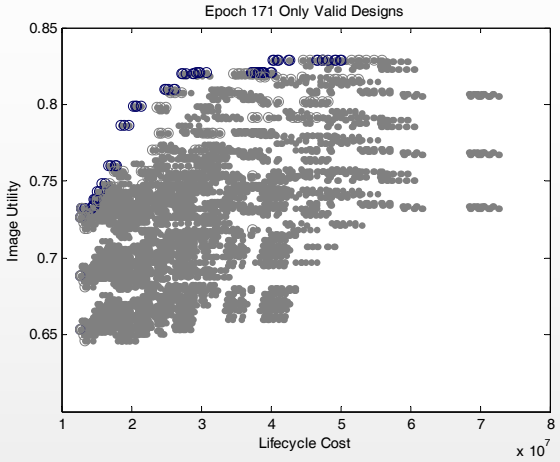
Calculating Pareto Trace to Uncover Value Robust Designs



Find non-dominated solutions within a given epoch (Pareto Set)

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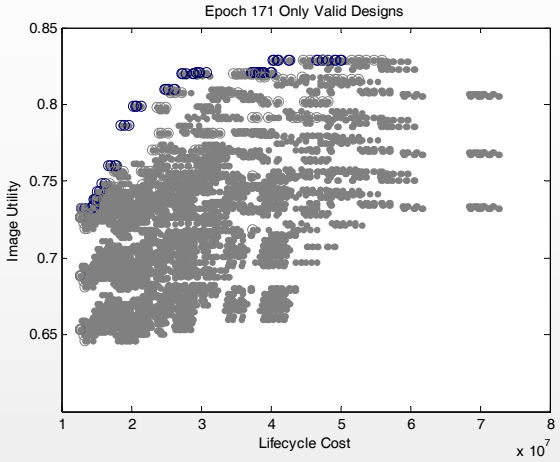
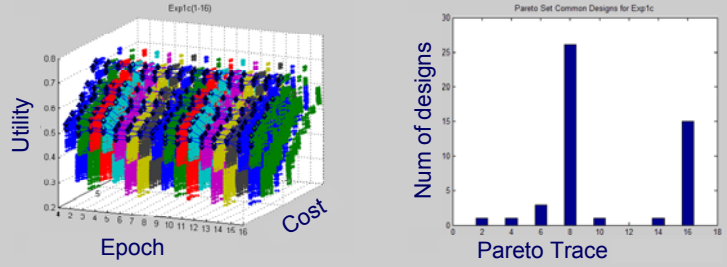
Calculating Pareto Trace to Uncover Value Robust Designs



Find non-dominated solutions within a given epoch (Pareto Set)

Pareto Trace

Pareto Sets containing design
(measure of passive robustness)



Across many epochs, track number of times solution appears in Pareto Set

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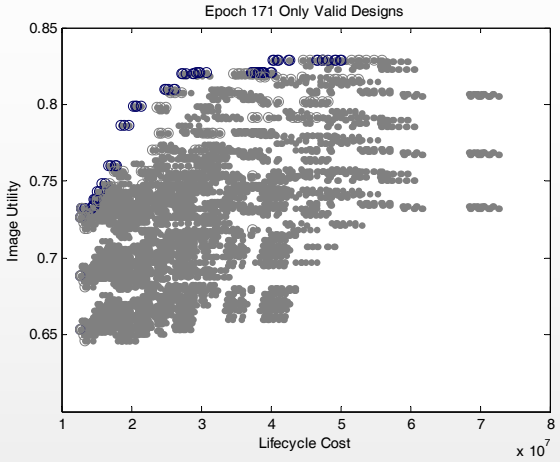
Calculating Pareto Trace to Uncover Value Robust Designs



Pareto Trace

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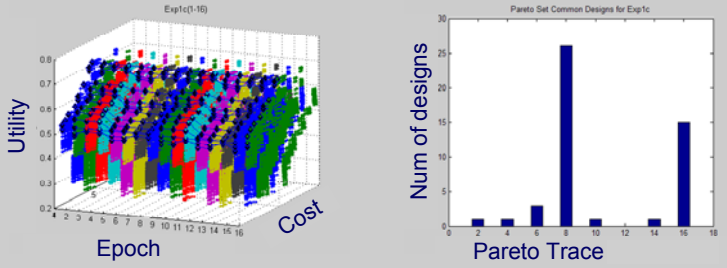
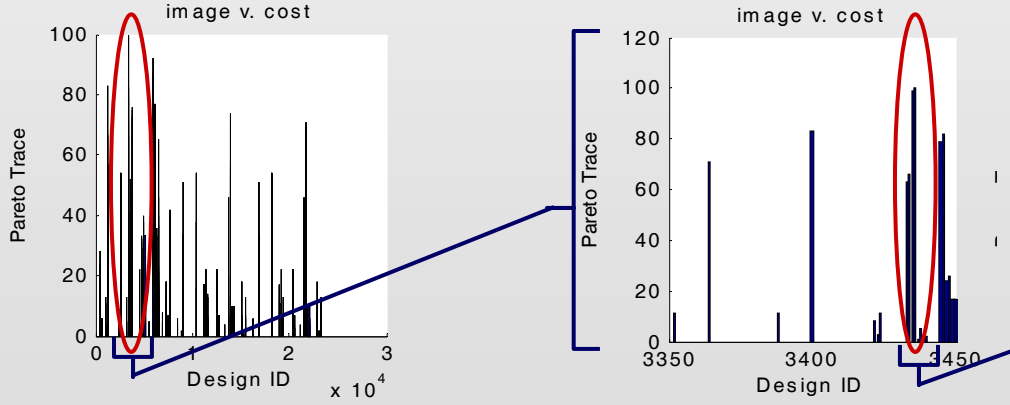


Find non-dominated solutions within a given epoch (Pareto Set)

Across many epochs, track number of times solution appears in Pareto Set



Identify designs with high Pareto Trace for further investigation

e.g. "design 3435" is in 67% of Pareto Sets

Higher Pareto Trace designs are more passively value robust

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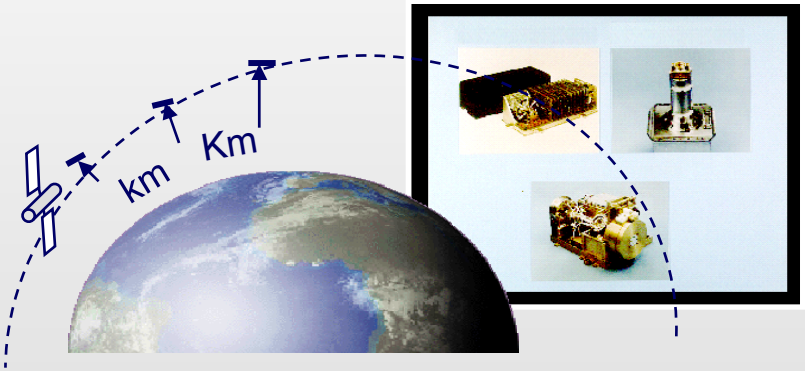
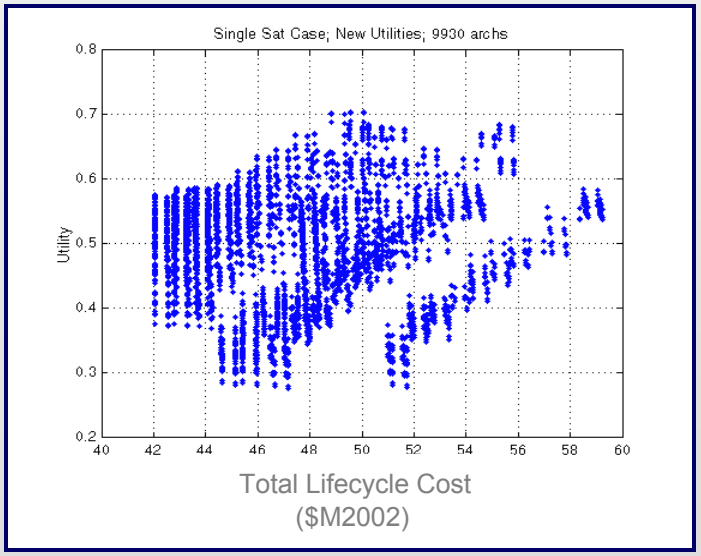
Case 1: Quantifying Robustness to Expectations Change

1. Apply needs (expectations) changes to tradespace
2. Assess Pareto Trace statistics across tradespaces
3. Find designs that remain preferred across epochs



Project X-TOS

Single-Satellite in-situ density measurements



DESIGN VARIABLES (9)

- Mission scenario, Apogee altitude (km), Perigee altitude (km), Orbit inclination (deg), Antenna gain, Communication architecture, Propulsion type, Power type, Delta V (m/s)

ATTRIBUTES (5)

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

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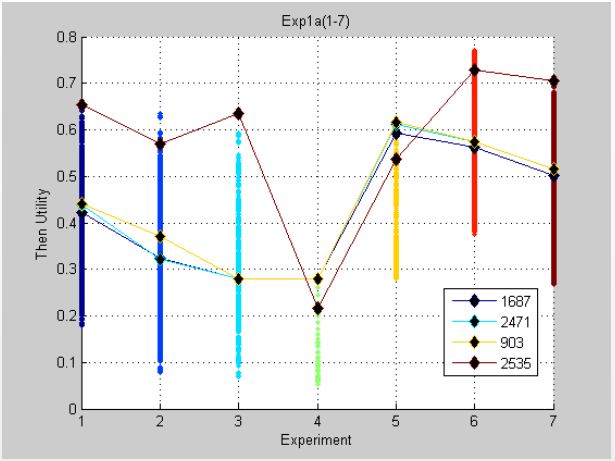
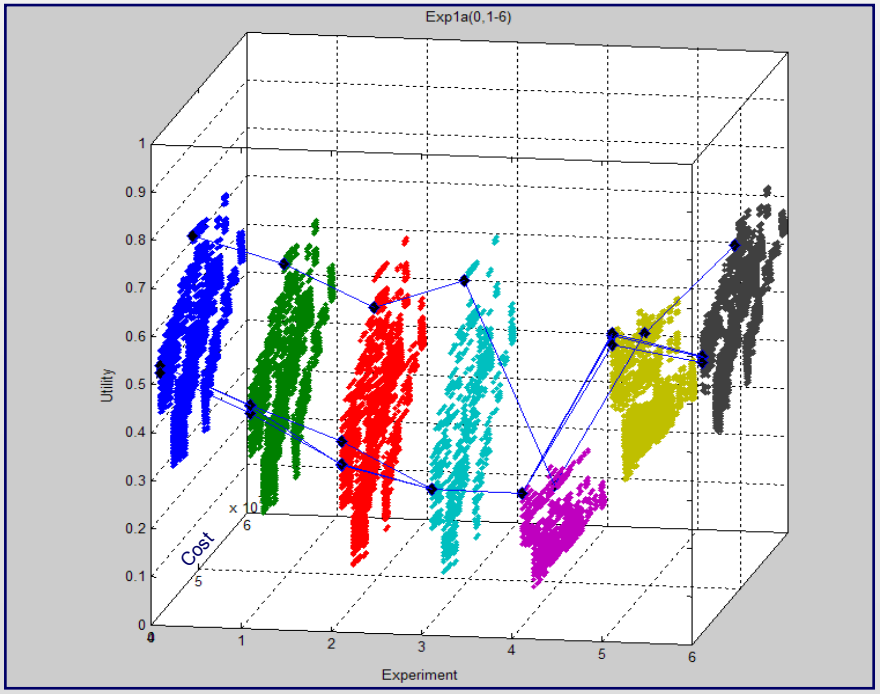
Pareto Set Tracing for Single DM (Δ attribute set)

What if you don't elicit all of the "right" attributes?

Exp1a:	1	2	3	4	5	6	7
DL	0.3	0.3	0.3			0.3	0.3
LD	0.125				0.125	0.125	0.125
ET	0.175	0.175			0.175	0.175	0.175
L					0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425	0.425	0.425
SM						0.2	





DV	2471	903	1687	2535
Inclination	**90**	**30**	**70**	**90**
Apogee	460	460	460	460
Perigee	150	150	150	**290**
Com Arch	TDRSS			
Delta V	1200			
Prop Type	Chem			
Pwr Type	Fuel Cell			
Ant Gain	Low			

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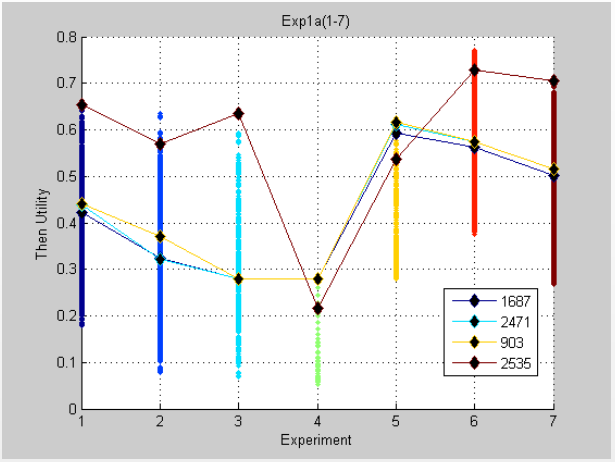
Pareto Set Tracing for Single DM (Δ attribute set)

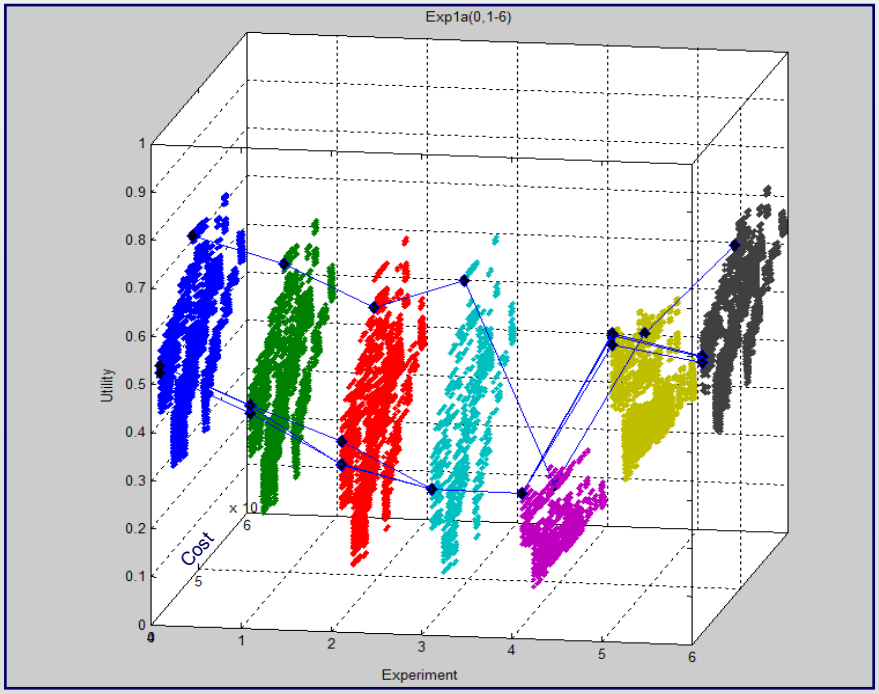
Design 2471 is in all 7 Pareto Sets

Designs 903, 1687, 2535 are in 5 Pareto Sets each

These points are "robust" in ranking to tested attribute set change

Exp1a:	1	2	3	4	5	6	7
DL	0.3	0.3	0.3			0.3	0.3
LD	0.125				0.125	0.125	0.125
ET	0.175	0.175			0.175	0.175	0.175
L					0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425	0.425	0.425
SM						0.2	





DV	2471	903	1687	2535
Inclination	**90**	**30**	**70**	**90**
Apogee	460	460	460	460
Perigee	150	150	150	**290**
Com Arch	TDRSS			
Delta V	1200			
Prop Type	Chem			
Pwr Type	Fuel Cell			
Ant Gain	Low			

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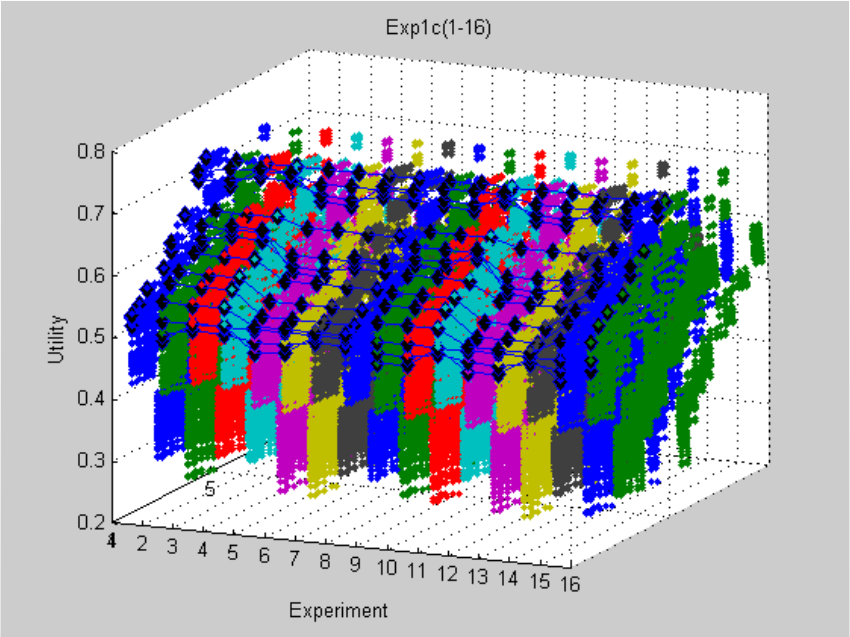
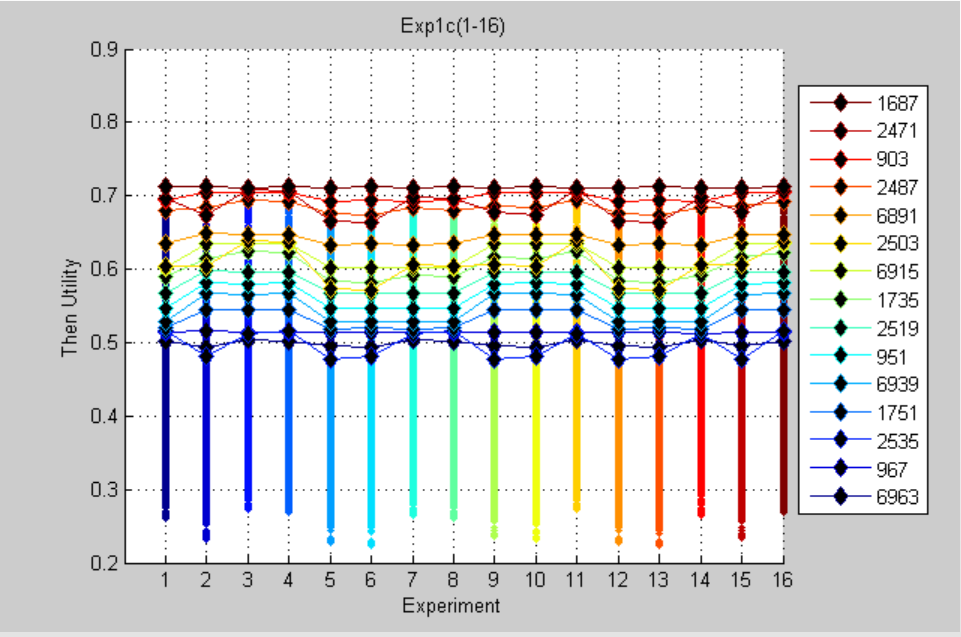
Pareto Set Tracing for Single DM (linearized preferences)





Expc:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
DL	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
LD	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175
L	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425
SM															

What if you don't elicit the "right" utility curve shape?

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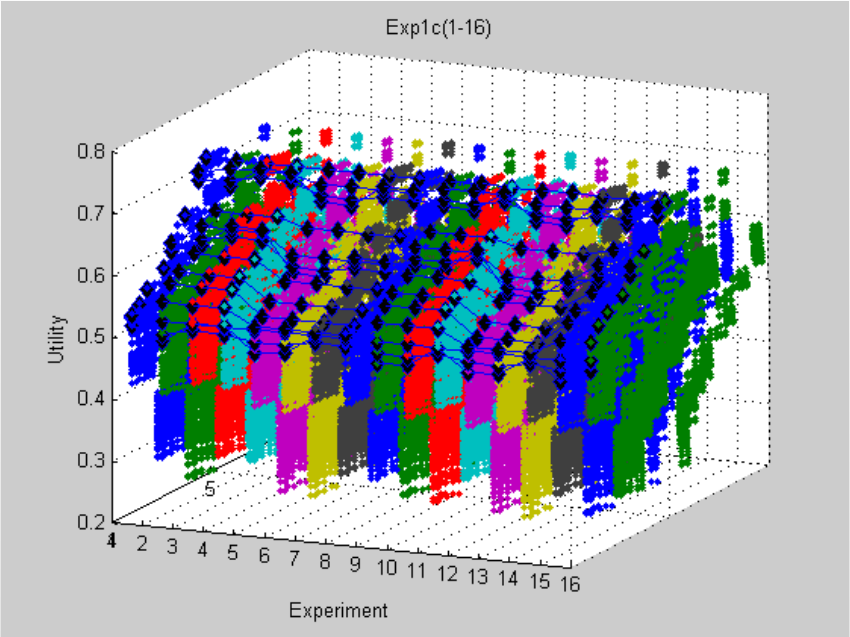
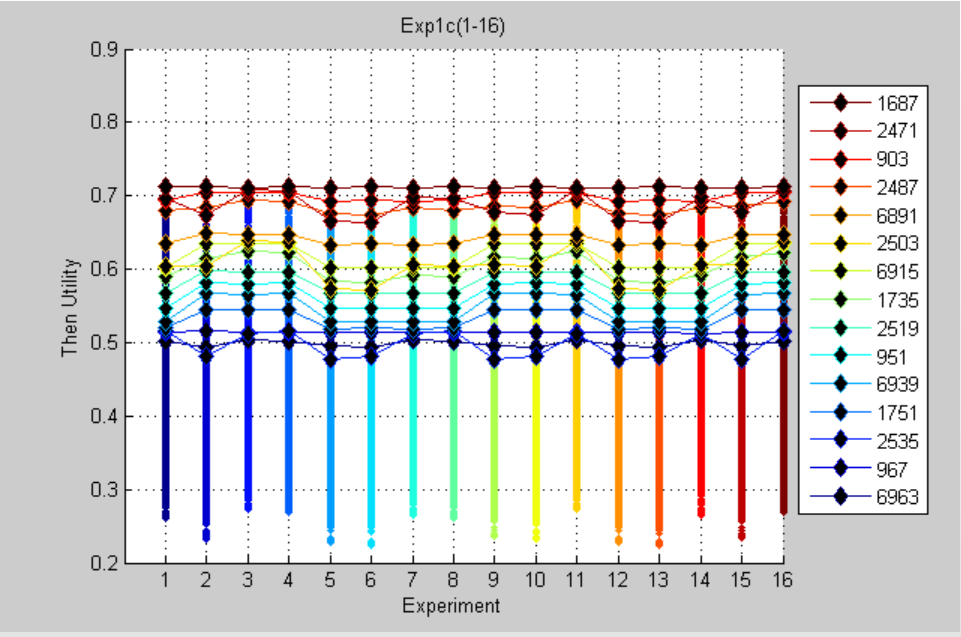
Pareto Set Tracing for Single DM (linearized preferences)





Expc:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
DL	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
LD	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175
L	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425
SM															

15 design options are in all 16 Pareto Sets and are “robust” to Exp1c preference variations (linearization of SAU)

Includes designs 2471, 903, 1687, 2535

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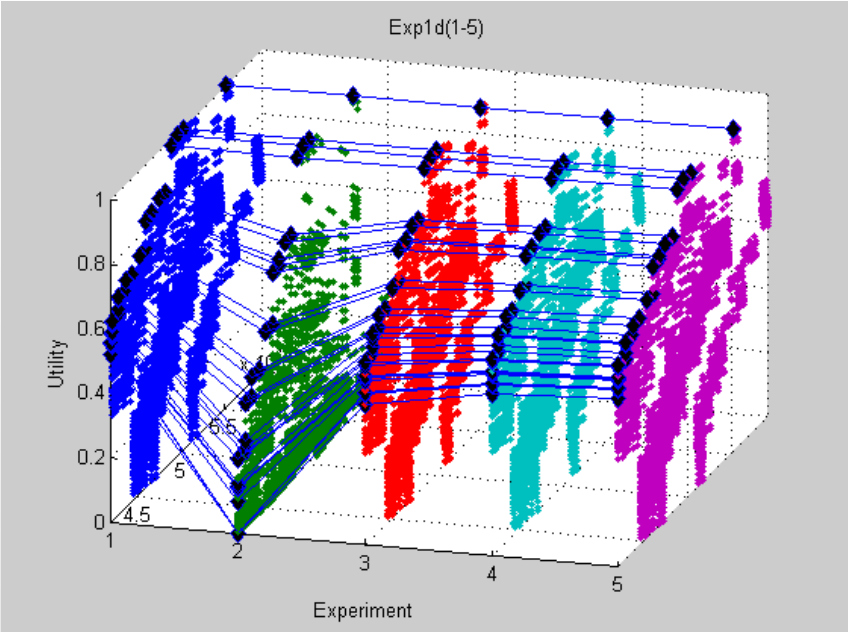
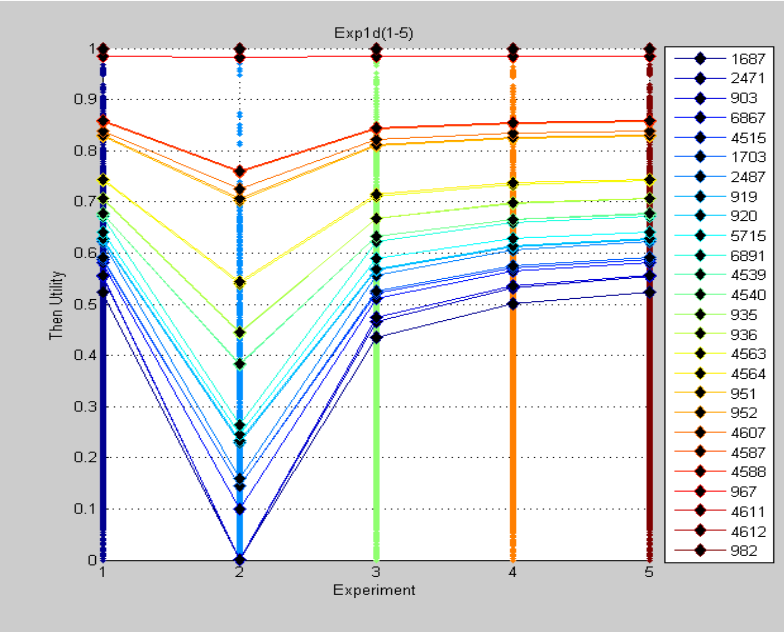
Pareto Set Tracing for Single DM (Δ Eval Fcn)





1 $$U = \frac{\left(\prod_{i=1}^{N}\left[Kk_iU_i + 1\right]\right) - 1}{K}$$

2 $$U = \prod_{i=1}^{N} k_iU_i$$

3 $$U = \prod_{i=1}^{N}\left[k_iU_i + 1\right]$$

4 $$U = \sum_{i=1}^{N} k_iU_i$$

5 $$U = \prod_{i=1}^{N}\left[Kk_iU_i + 1\right]$$

Expd:	1	2	3	4	5
DL	0.3	0.3	0.3	0.3	0.3
LD	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175
L	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425
SM					
$U(U_i)$	MAUF	M1	M2	M3	1-M4

What if you don't use the "right" utility aggregating function?

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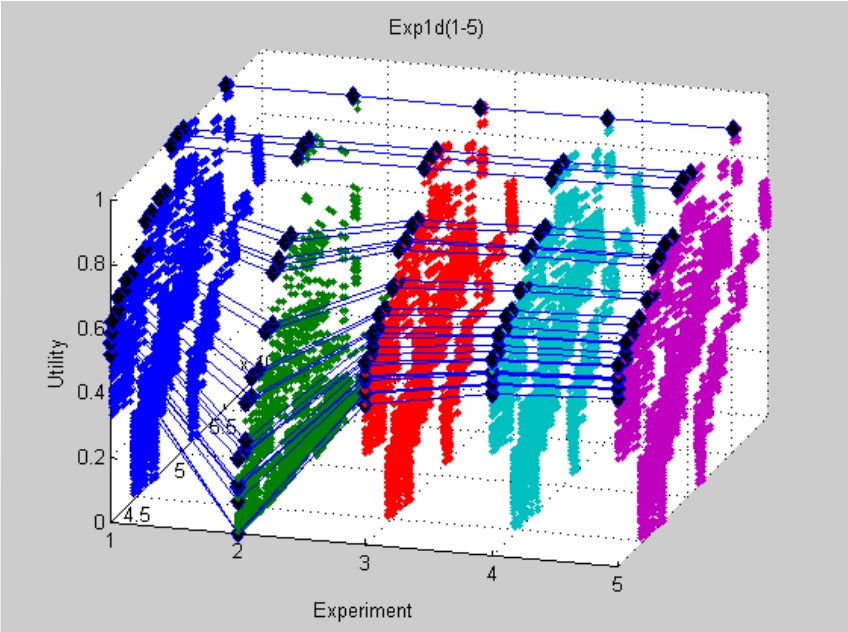
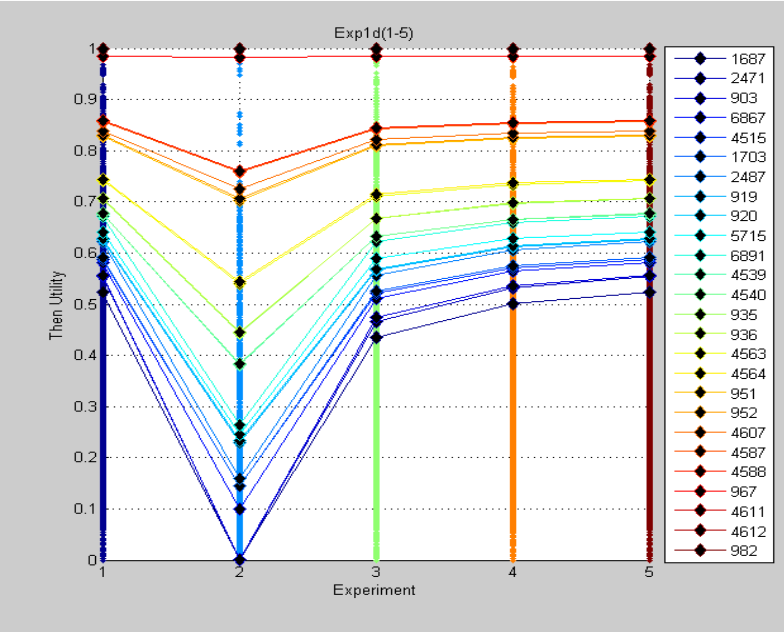
Pareto Set Tracing for Single DM (Δ Eval Fcn)





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ET	0.175	0.175	0.175	0.175	0.175
L	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425
SM					
$U(U_i)$	MAUF	M1	M2	M3	1-M4

26 design options are in all 5 Pareto Sets and are "robust" to Exp1d preference variations (MAU functional forms)

Includes designs 2471, 903, 1687

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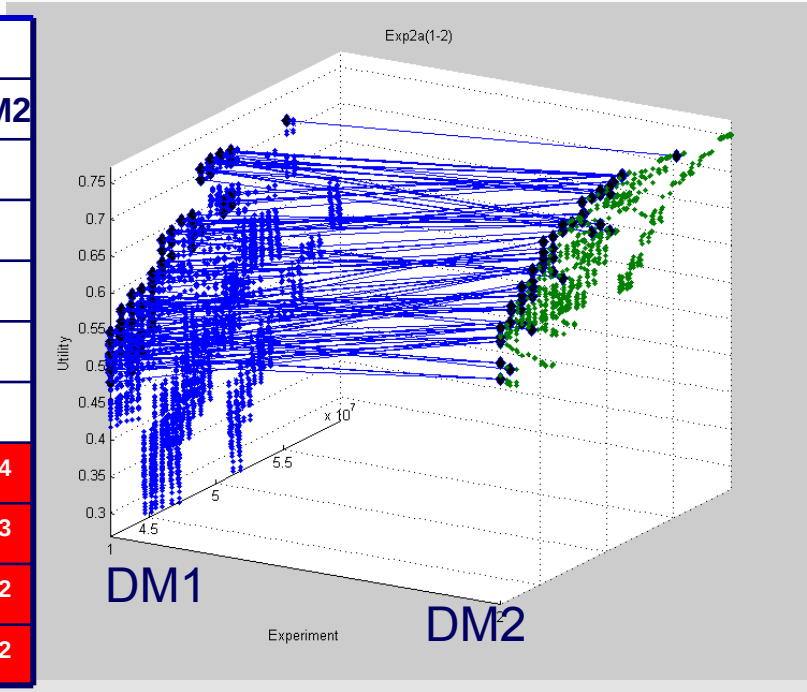
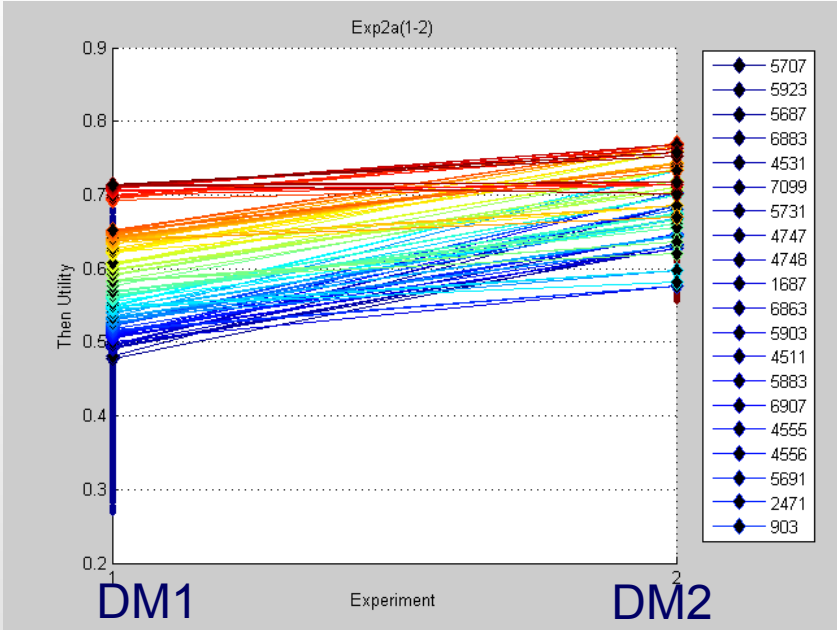
Pareto Set Tracing for Dual DM (additional of second DM)

Exp2a:	1	
	DM1	DM2
DL	0.3	
LD	0.125	
ET	0.175	
L	0.1	
SA	0.425	
IOC		0.4
DT		0.3
SL		0.2
SM		0.2





What if a second decision maker enters the mix?

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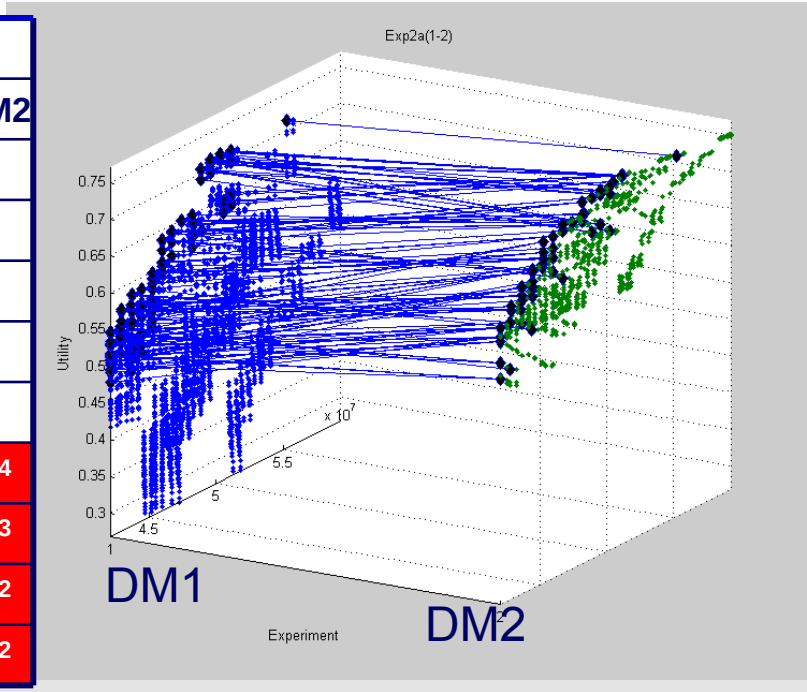
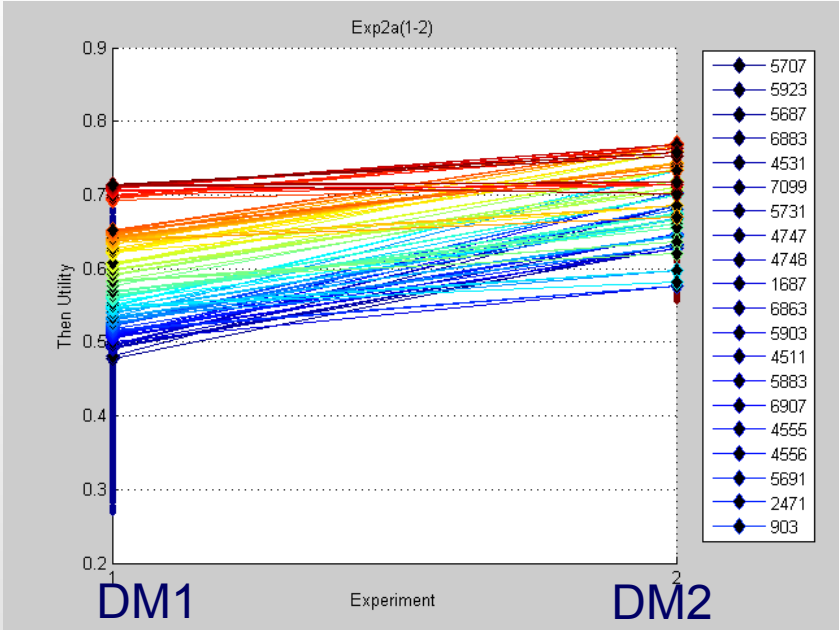
Pareto Set Tracing for Dual DM (additional of second DM)

Exp2a:	1	
	DM1	DM2
DL	0.3	
LD	0.125	
ET	0.175	
L	0.1	
SA	0.425	
IOC		0.4
DT		0.3
SL		0.2
SM		0.2





Multiple tradespaces are differentiated by Decision Maker instead of time

Joint Pareto Set contains 122 common designs, including design 2471!

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Discovering "Compromises"

Designs in Joint Pareto Set

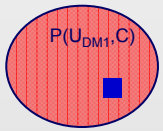
DM1 Pareto Set | DM2 Pareto Set | Compromise Pareto Set | Both Pareto Sets

903	919	920	933	935	936	951	952	965	967	981
982	983	984	997	1687	1703	1735	1749	1751	1765	1767
1781	2471	2487	2501	2503	2519	2533	2535	2549	2551	2565
4511	4515	4531	4535	4536	4539	4540	4555	4556	4559	4560
4563	4564	4579	4580	4583	4584	4587	4588	4603	4604	4607
4608	4611	4612	4627	4628	4631	4632	4633	4707	4708	4727
4728	4747	4748	4771	4773	4795	4796	4797	5687	5691	5707
5711	5715	5731	5735	5739	5755	5759	5779	5783	5787	5803
5807	5809	5883	5903	5923	5947	5949	5971	5973	6863	6867
6883	6887	6891	6907	6911	6915	6931	6935	6939	6955	6959
6963	6979	6983	6985	7059	7079	7099	7123	7125	7147	7148
7149										

"Optimal" solutions per DM are (a) or (b)

"Optimal" solutions for both DM are (c)

Compromise set (d) difficult to determine through traditional means

(a) 

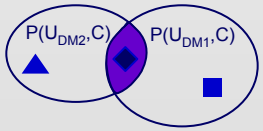
"Best" for DM1

36 designs

(b)

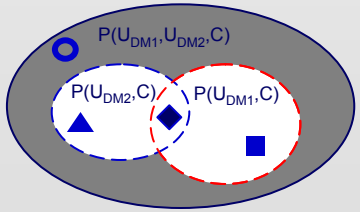
"Best" for DM2

26 designs

(c) 

"Best" for DM1 & DM2, no compromise

6 designs

(d) 

Compromise set

66 designs

Approach can be used to discover "efficient" compromises as basis for negotiation

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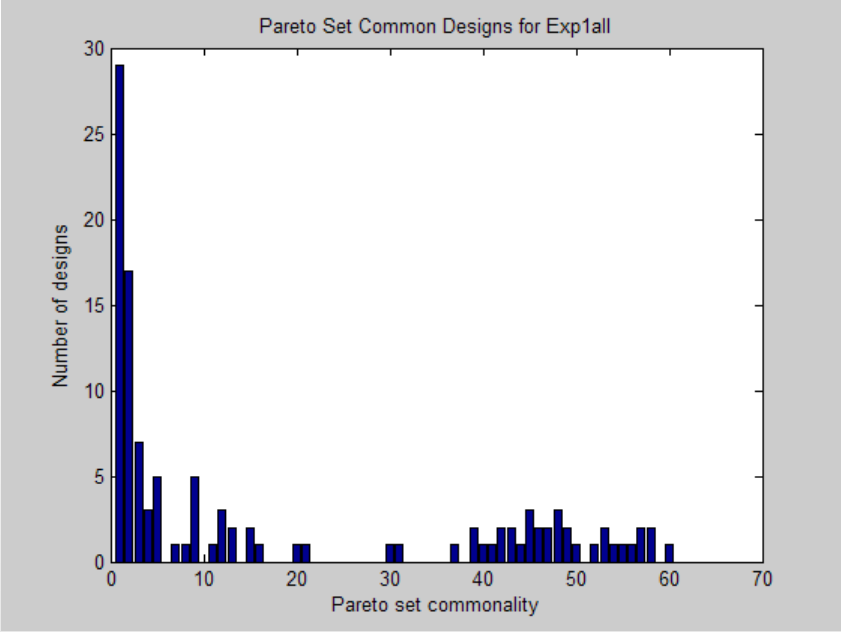
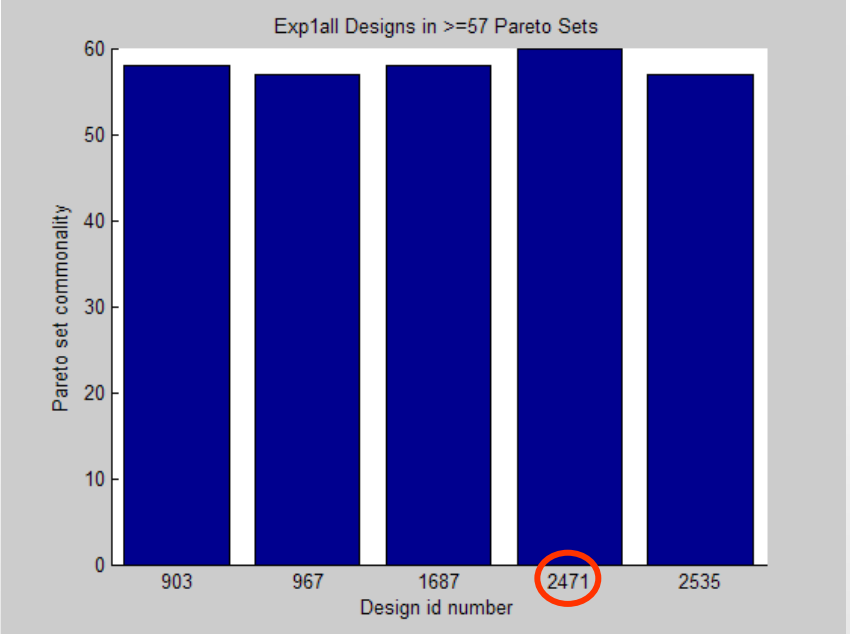
X-TOS Pareto Tracing Results





1 design option, 2471, is in all 60 Pareto Sets and is "robust" to all preference variations (+/- {X^i}, k_{ij} linear SAU, MAU forms)

4 more designs are in 57 or more Pareto Sets, including designs 903, 967, 1687, and 2535

DV	2471	903	1687	2535
Inclination	**90**	**30**	**70**	**90**
Apogee	460	460	460	460
Perigee	150	150	150	**290**
Com Arch	TDRSS			
Delta V	1200			
Prop Type	Chem			
Pwr Type	Fuel Cell			
Ant Gain	Low			

Pareto Tracing can be used to identify obvious or non-obvious passively value robust designs

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Performing Pareto Tracing

Perform anticipatory exploration of possible preference permutations

- Answering "what if" questions on needs…
  - What if you don't elicit the "right" attribute priorities?
  - What if you don't elicit all of the "right" attributes?
  - What if you don't elicit the "right" utility curve shape?
  - What if you don't use the "right" utility aggregating function?
  - What if a second decision maker enters the mix?
  - …
- Find designs common in Pareto Sets across varying "needs" and "contexts" epochs

Pareto Trace is a metric of passive value robustness across epoch variations

But what does absolute Pareto Trace mean, and what about designs that are "close" to the Pareto Front? Aren't these "good" also?

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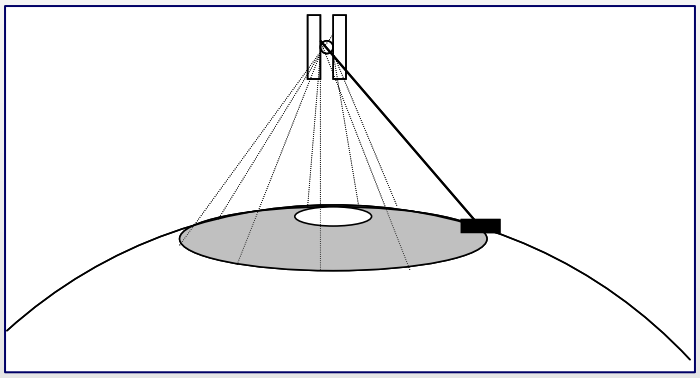
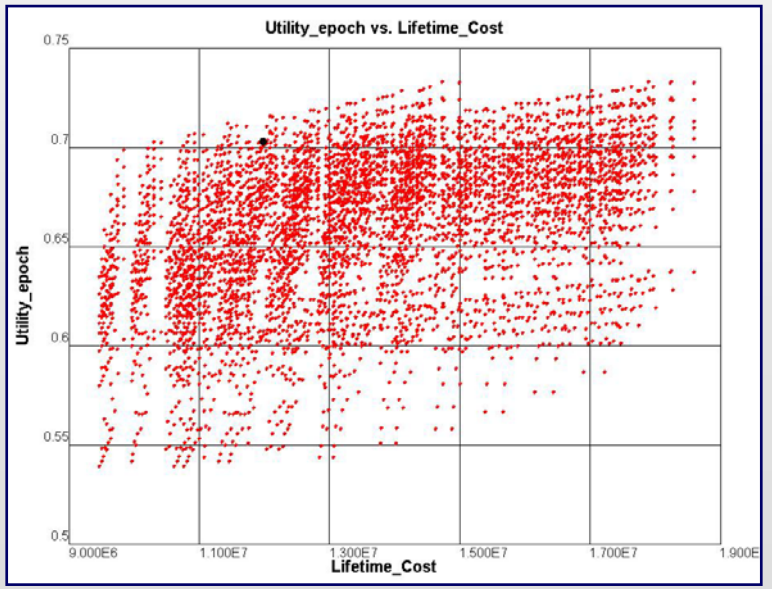
Case 2: Quantifying Robustness to Epoch Changes

1. Apply epoch changes (needs and contexts) to tradespace
2. Assess Pareto Trace statistics across tradespaces
3. Find designs that remain preferred across epochs



Project SRS

Satellite radar multi-mission system of system



DESIGN VARIABLES (10)

- Orbit Altitude (km), Constellation design, Antenna size (m^2), Peak power (kW), Radar bandwidth (GHz), Comm arch, Tactical downlink, Tugabilty, Maneuver package, Constellation option

EPOCH VARIABLES (6)

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

ATTRIBUTES (3 “missions”, 15 total)

- Tracking (GMTI), Imaging (SAR), Programmatic

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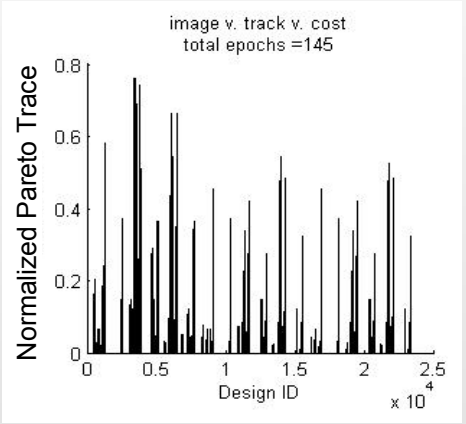
Addressing Epoch-Sampling Bias

Since there are infinite permutations of possible needs and contexts…
normalize Pareto Trace to determine robustness as fraction of considered "futures"

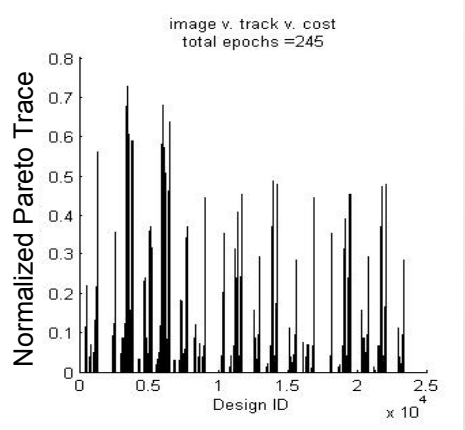
$$\text{Normalized Pareto Trace (NPT)} = \frac{\text{Pareto Trace}}{\text{Total Number of Epochs Considered}}$$

Total enumerated epochs = 648

Sampling strategy



145 epochs



245 epochs

Randomized sampling of epochs seeks to balance computation with stability of NPT

NPT *will be* dependent on epochs considered. Correlation between high NPT designs and epochs gives insights into epoch-specific classes of "best" designs

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Extending Pareto Tracing

Fuzzy Pareto Optimality*

Adding "fuzziness factor" allows for inclusion of "good" designs

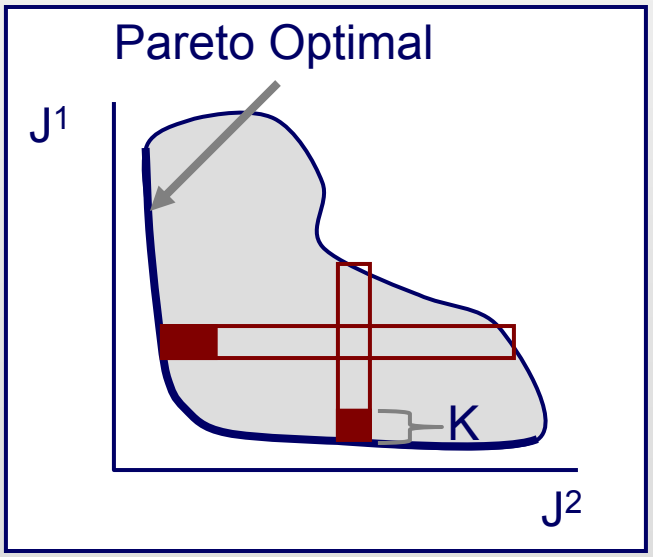
Assuming goal is to minimize J^1 and J^2,

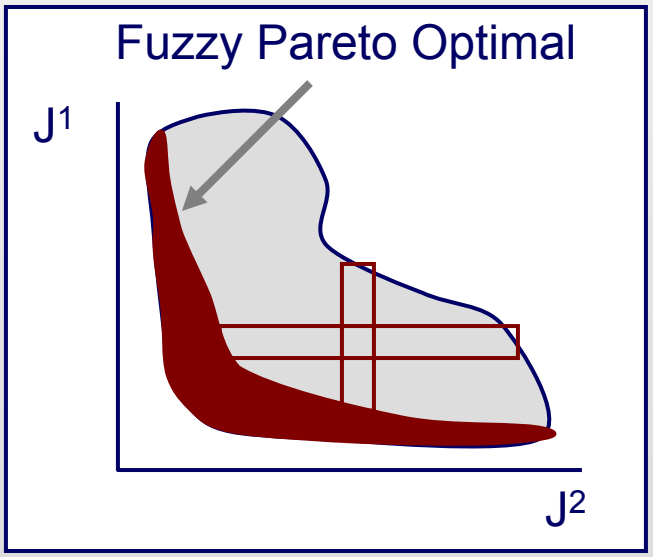
J^1 dominates J^2 if:

$$J^1 + K(J^{max} - J^{min}) \leq J^2, \text{ and } J^1 \neq J^2 \quad (1)$$

$$J^1_i + K(J^{max}_i - J^{min}_i) \leq J^2_i \ \forall \ i \text{ and} \quad (2)$$

$$J^1_i + K(J^{max}_i - J^{min}_i) < J^2_i \text{ for at least one } i, \quad (3)$$





R. Smaling, "System Architecture Analysis and Selection under Uncertainty," Cambridge, MA: MIT, PhD in Engineering Systems, pp. 48-50, June 2005.

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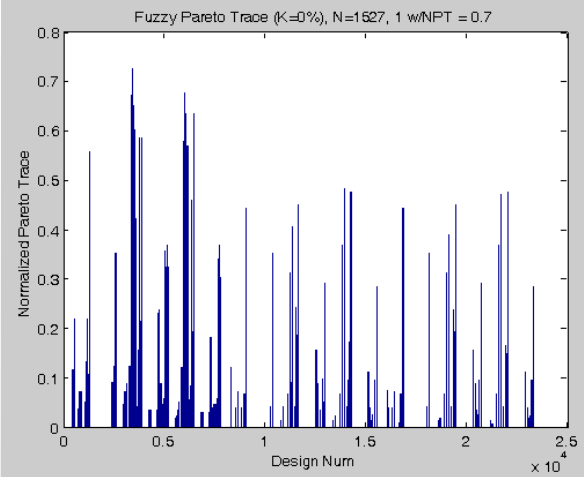
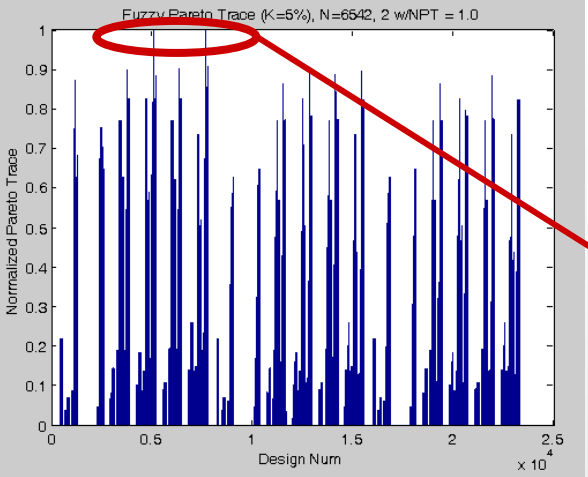
Fuzzy Pareto Trace, Varying K

K=0%

Max NPT=0.7

1 Design





K=5%

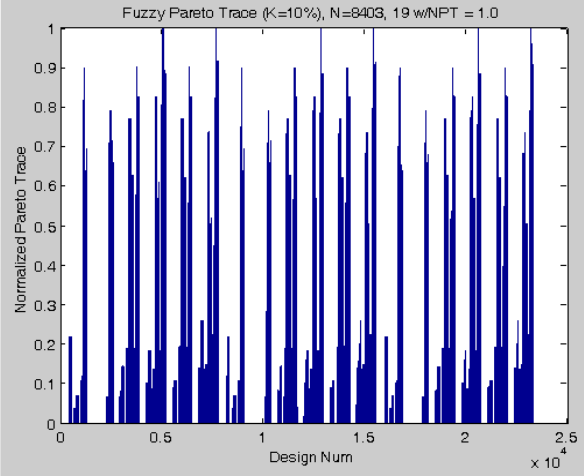
Max NPT=1.0

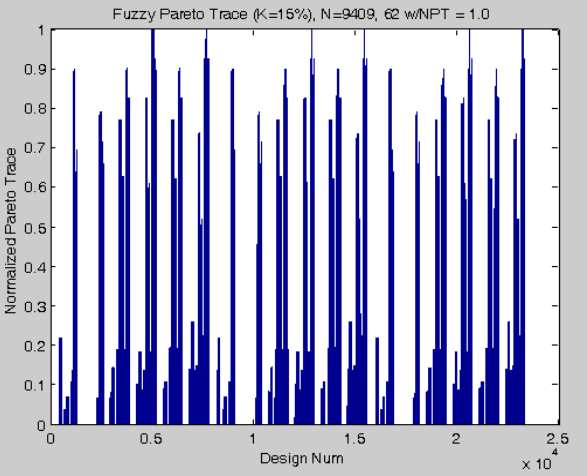
2 Designs

K=10%

Max NPT=1.0

19 Designs





K=15%

Max NPT=1.0

62 Designs

Tuning K allows for discovery of “good” designs

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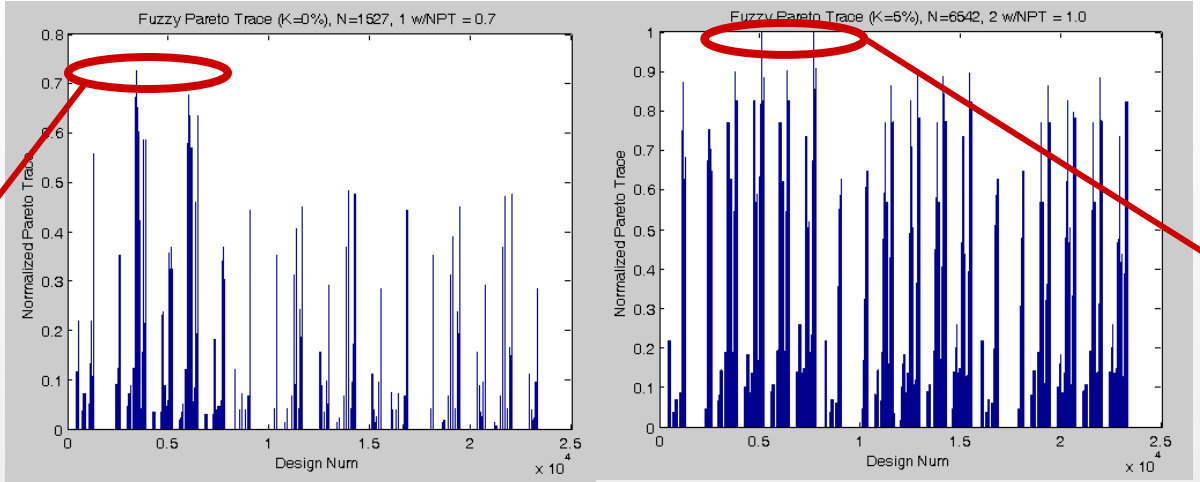
Discovery of "Good" Designs

K=0%

Max NPT=0.7

1 Design

Design
3435



K=5%

Max NPT=1.0

2 Designs

Designs
5067
7659

New designs that were "almost" best are discovered at K=5%

Design ID Number	3435	5067	7659	Enumerated Range
Normalized Pareto Trace	0.7 (K=0)	1.0 (K=5%)	1.0 (K=5%)	
Orbit Altitude (km)	1500	1500	1200	[800, 1200, 1500]
Walker ID	53deg. 10sat 5planes	67deg. 20sat 5planes	67deg. 20sat 5planes	[1:8]
TX Freq (GHz)		10		[10]
Antenna Area (m^2)		40		[10,40,100]
Antenna Type		AESA		[0]
Radar Bandwidth (GHz)		2		[0.5,1,2]
Peak Power (kW)	10	20	20	[1.5,10,20]
Communication Downlink		Ground		[0,1]
Tactical Downlink		Yes		[0,1]
Tugable		Yes		[1]
Maneuver		Baseline		[4,5,6]
Procurement Strategy		No Spares		[1:3]

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Discussion

- Changes in static analysis assumptions should not be a post-analysis consideration (*e.g.*, "sensitivity analysis")
- Using Pareto Trace with Multi-Epoch Analysis makes such considerations a central part of trade studies
- (F)NPT can be used to gain insight into:
  - Differential impact on systems of non-subtle, discrete changes in
    - Expectations or needs
    - Contexts
  - Epoch-specific valuable families of solutions
  - Inclusion of "satisficing" designs (*i.e.*, slightly "suboptimal")

Metric is most useful as an indicator for further investigation
(e.g., What is "so special" about these designs? In what epochs do they perform well and why?)

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Summary

For Multi-Epoch Tradespace Exploration…

Three metrics for passive value robustness

- Pareto Trace (PT)
  - # Pareto Sets across epochs in which design is considered "best"
- Normalized Pareto Trace (NPT)
  - Fraction of epochs in which design is considered "best"
- Fuzzy Normalized Pareto Trace (FNPT)
  - Fraction of epochs in which design is considered "good"

Passive value robustness is only part of the story…
Complementary research addresses active value robustness and developing system evolution strategies…

Questions?

For more information, please visit http://seari.mit.edu
or contact: adamross@mit.edu, rhodes@mit.edu

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Back-up Slides

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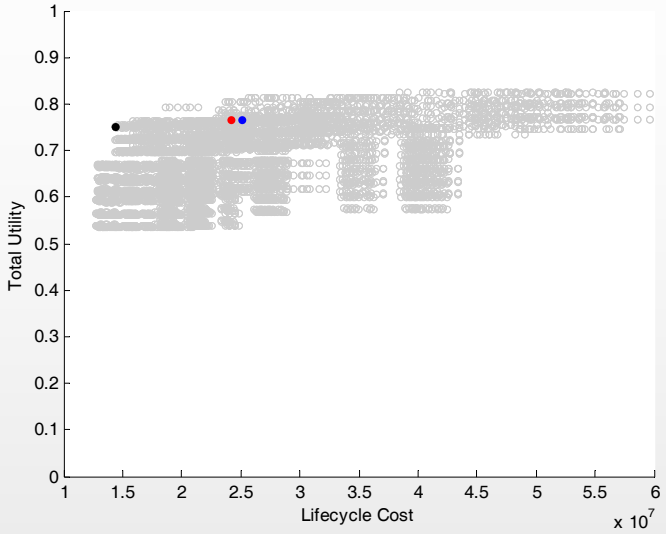
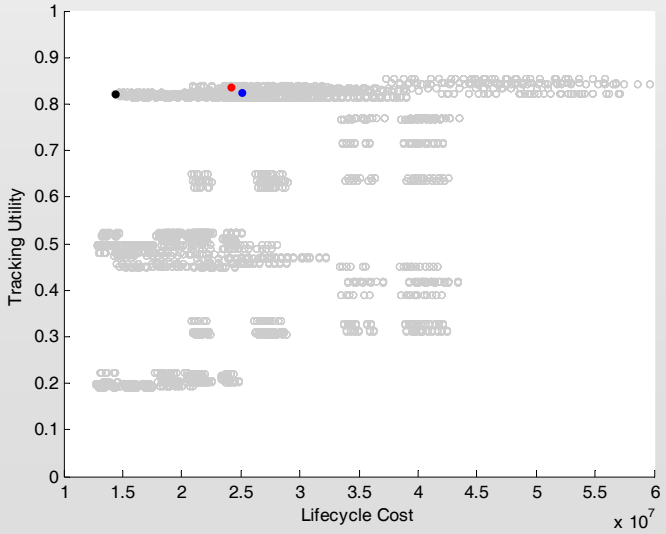
Tradespaces with Highest NPT Designs

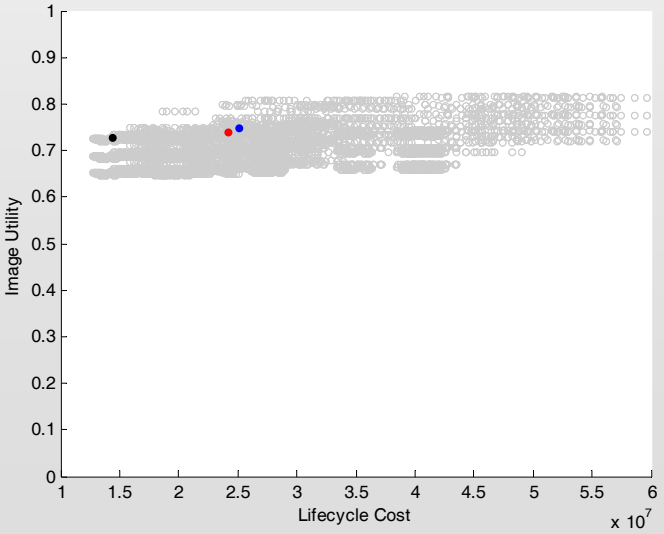


Black=3435 (NPT=0.7@K=0%)

Red=5067 (FNPT=1.0@K=5%)

Blue=7659 (FNPT=1.0@K=5%)





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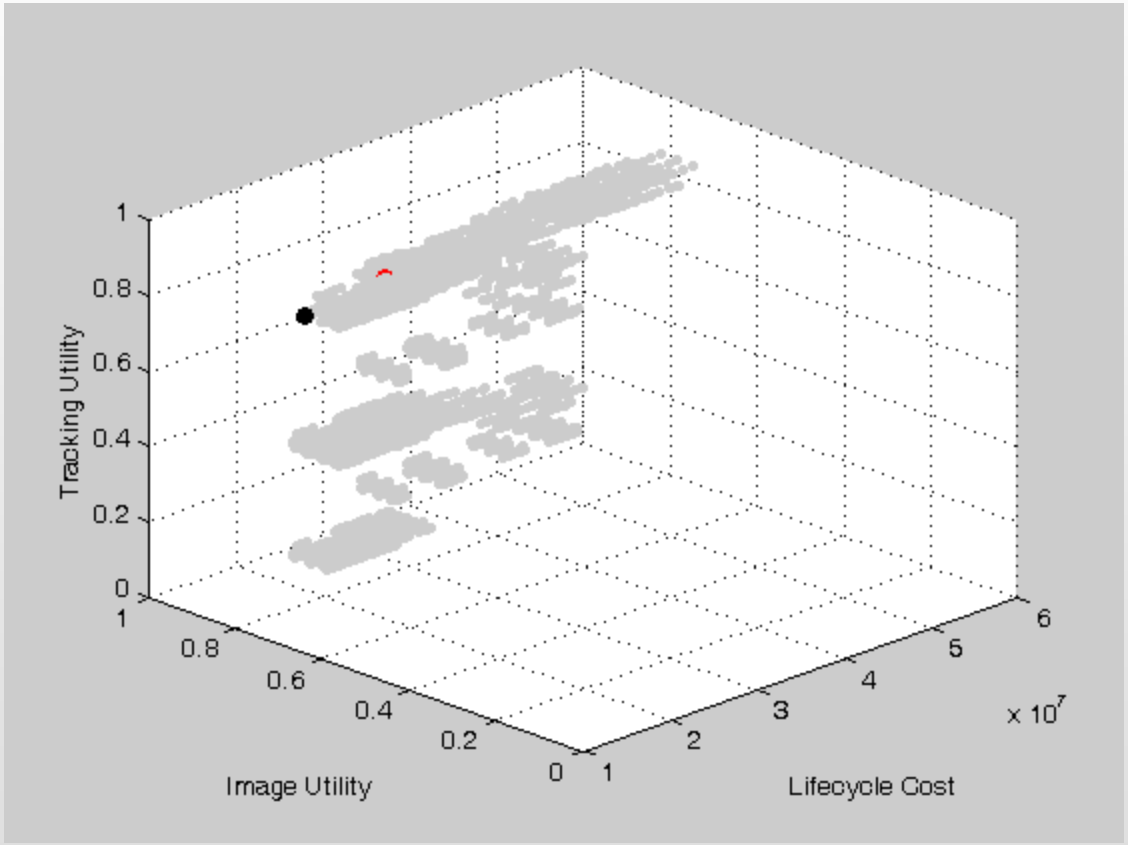
High NPT Designs in U-U-C Tradespace



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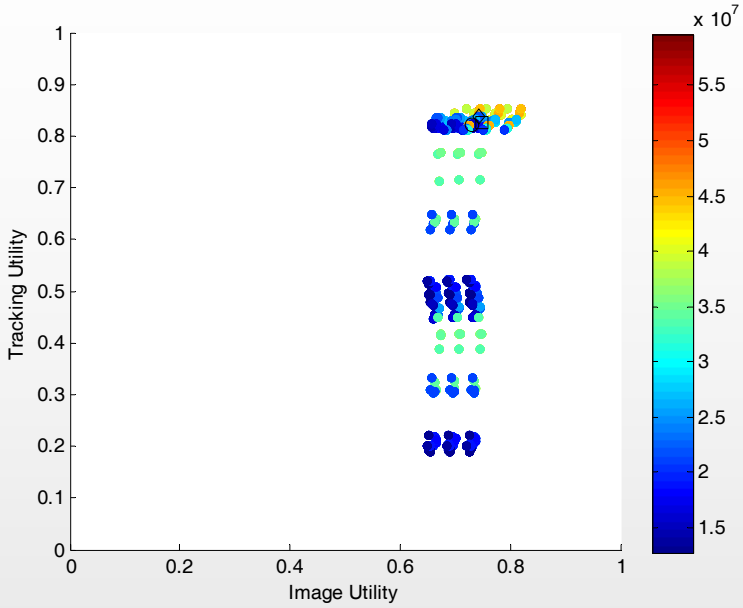
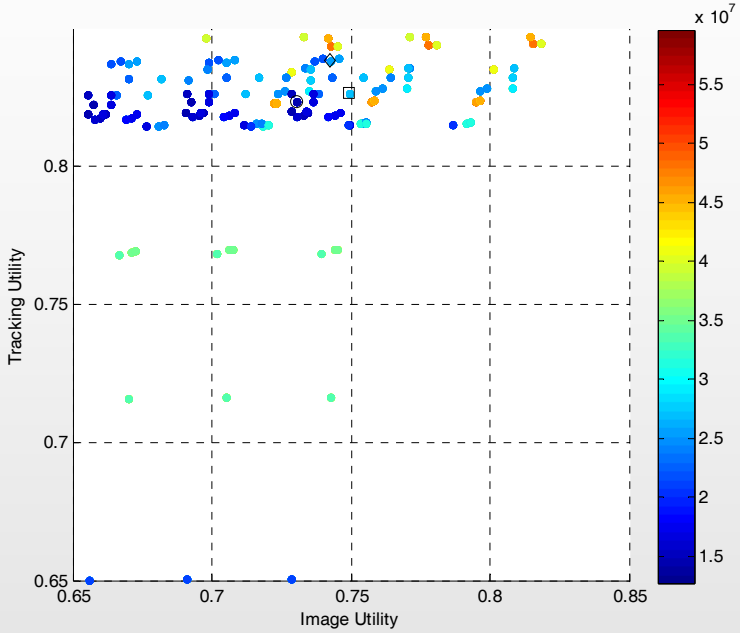
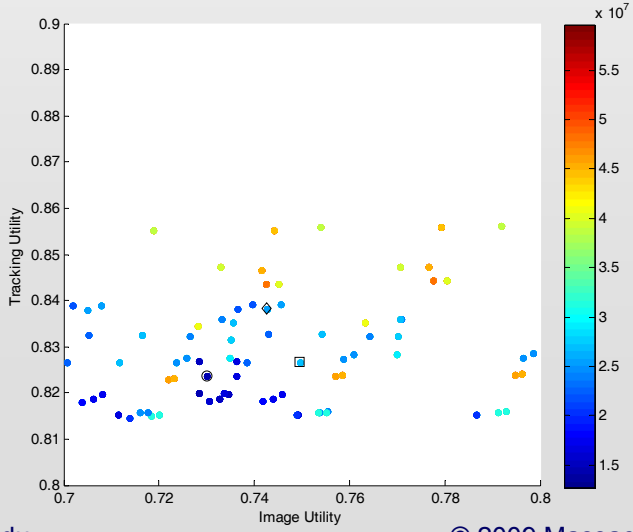
High NPT Designs in U-U-C Tradespace







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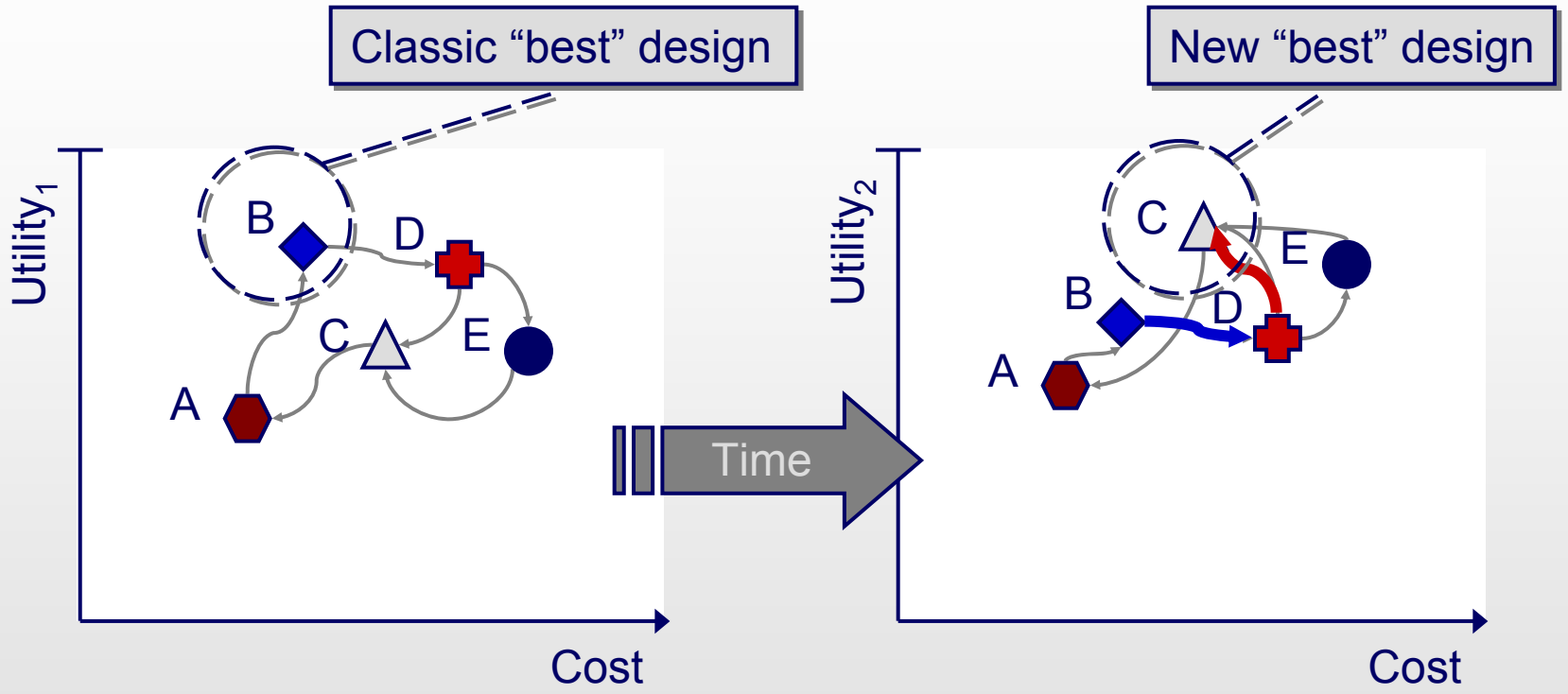
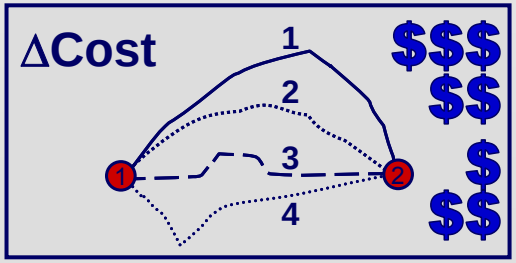
Tradespace Networks: Changing Designs over Time



Generate tradespace networks

Tradespace designs = nodes

Applied transition rules = arcs



"Best" designs in new contexts may differ; Changeability may provide opportunity

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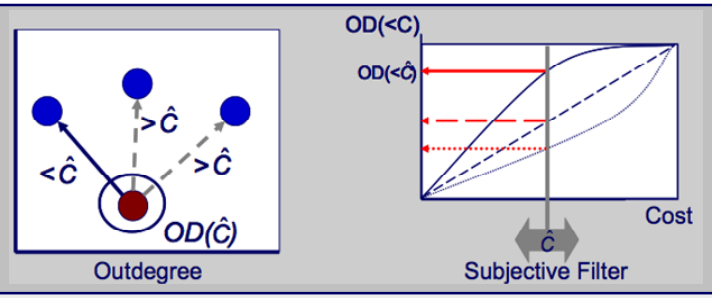
Calculating Filtered Outdegree to Uncover Changeable Designs

Filtered Outdegree

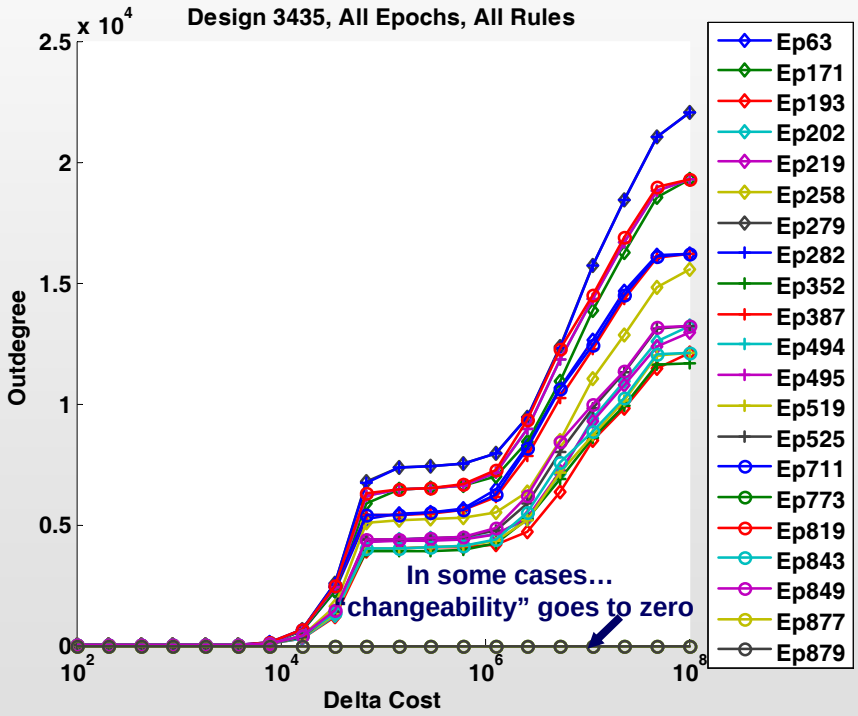
outgoing arcs from design at acceptable "cost" (measure of changeability)



Defined 8 System Transition Paths (Rules)

1. Redesign *(Design Phase)*
2. Redesign *(Build Phase)*
3. Redesign *(Test Phase)*
4. Add satellites to constellation *(Ops Phase)*
5. Alter altitude with on-orbit fuel *(Ops Phase)*
6. Alter altitude through tug *(Ops Phase)*
7. Alter inclination with on-orbit fuel *(Ops Phase)*
8. Alter inclination through tug *(Ops Phase)*

Variation in design "changeability" in response to context change



One can identify "changeable" designs and design choices (real options) by determining the filtered outdegree at a given acceptable transition "cost" threshold

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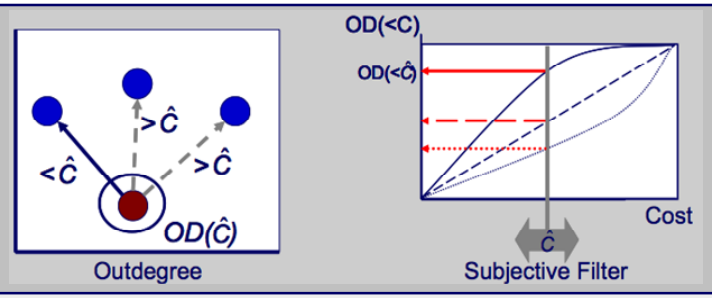
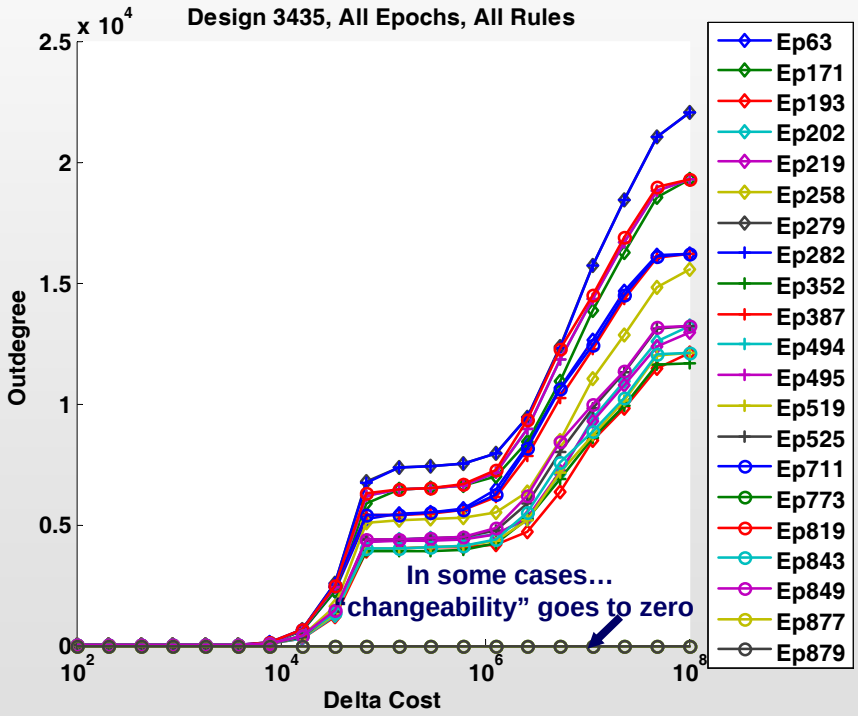
Calculating Filtered Outdegree to Uncover Changeable Designs

Filtered Outdegree

outgoing arcs from design at acceptable "cost" (measure of changeability)



Variation in design "changeability" in response to context change



Quantification and specification of "ilities" can be made explicit (*e.g.*, flexibility, adaptability, scalability, survivability, etc.)

One can identify "changeable" designs and design choices (real options) by determining the filtered outdegree at a given acceptable transition "cost" threshold

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