Systems Engineering: Bridging Industry, Government and Academia

The Tradespace Exploration Paradigm

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MIT

INCOSE International Symposium
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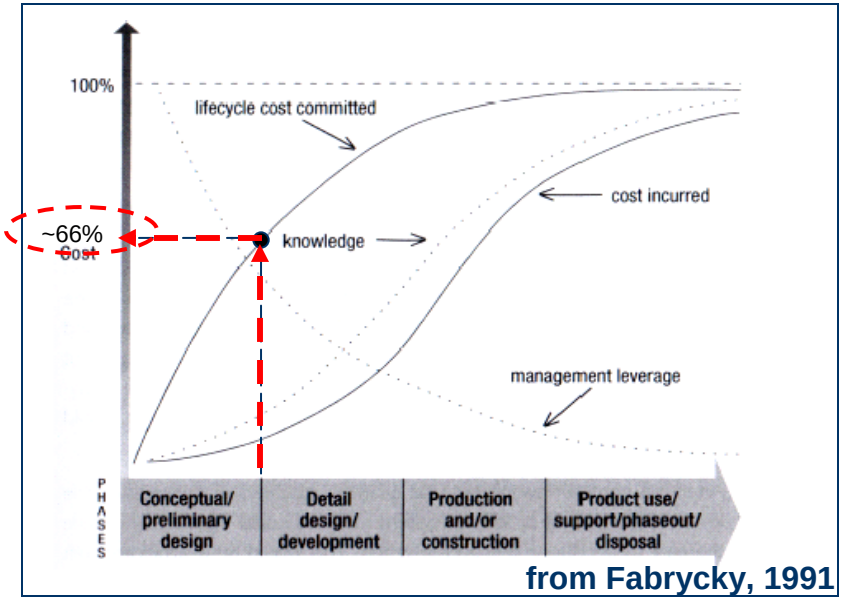
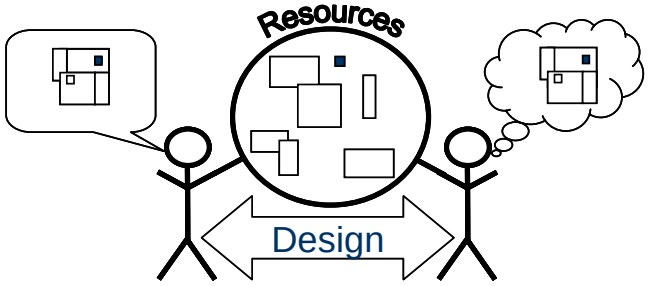
Motivation

Conceptual Design is a high leverage phase in system development

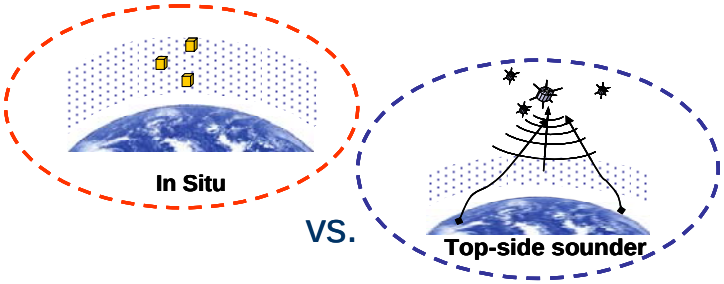


from Fabrycky, 1991

Need Captured



Resources Scoped



Concept Selected

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Glossary

- **Attribute.** A decision-maker perceived metric that measures how well a decision maker-defined objective is met
- **Decision Maker.** A type of stakeholder that has significant influence over defining system objectives or allocation of resources (DM)
- **Design Variables.** Designer controlled 'knobs' that represent aspects of the system concept
- **MATE-CON.** Multi-Attribute Tradespace Exploration with Concurrent Design couples *broad tradespace exploration* with *explicit decision maker value functions*
- **Tradespace.** The space spanned by the completely enumerated design variable set, often represented by (cost, utility) per DM
- **Utility.** Dimensionless parameter that reflects the 'perceived value under uncertainty' of an attribute; a 'rational' DM seeks to maximize utility
- **Value.** Like Beauty, perception of goodness (value) is often subjective

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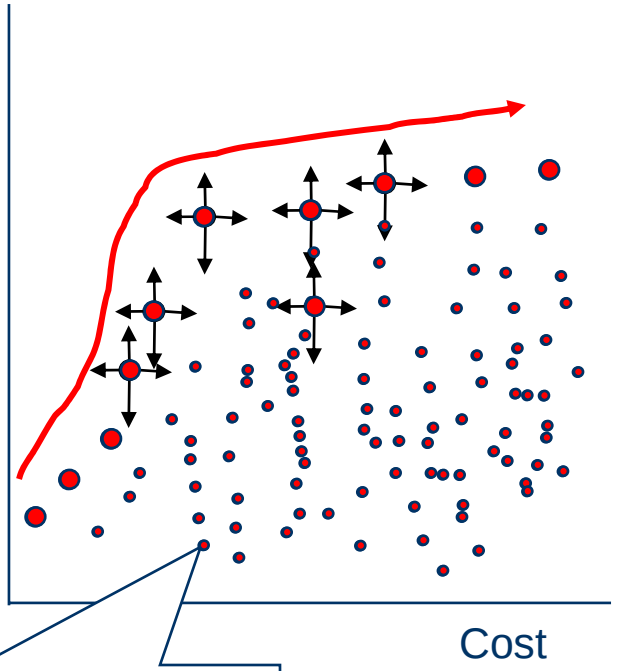
Avoiding Point Designs

Differing types of trades

1. Local point solution trades
2. Frontier subset solutions
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

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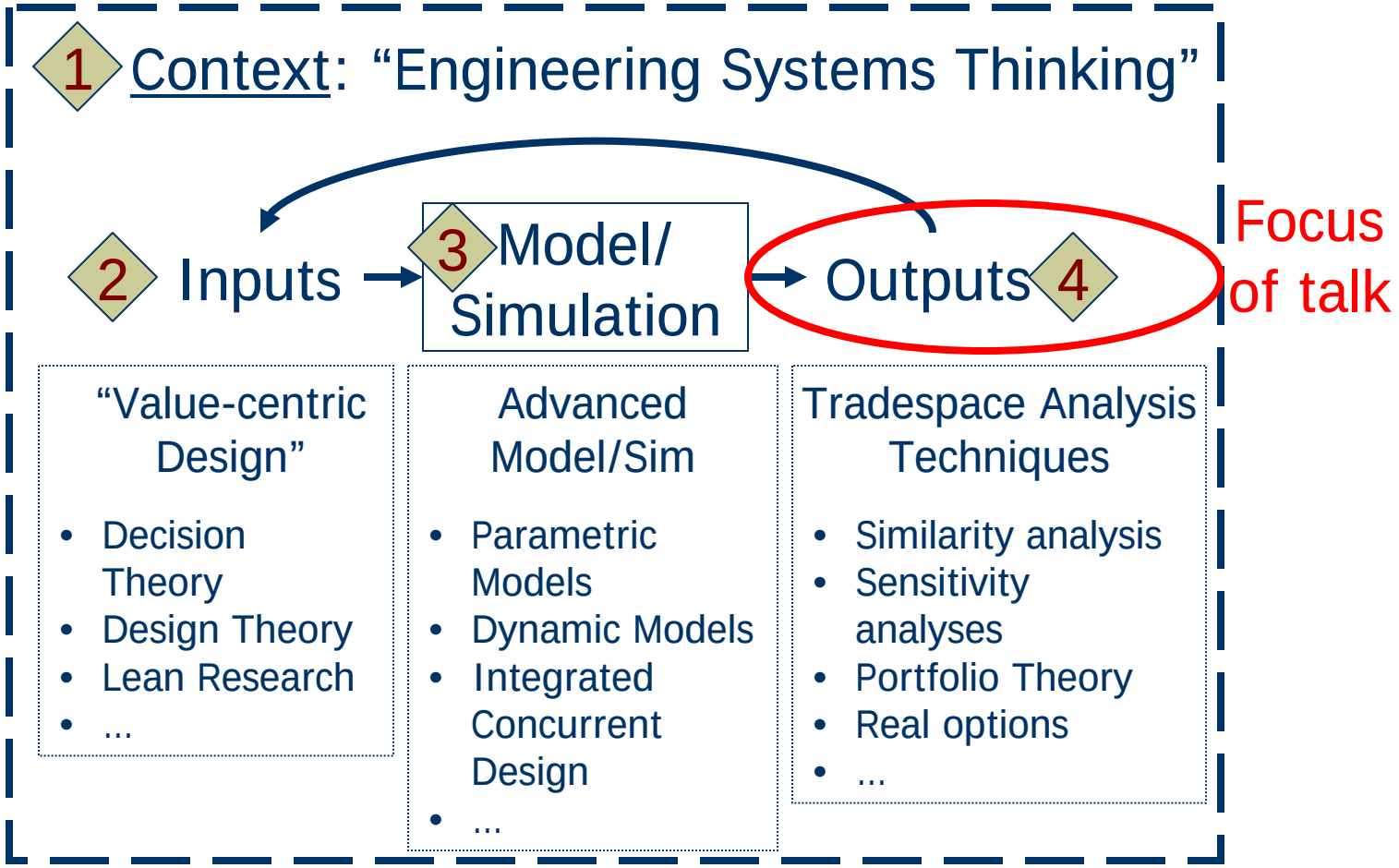
Multi-Attribute Tradespace Exploration



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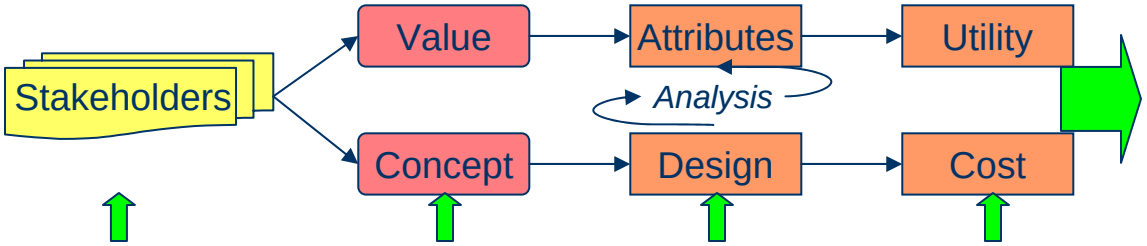
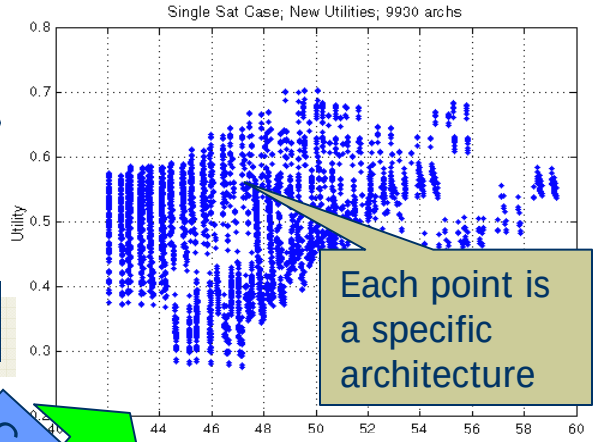
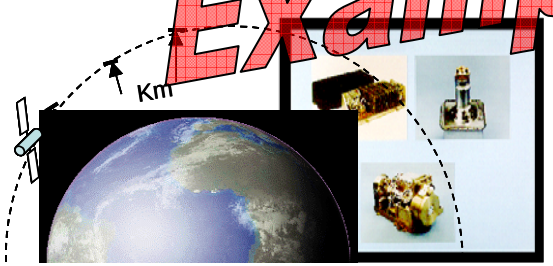
What is an Architecture Tradespace?





Tradespace: {Design,Attributes} ←→ {Cost,Utility}

X-TOS
Small low-altitude science mission



DESIGN VARIABLES:
Architectural trade parameters

Orbital Parameters
- Apogee Altitude (km)
- Perigee Altitude (km)
- Orbit Inclination (deg)

Spacecraft Parameters
- Antenna Gain
- Communication Architecture
- Propulsion Type
- Power Type
- Total Delta V

ATTRIBUTES:
Architectural decision metrics
- Data Lifespan (yrs)
- Equatorial Time (hrs/day)
- Latency (hrs)
- Latitude Diversity (deg)
- Sample Altitude (km)

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

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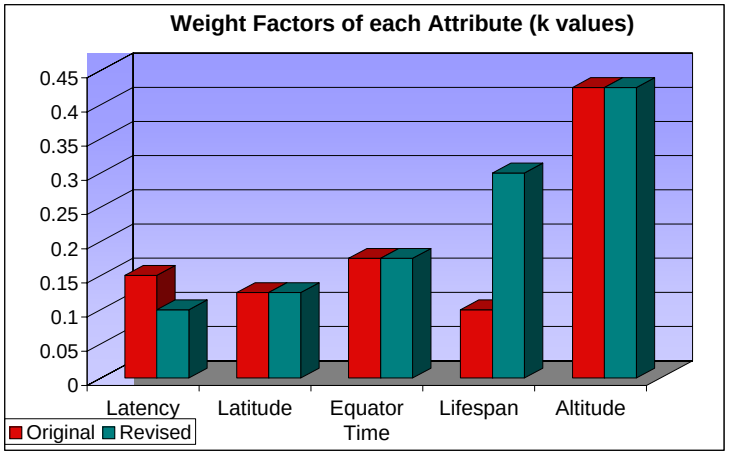
Insights: Δ "Rqmts" Easily Assessed

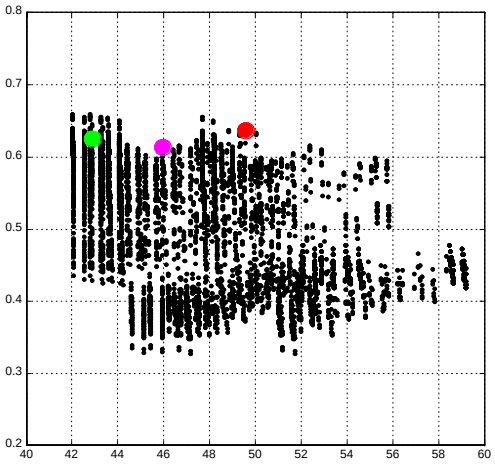


Architecture tradespace re-evaluated in less than one hour

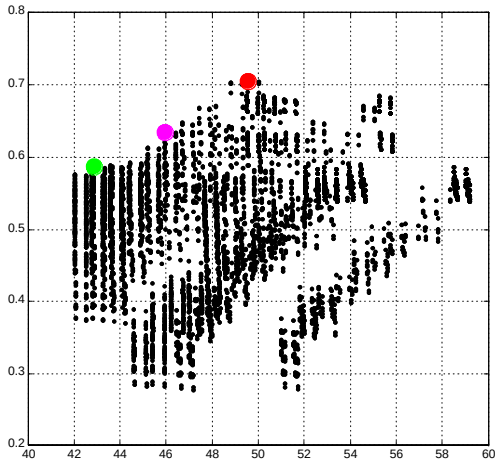
User changed preference weighting for lifespan

X-TOS

Original



Revised



From Ross, 2003

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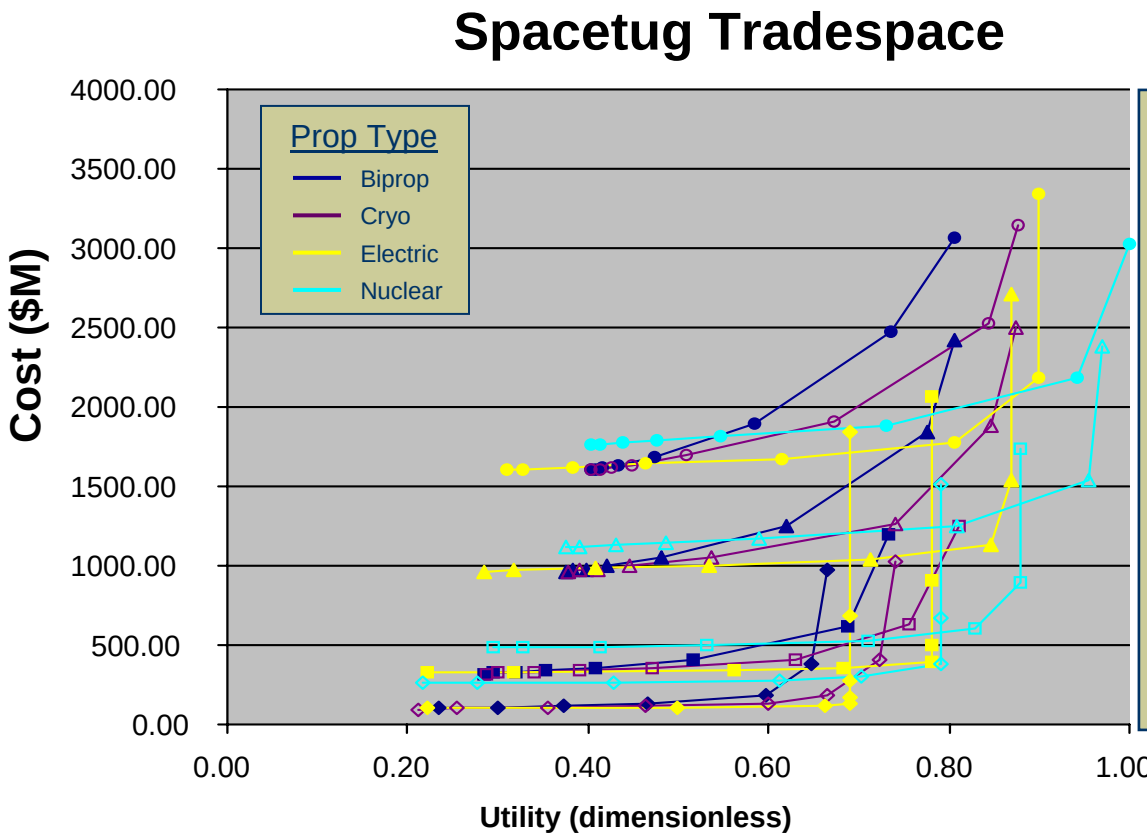
Insights: Understanding Limiting Physical or Mission Constraints



SPACETUG

- General purpose orbit transfer vehicles
- Different propulsion systems and grappling/ observation capabilities
- Lines show increasing fuel mass fraction

See McManus and Schuman, 2003

Hits “wall” of either physics (can’t change!) or utility (can)

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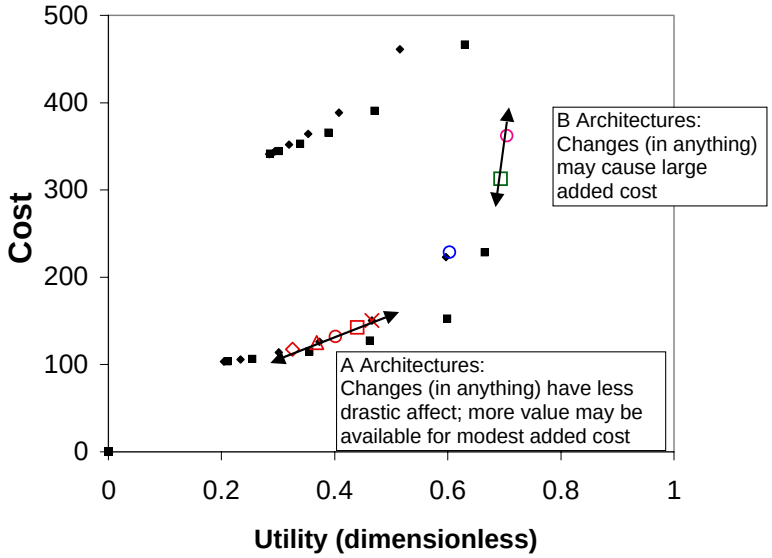
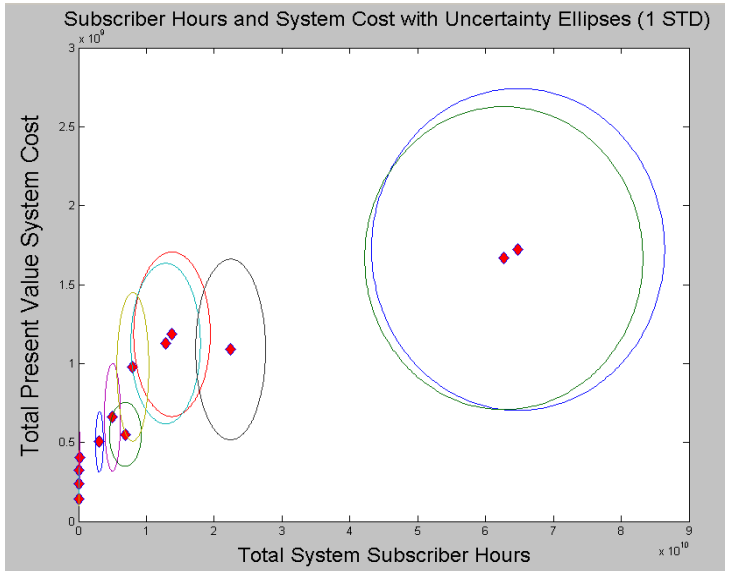
Tradespace Exploration w/ Uncertainty





From Walton, 2002

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

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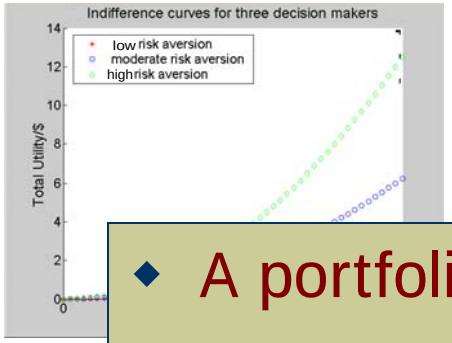
Portfolio Analysis: 3 DM's



Uncertainty in the High Risk Aversion Portfolio is less than each of its assets

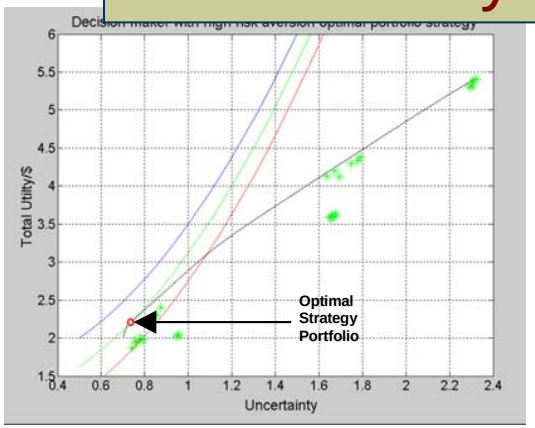
Risk "covered" by investment in small system that only does one mission

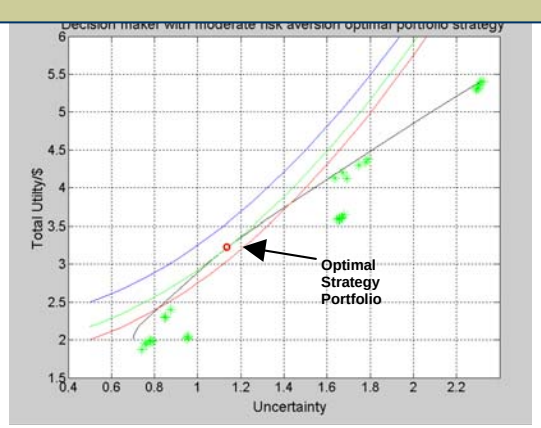
- A portfolio is investment in multiple designs
- *If designs are anticorrelated with respect to uncertainties*, portfolios can have lower uncertainty than individual designs

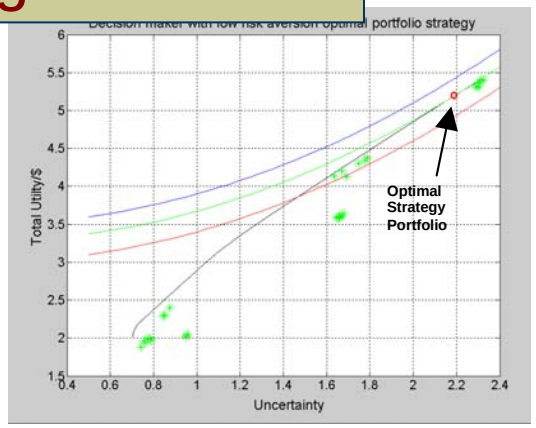
folio contains
. Highest TU/$)

on

Percentage of Portfolio				Total Utility/$	Uncertainty
52%				5.4	2.3
48%				4.2	1.7
100%				5.2	2.2







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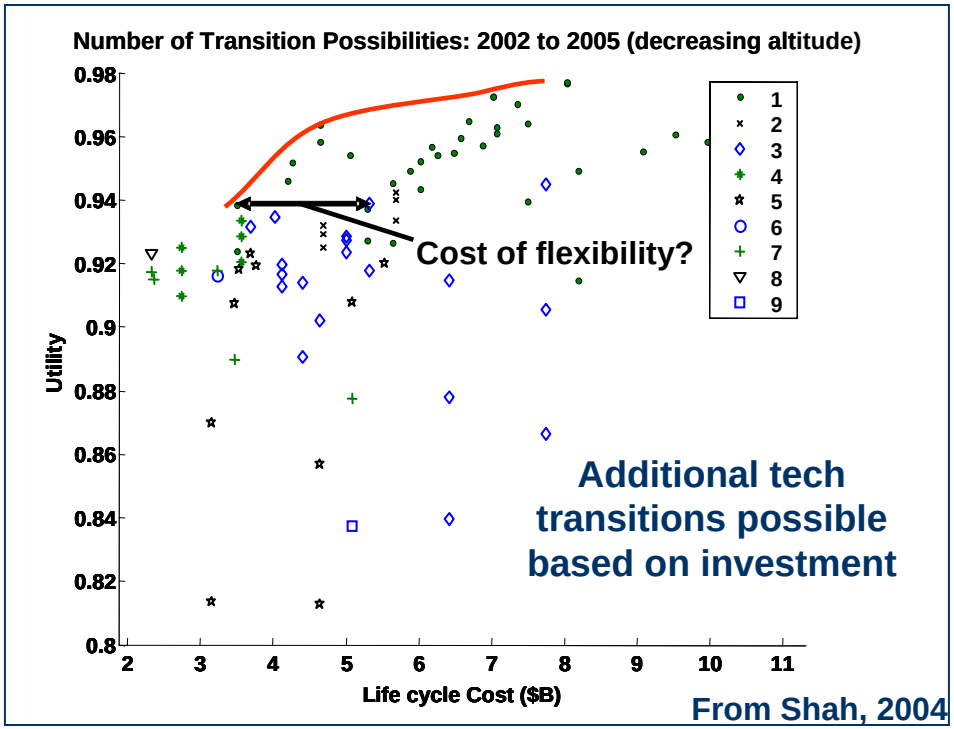
From Walton, 2002

Flexibility Over Time: SBR

Technology and Programmatic Flexibility Over Time for Space-Based Radar (SBR)



- "Transitionability" relates to "distance" between architectures
- Transition costs vary widely based on transition path
- "Optimality" not defined when fitness function changes over time

Pareto Front may not provide best answers

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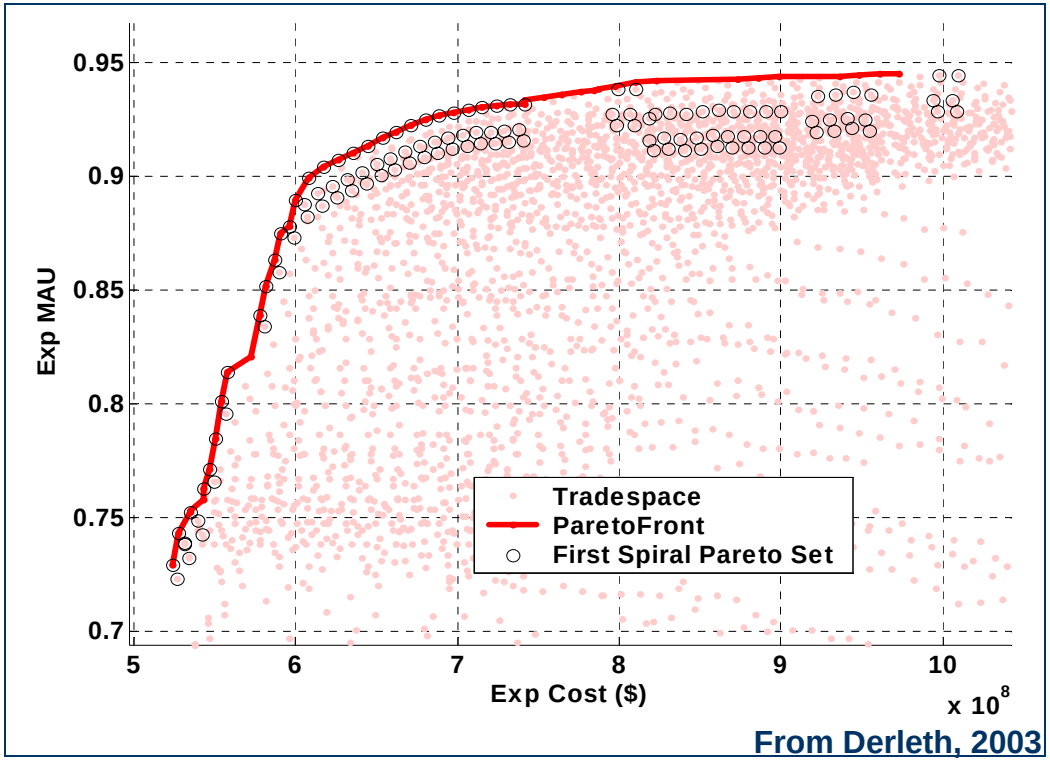
Application: Spiral Development

Evolution of Capability in Second Spiral for Small Diameter Bomb



From Derleth, 2003

- Pareto set differentiates over time
- Marginal cost versus rank statistics reveal best "baselines"

System concept is a small, airplane-carried bomb
Spiral two adds new attributes to utility function

Tradespace gives insights in planning for spiral development

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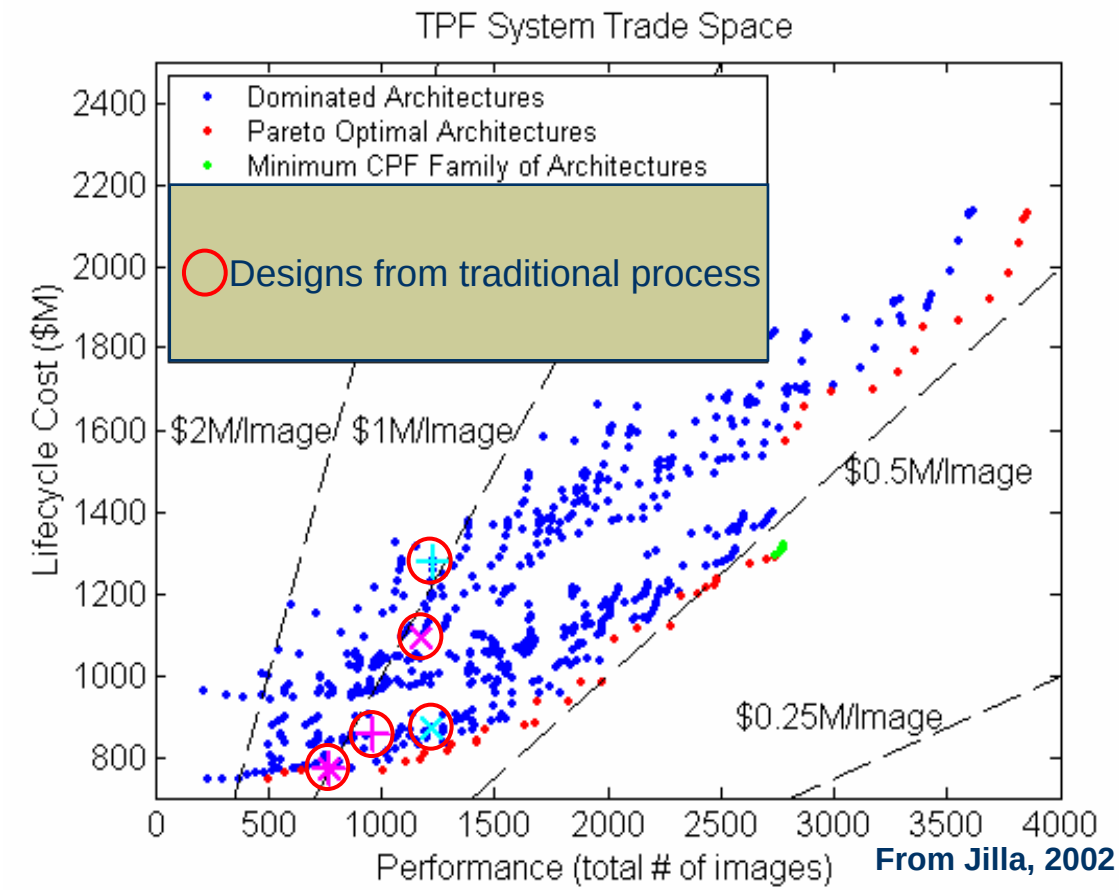
Application: Comparing Point Designs



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]

Existence of dominated point designs focus discussion

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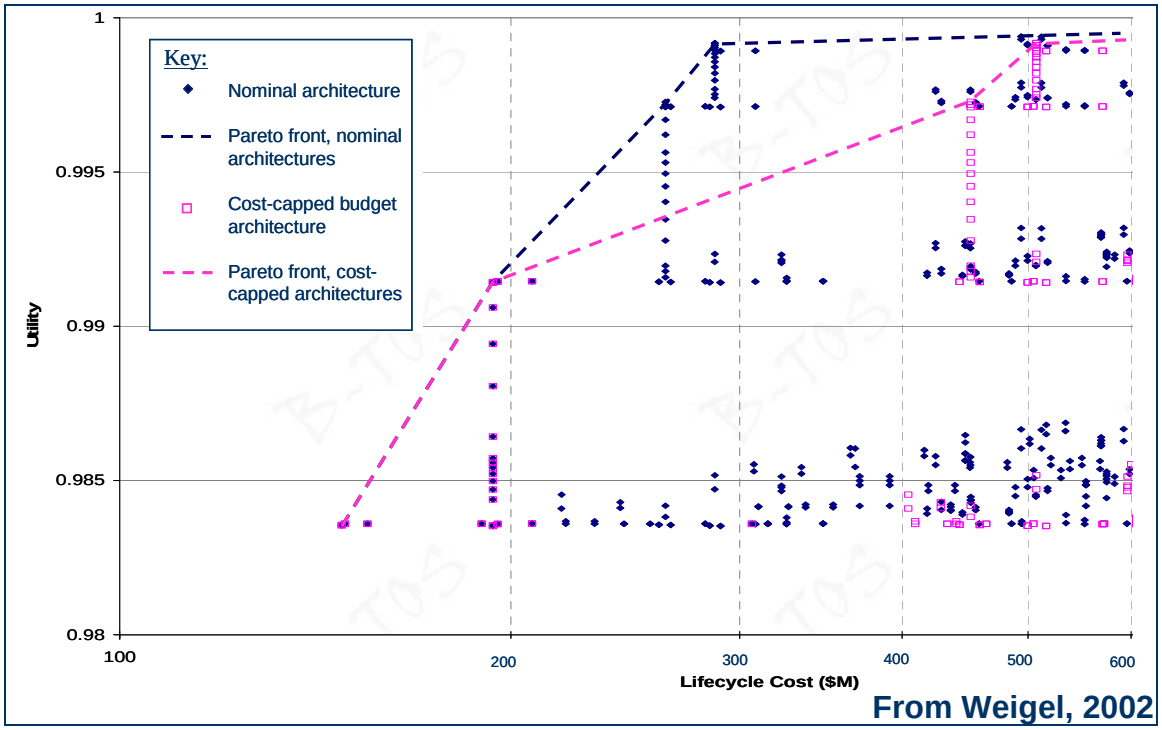
Application: Budget Cap Policy

Policy Intervention: $35M Annual Program Budget Cap Imposed by Congress



From Weigel, 2002

- Policy results in differential cost increases
- Policy-robust points remain in Pareto set

System concept is a satellite swarm that samples Earth's ionosphere

Cost-capping policy pushes Pareto Front to the right

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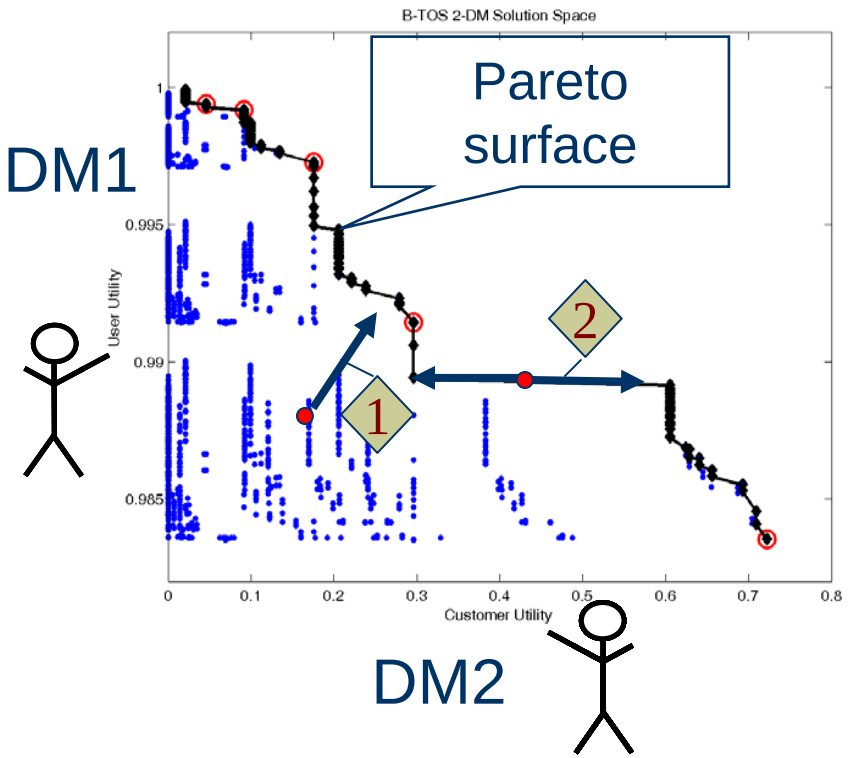
Application: Multi-DM Negotiation

Multiple Decision Maker Tradespace



- In general, no optimum solution to problem with multiple stakeholders having conflicting needs (See Arrow's Impossibility Theorem in Hazelrigg, 1996)
- Tradespace aids negotiation
  1. Finding the win-win changes (moving toward Pareto front)
  2. Finding the real trades (along the Pareto front)
- Negotiation advantage for stakeholders who understand tradespace

Explicit value conflict and congruity become apparent in tradespace

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Conclusion

- Tradespace exploration is a unified framework that enables...
  - Consideration of diverse and dynamic value functions
  - Comparison of diverse and dynamic concepts
  - Characterization and mitigation of various uncertainties
  - Quantification of system properties (e.g., flexibility, robustness)
- Applications have included: policy sensitivity analysis, spiral development, cross-proposal evaluation
- On-going research seeks to standardize TSE, including theory, method and applications

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Citations

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