Revisiting the Tradespace Exploration Paradigm: Structuring the Exploration Process

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Track 40-MIL-2: Technology Transition
AIAA Space 2010

Outline

- Introduction
- Advances in Tradespace Exploration
- Question-guided TSE
- Discussion
- Conclusion

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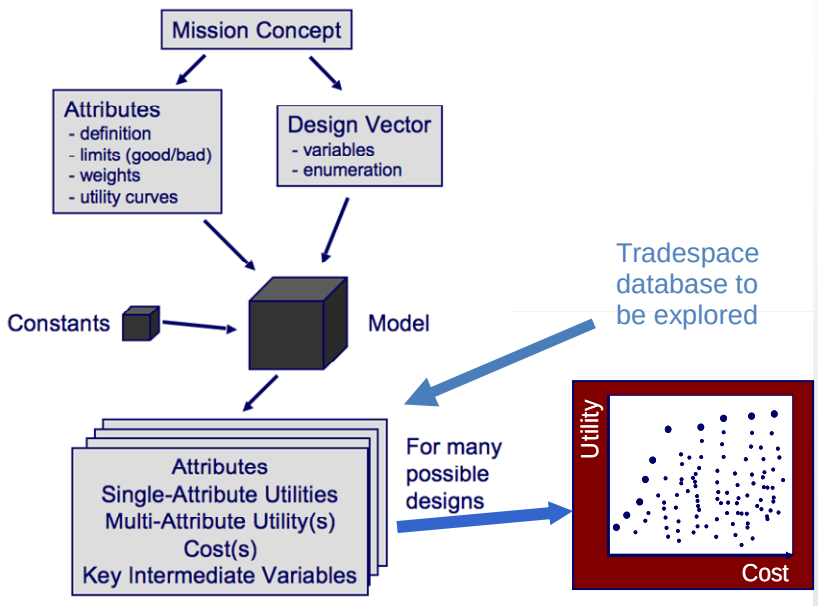
Introduction

- Early design process is high leverage, with consequences for achievable benefits and cost goals
- Early design is rife with uncertainty and possibilities as well, making "good" decisions more difficult
  - Many possible designs
  - Many possible (changing?) needs and stakeholders
  - New (changing?) technology
  - New contexts (and missions)



- 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)

Value-based assessments allow for comparison of many different alternatives

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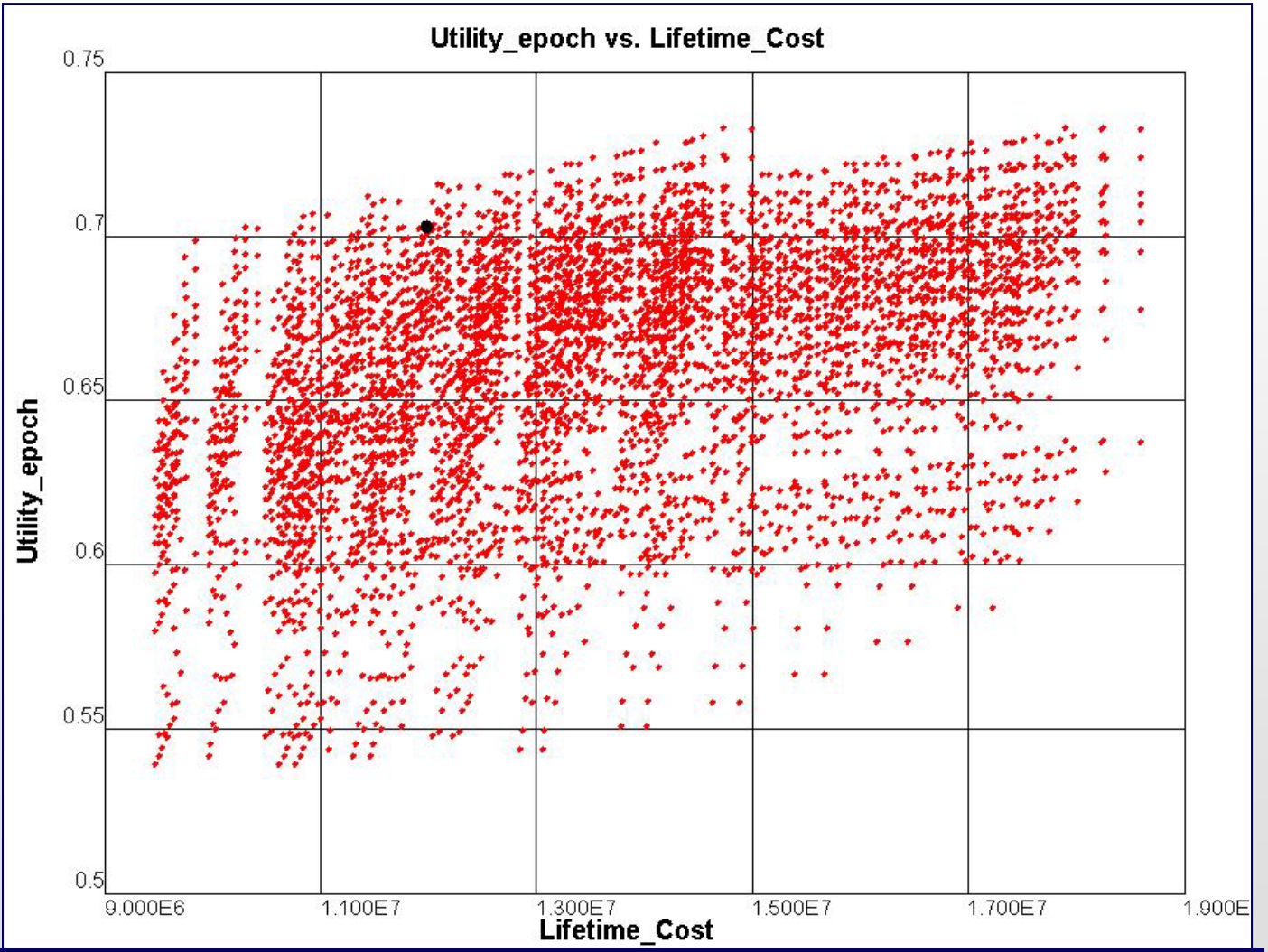
Tradespace Data Representation

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

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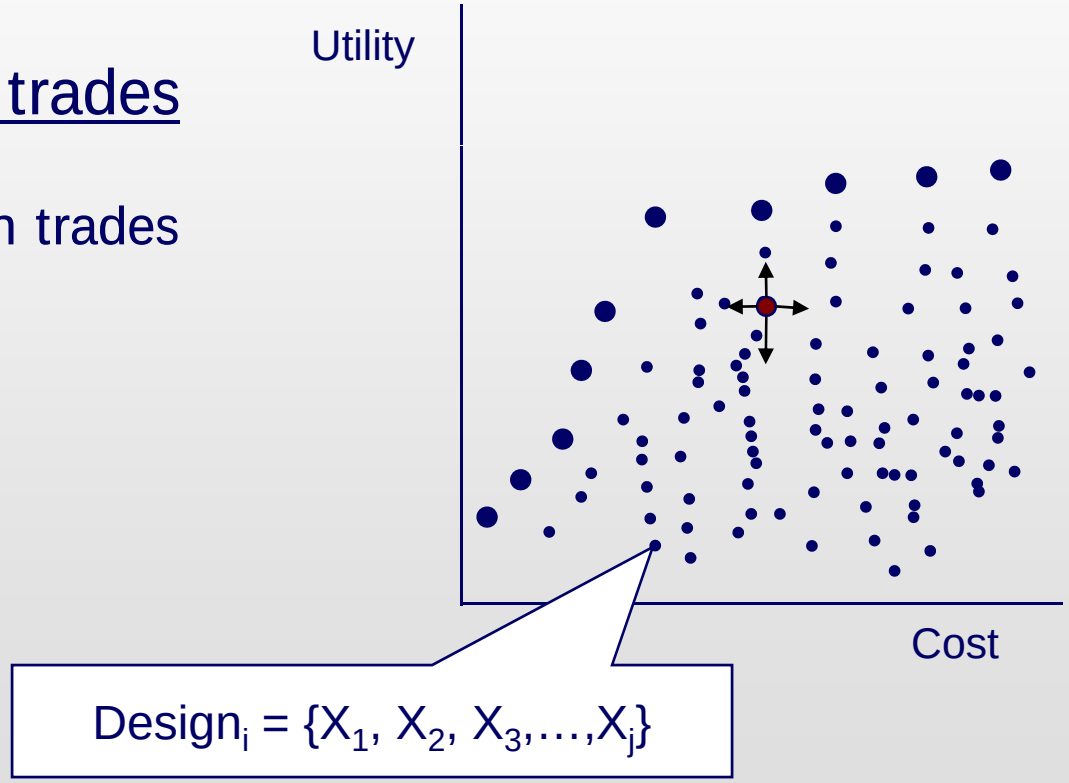
Tradespace Exploration Paradigm: Avoiding Point Designs (2005)

Ross, A.M. and Hastings, D.E., "The Tradespace Exploration Paradigm," INCOSE International Symposium 2005, Rochester, NY, July 2005.

Differing types of trades

1. Local point solution trades



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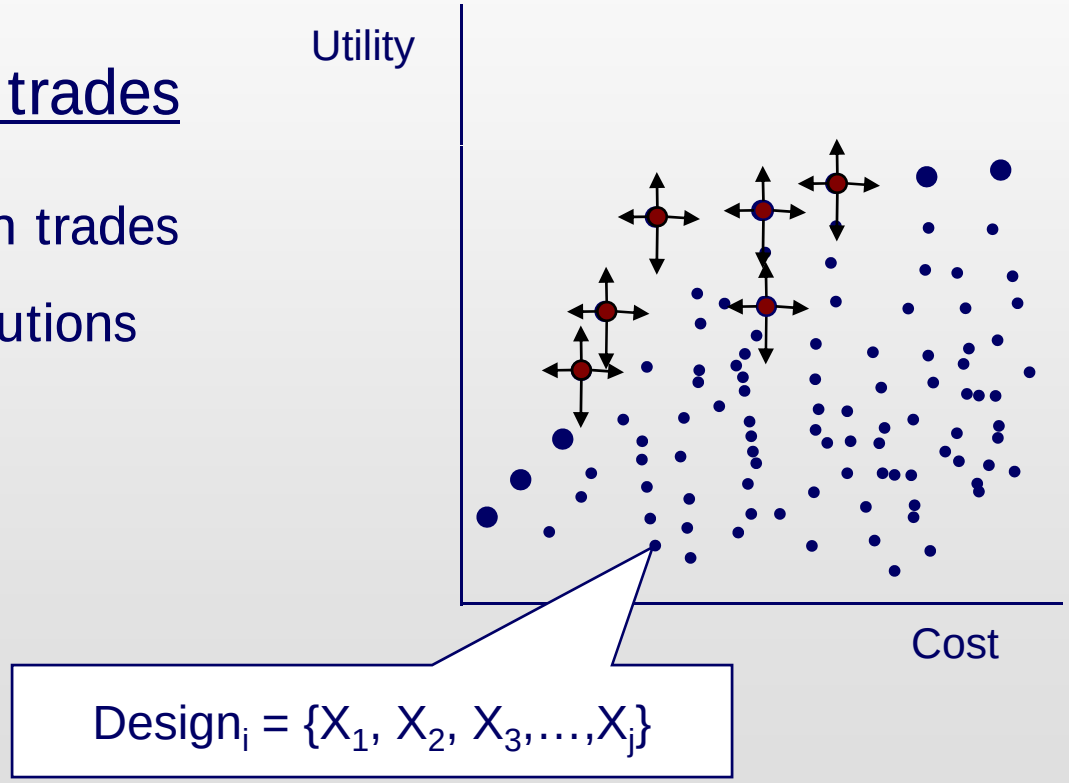

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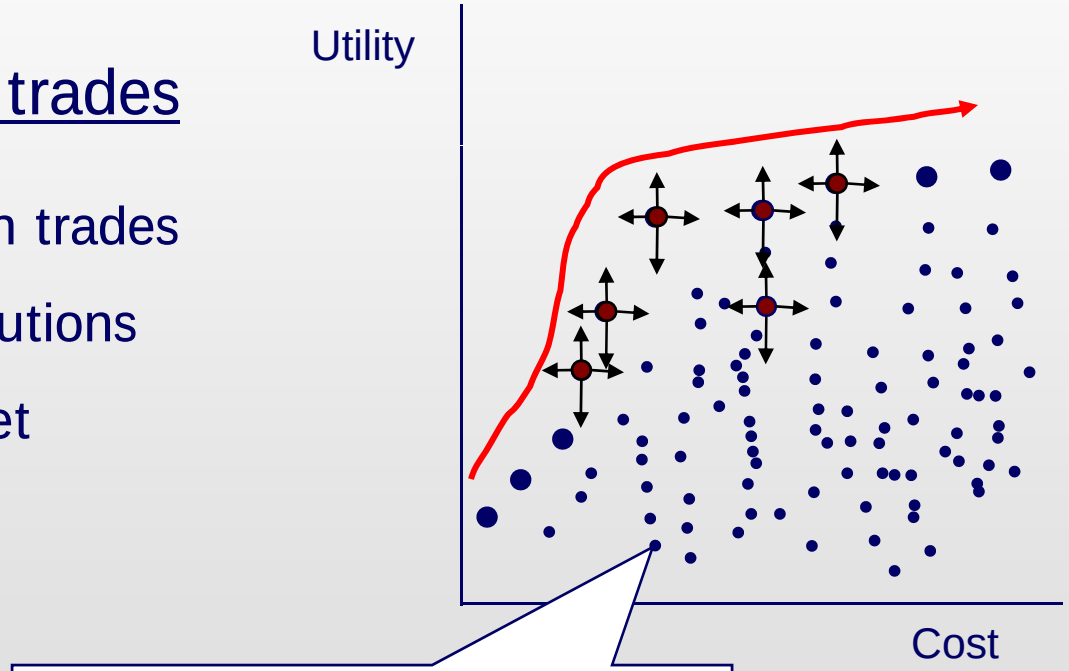

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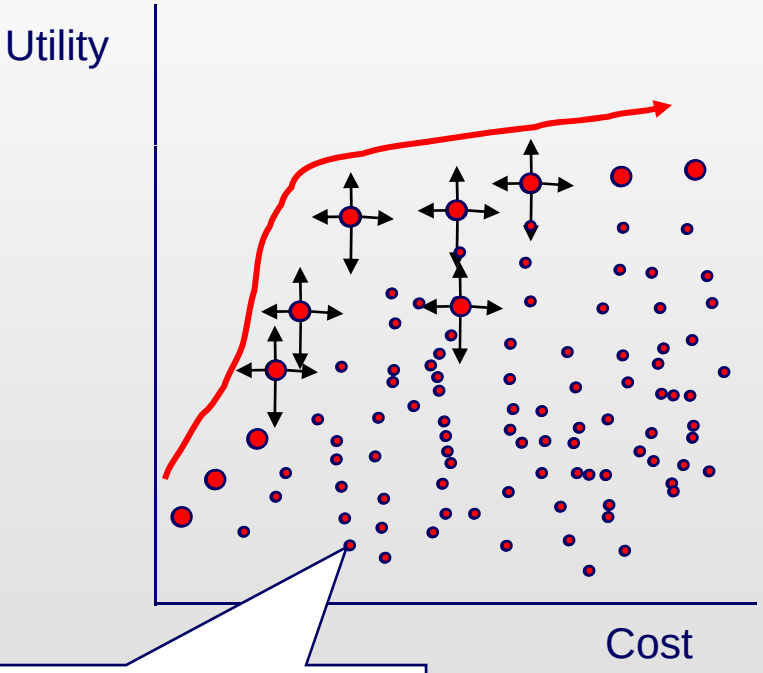
Differing types of trades

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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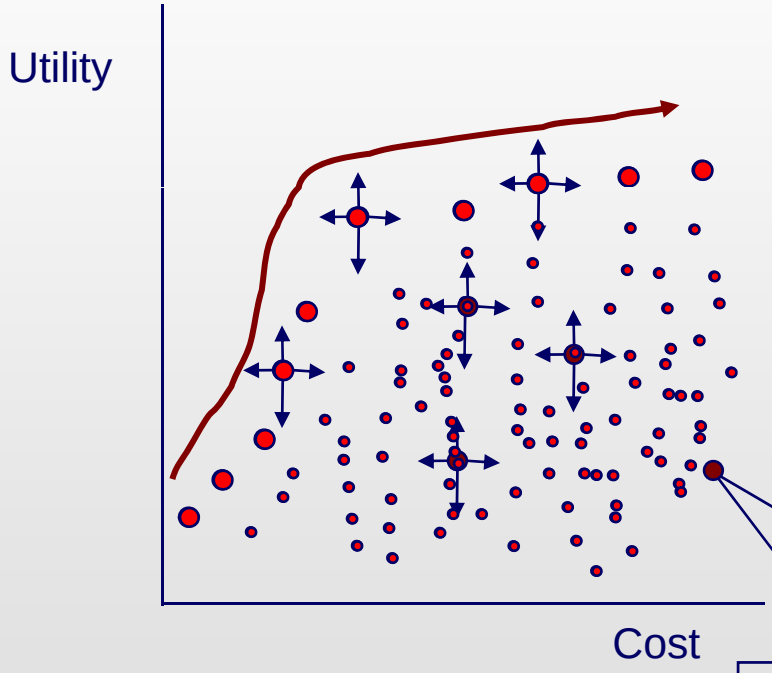
Tradespace Exploration Paradigm: Avoiding Point Designs (2010)



Differing types of "trades"

0. Choose a solution
1. Local point solution trades
2. Multiple points with trades
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4. Full tradespace exploration

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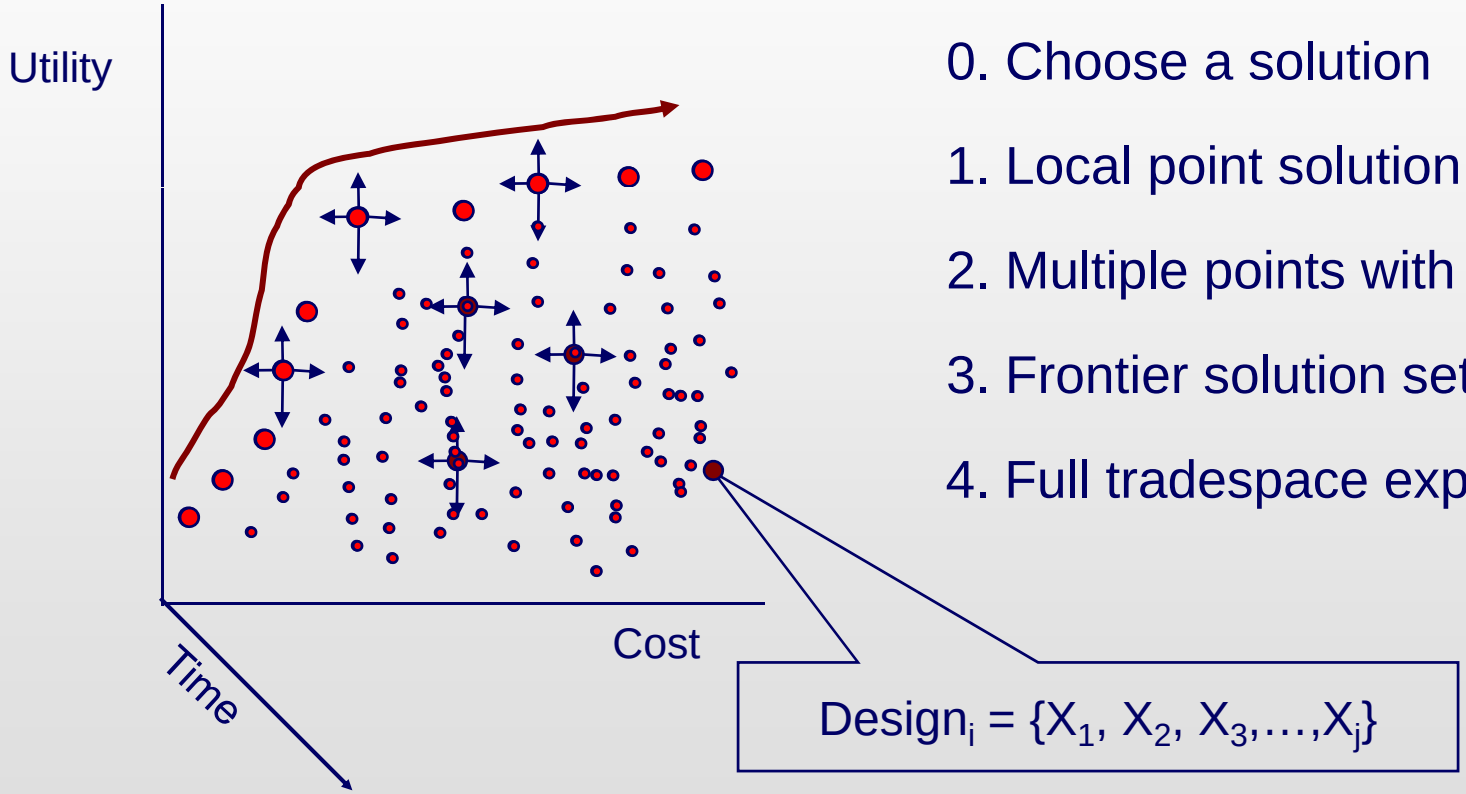

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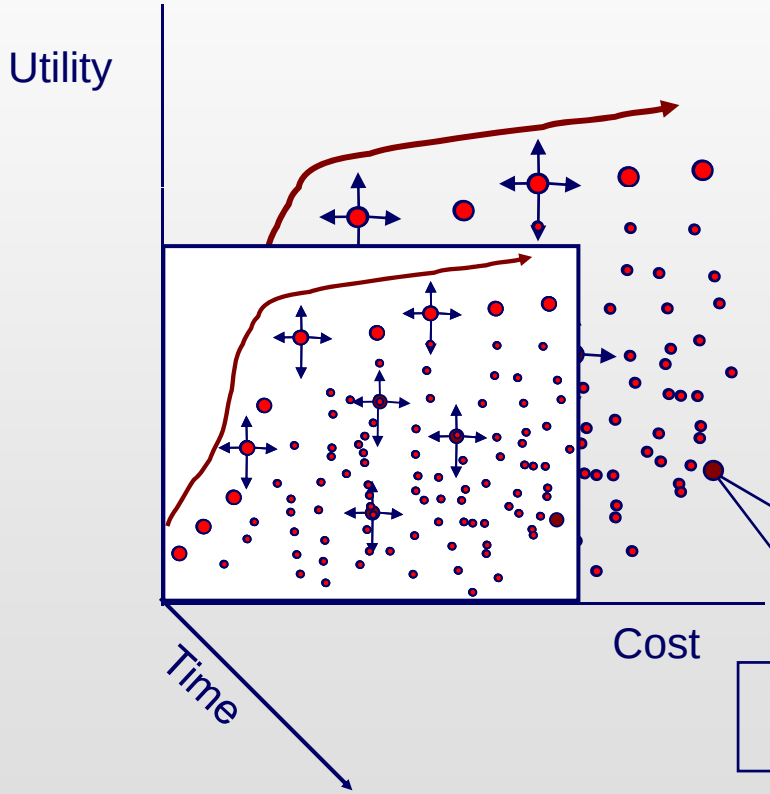

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Differing types of "trades"

0. Choose a solution
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Tradespace exploration enables big picture understanding

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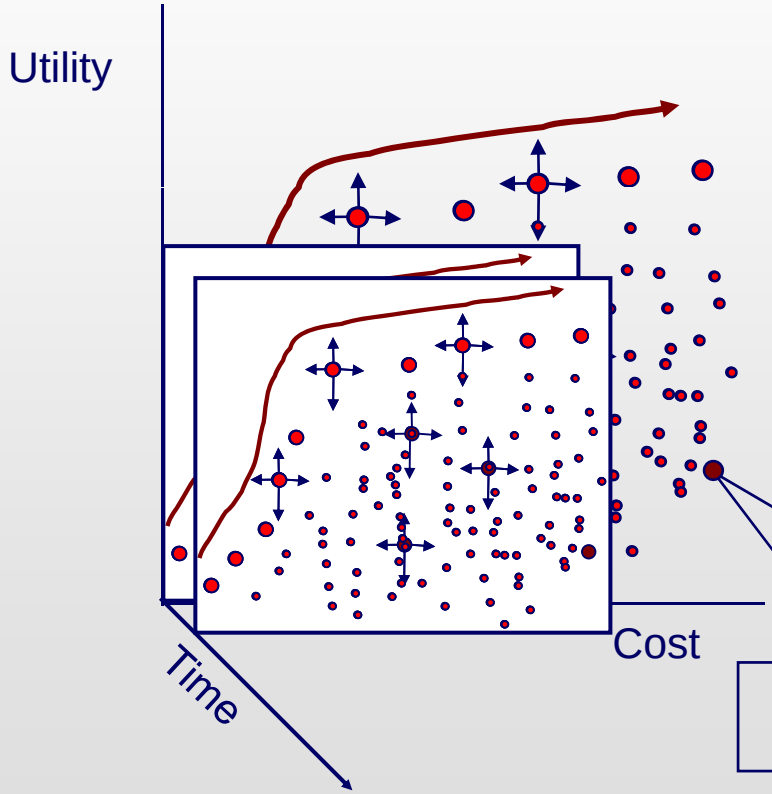

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Differing types of "trades"

0. Choose a solution
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Tradespace exploration enables big picture understanding

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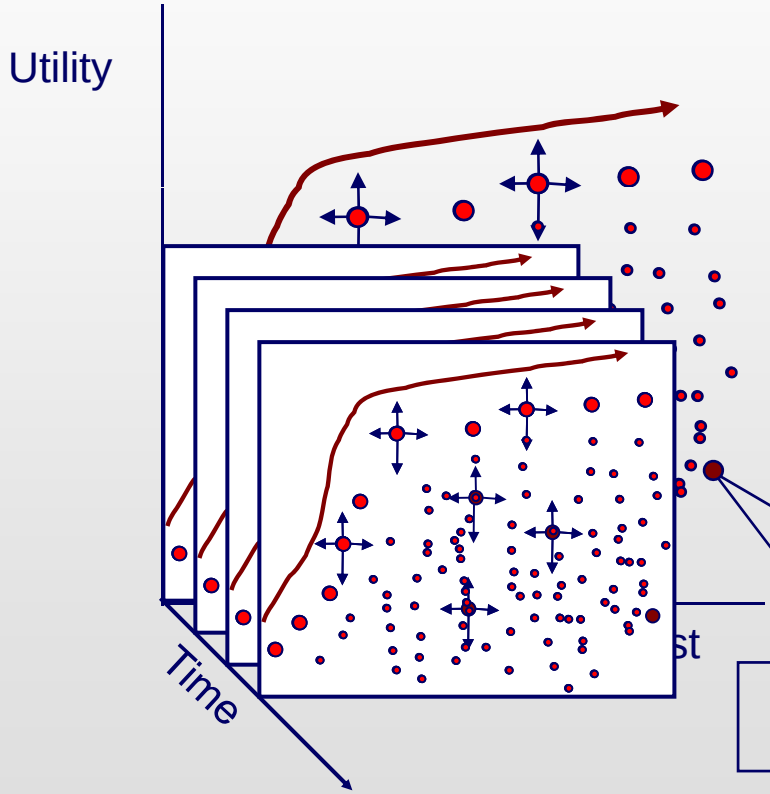

Design$_i$ = {X_1, X_2, X_3,…,X_j}

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
5. Many tradespace explorations

Tradespace exploration enables big picture understanding

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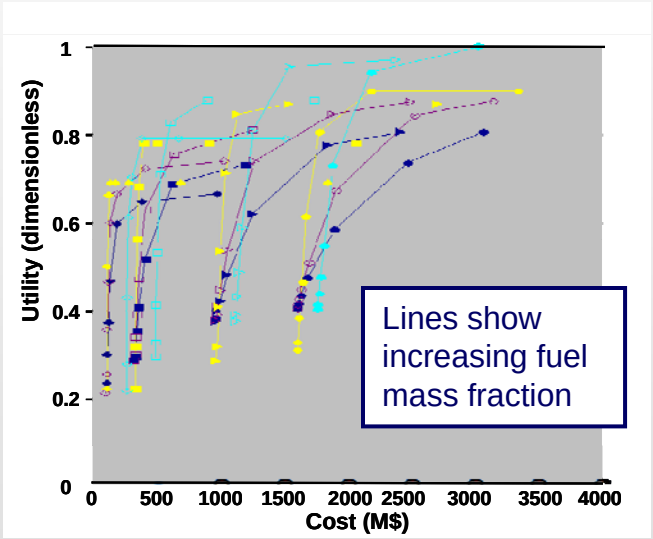
Example Tradespace Insights

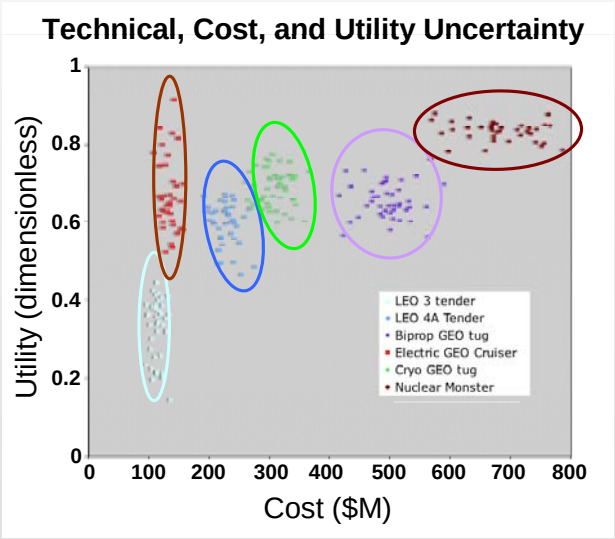
SPACETUG
- General purpose orbit transfer vehicles
- Trades propulsion systems and grappling/observation capabilities

Understanding limiting physical or mission constraints



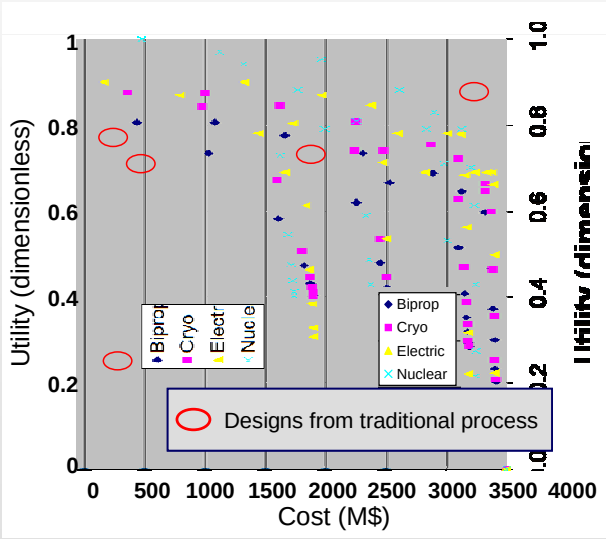
Hits "wall" of either physics (can't change) or utility (can)

Understanding differential uncertainty



Different designs subject to different risks

Comparing alternatives on common basis



Common "value" definition can compare old and new heterogeneous systems

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Multi-Concept Operationally Responsive Disaster Surveillance

Chattopadhyay, D., Ross, A.M., and Rhodes, D.H., "Demonstration of System of Systems Multi-Attribute Tradespace Exploration on a Multi-Concept Surveillance Architecture," 7th Conference on Systems Engineering Research, Loughborough University, UK, April 2009.

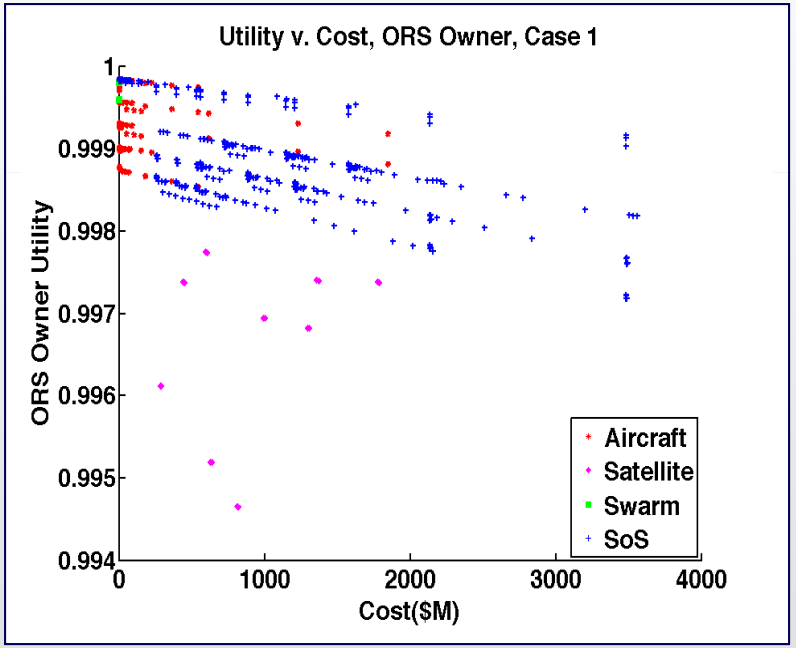
Design Concepts

- Aircraft
- Satellite
- Sensor Swarm
- **SoS designs** consisting of any two of above

Stakeholders

Firefighter

ORS Owner



Diverse concepts can be compared on same basis; satellites only make sense if costs can be amortized over many disasters…

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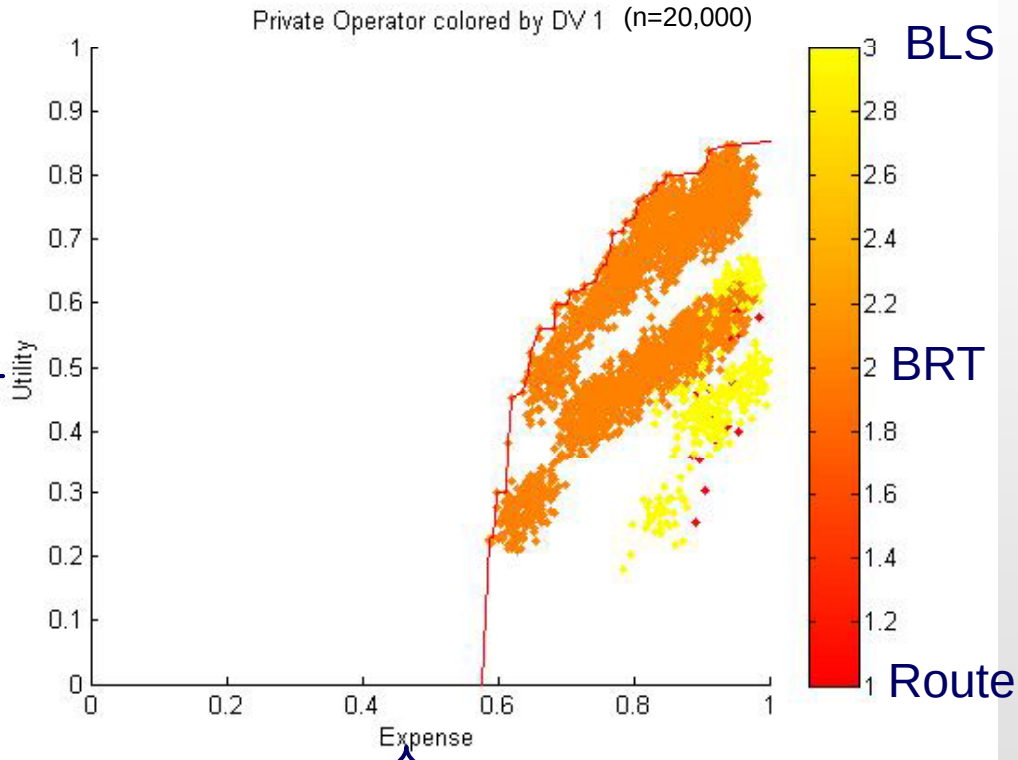
Transportation Planning

Nickel, J., "Using Multi-Attribute Tradespace Exploration for the Architecting and Design of Transportation Systems," Master of Science Thesis, *Engineering Systems Division*, MIT, Cambridge, MA, February 2010.

- **Freedom to make changes**
- **Competition agreements**
- **QOS:**
  - **Fare level**
  - **Frequency**
  - **Travel time**
  - **Amenities**
  - **Span of service**



BLS

BRT

Route 2

- **Operating costs**
- **Concession payment**

Prematurely focusing on point solutions is not unique to aerospace!

Route 2 (dominated) is the only concept planners had initially considered

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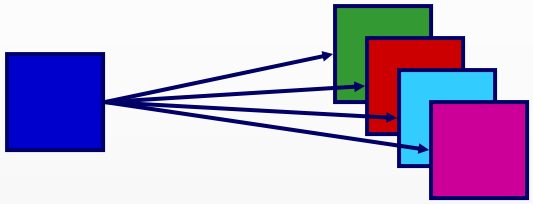
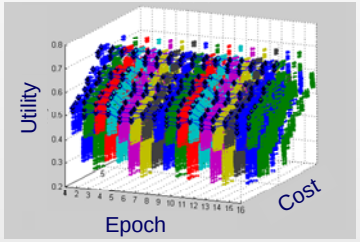
Tradespaces Over Time



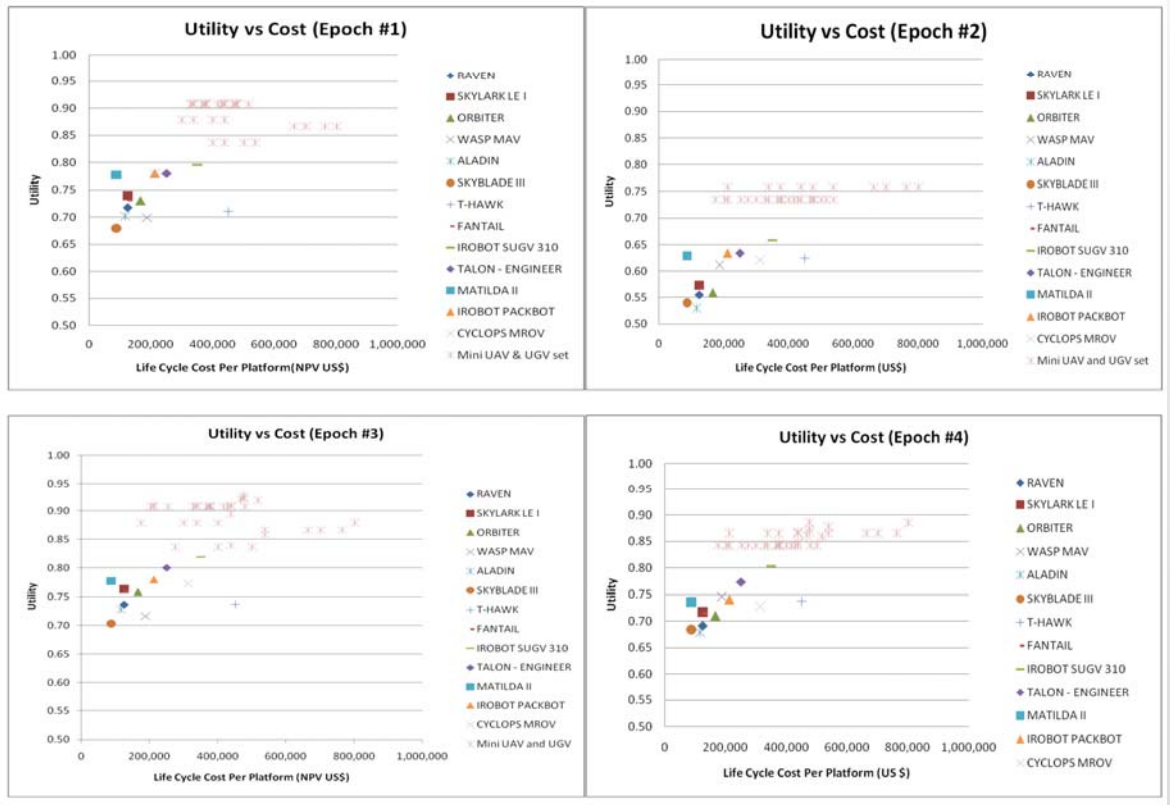
Today Possible futures (epochs)

Koo, C.K.K., "Investigating Army Systems and Systems of Systems for Value Robustness," Master of Science in Engineering Management, *System Design and Management Program*, MIT, Cambridge, MA, February 2010.



Demonstrations

- Diverse set of "point designs" compared on common basis
- Many tradespaces evaluated over changing contexts (e.g., technology levels) and needs (e.g., missions and utilities)
- Allows for identification of alternatives robust against uncertainties revealed over time



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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

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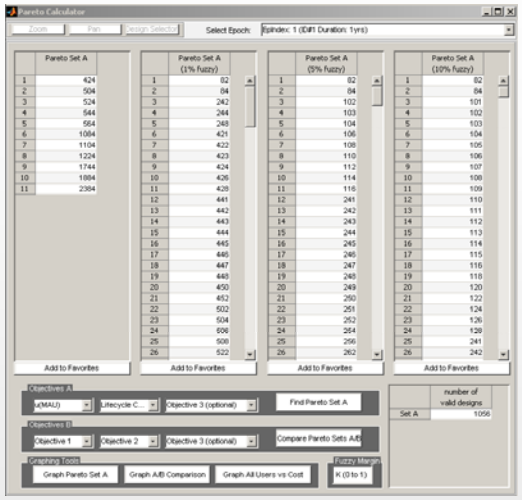
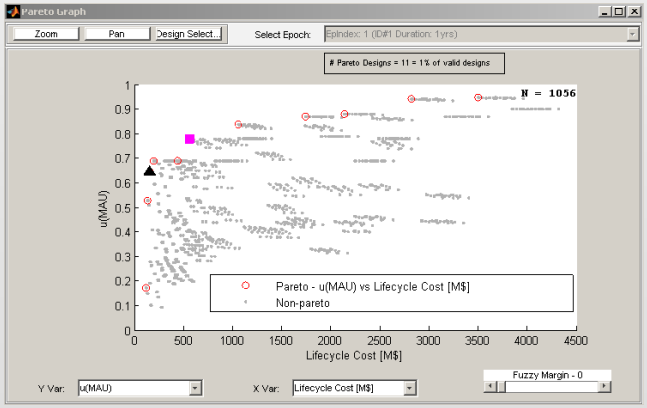
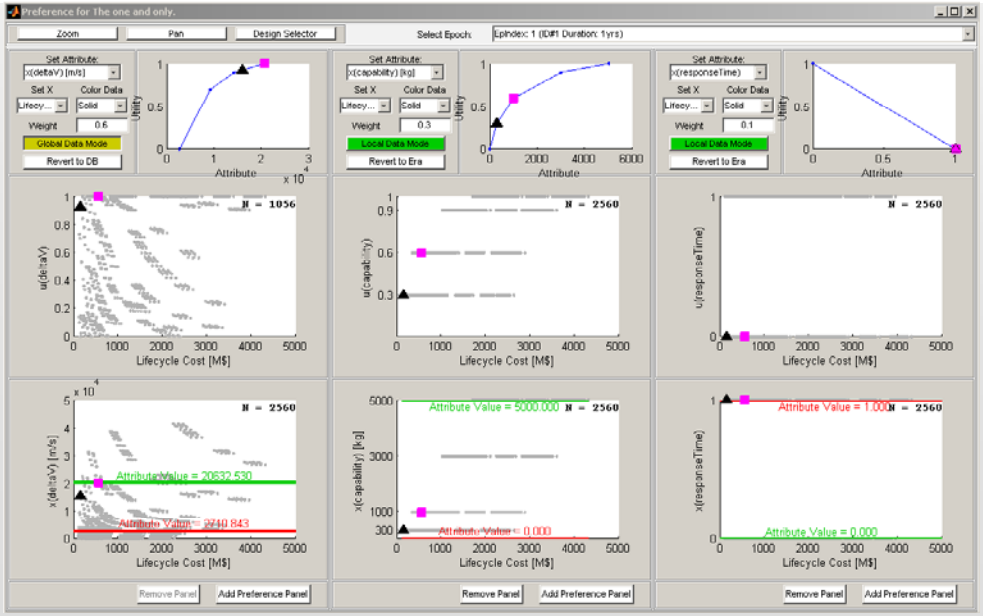
TSE Input and Calculation Tools



In order to conduct the question-guided exploration, the following input and calculation tools are needed:

Name	Function
Pareto Calculator	Find the Pareto front on any plot. Multi-dimensional Pareto capability also useful.
Preference Input	Ability to accept changes in the Worst and Best values, and the Weights, for Attributes. Also ability to change the utility curves.
Preference Calculator	Ability to recalculate the single- and multi-attribute utilities using the new preferences, and use them as the basis for all of the above displays.





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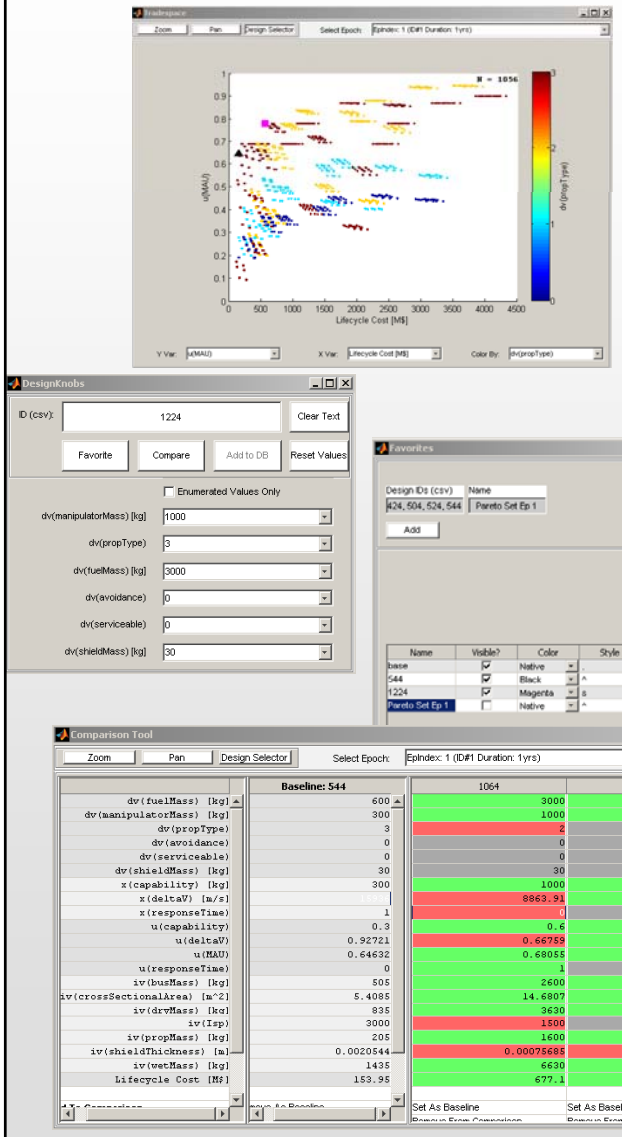
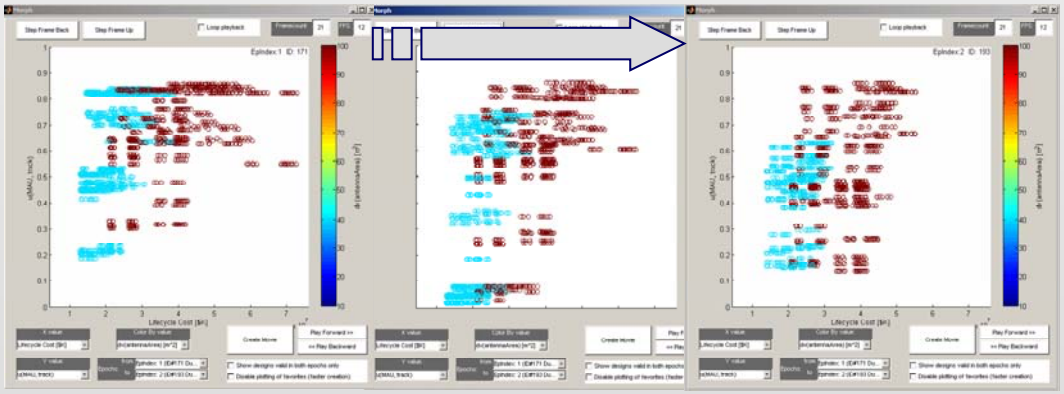
TSE Display Tools



Name	Function
Tradespace Plot	Plot single- or multi-attribute utilities versus cost. Use color to represent a third dimension (e.g., design vector values).
Strength/Weakness Plots	Multiple plots showing physical attributes and their associated utilities, against cost or other factors. Use color for a third dimension.
Sensitivity Plots	Multiple plots showing sensitivities of one factor to another (e.g., attributes to design vector values).
Design Definition	Ability to pick a point on any of the above plots and find out what design it is associated with.
Favorites List	List of favored designs, with key information and a symbol or icon. Display these designs on all plots using their special symbol.
Comparison Table	Display and compare the physical characteristics (design vector values) and performance (attributes and utilities) of selected designs.
Era Viewer	Multiple plots showing a tradespace under a variety of conditions (epochs) that together represent a scenario for changes over time.
Era Animator	Animation of the era; a single plot that shifts as conditions change across epochs.



These display tools allow for rapid TS interpretation

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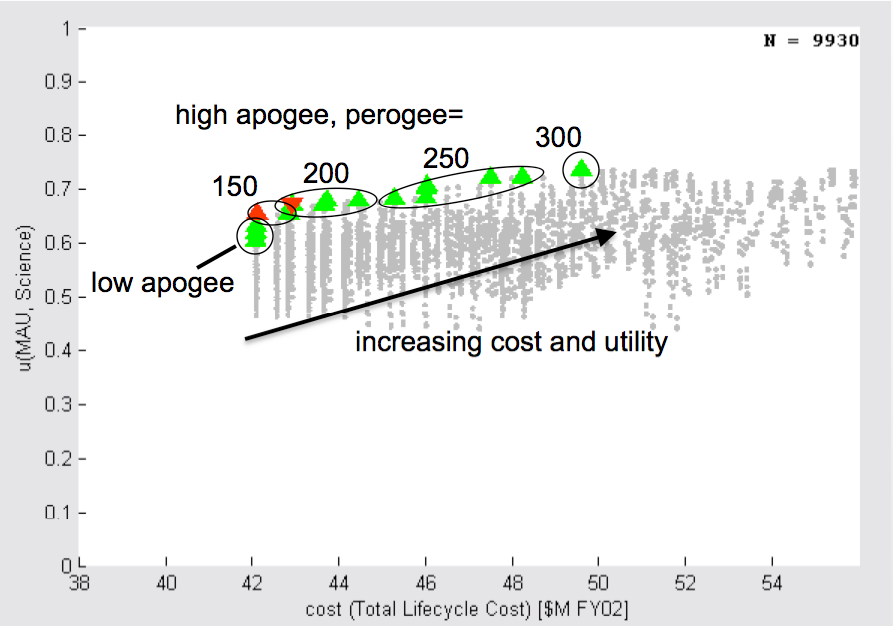
Q1: *Can we find good value designs?*

- Define “good”
- Identify good value designs
  - Find high utility, low cost designs, with associated physical design parameters
- Understand utility vs. cost tradeoffs
  - Find Pareto front, investigate design relationships
- Look at details
  - Understand design and performance variations along Pareto front
  - Develop first set of interpretations
- Cautions
  - develop trust in model,
  - avoid anchoring,
  - do not assume Pareto front has all good designs



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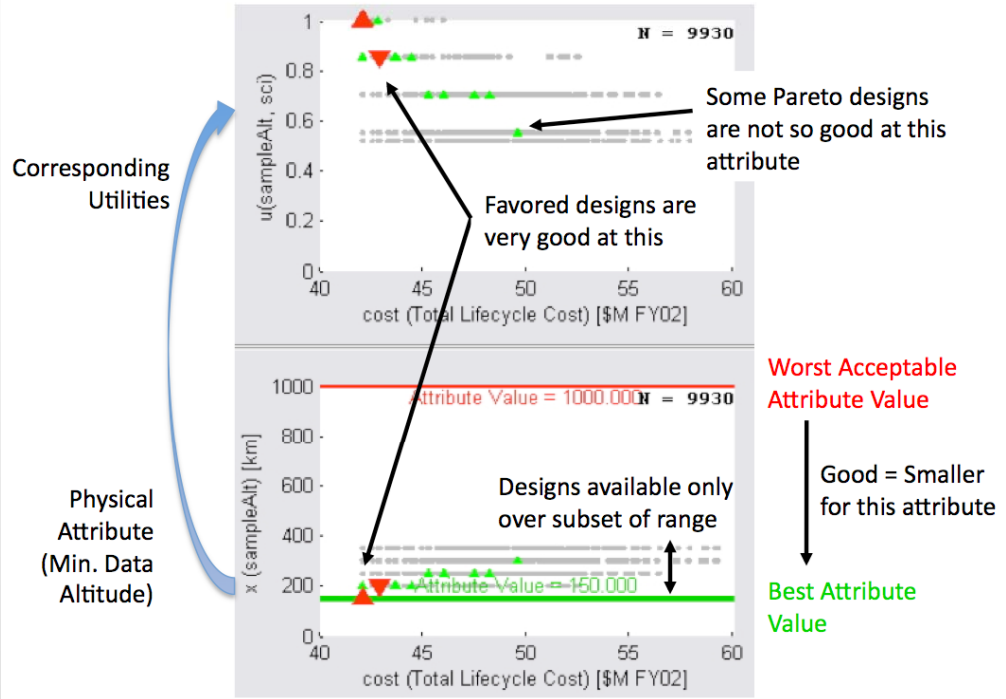
Q2: *What are the strengths and weaknesses of selected designs?*

- Quick look
  - Tabulate performance of favored designs,
  - Compare to acceptance ranges,
  - Compare to achievable values of other designs
- Tradespace look
  - Observe tradespace achievable ranges for each attribute
  - Compare location of Pareto front designs to other designs
- Cautions
  - Insights may be relative to specifically evaluated tradespace
  - Attribute performance may be coupled



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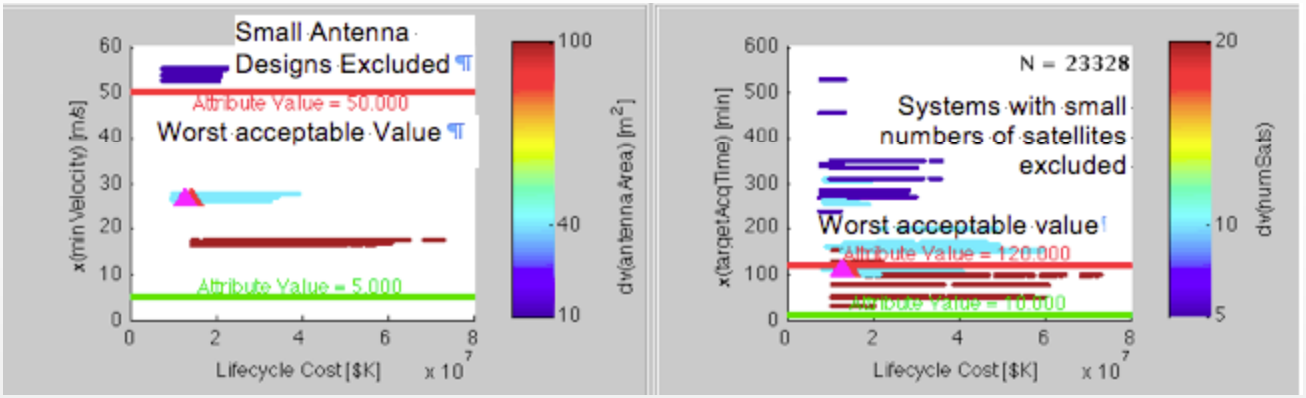
Q3: *Are lower cost designs feasible?*



- Find “low cost” designs in Pareto front
- Determine if attribute acceptance ranges exclude lower cost designs
  - Experimentally relax attribute ranges and replot
- Expand design space to include more low cost designs
  - Enumerate new levels of design parameters
  - Propose new design parameters that may lead to lower cost designs
- Re-evaluate tradespace if needed (e.g., new designs types or models needed)
- Cautions
  - Tradeoff of cost for utility can only be interpreted by decision maker
  - “Small” differences in utility is difficult to determine in “utility-space”
  - Relaxation of attribute ranges must be accepted by affected decision maker

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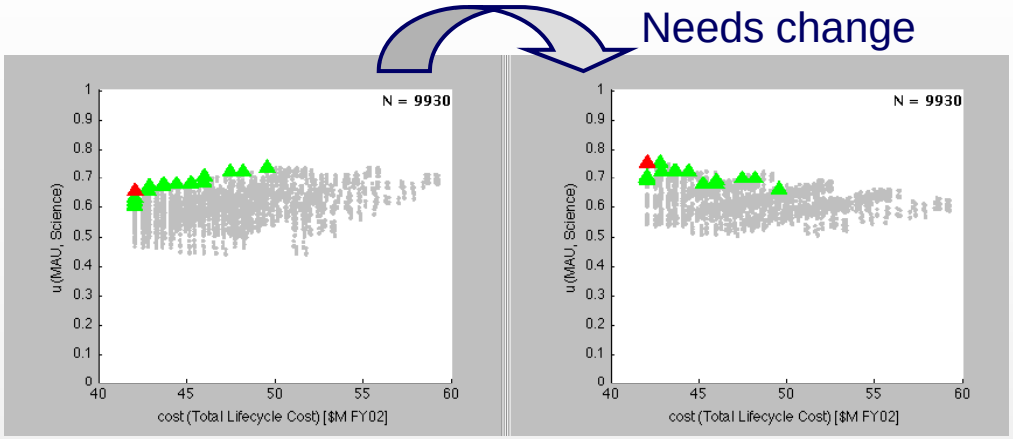
Q4: *What about time and change?*



- Define and evaluate epochs
  - Needs, contexts
  - Rerun model as needed
- Use multi-epoch metrics to identify interesting designs and epochs
  - Pareto Trace, Fuzzy Pareto Trace, tradespace yield
- Define an era (time ordered sequence of epochs)
- Identify differences across epochs
  - Colors and animations can help to illustrate
- Cautions
  - Balance completeness with practicality when enumerating epochs and eras

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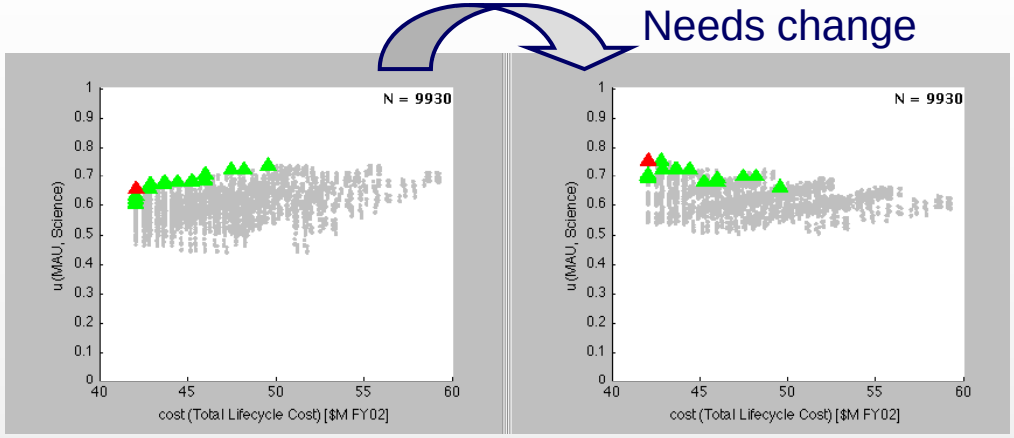
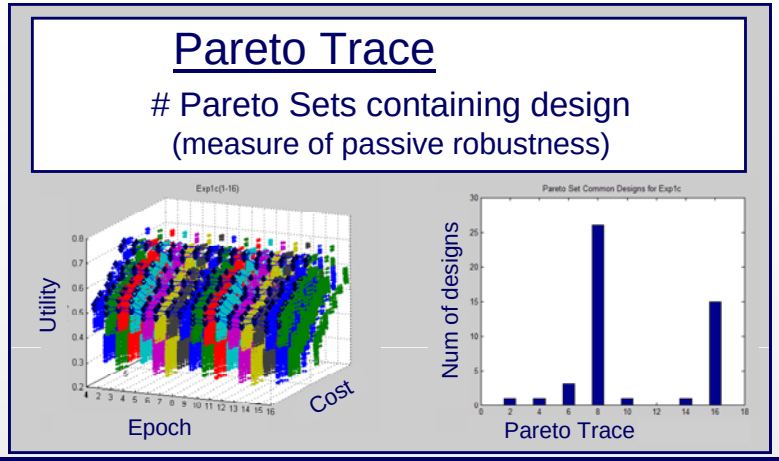
Q4: *What about time and change?*





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

- Define and evaluate epochs
  - Needs, contexts
  - Rerun model as needed
- Use multi-epoch metrics to identify interesting designs and epochs
  - Pareto Trace, Fuzzy Pareto Trace, tradespace yield
- Define an era (time ordered sequence of epochs)
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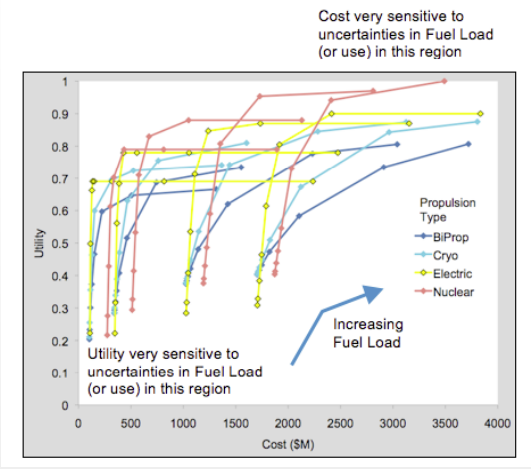
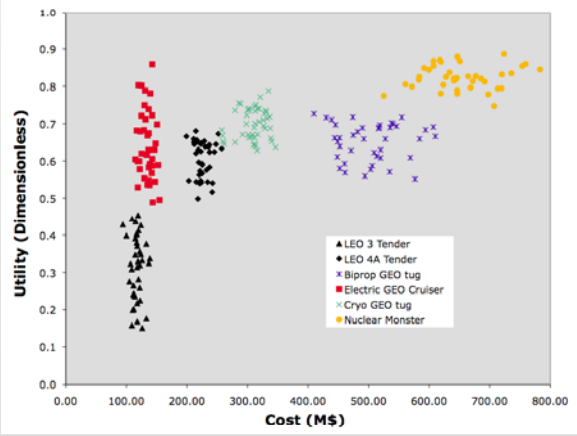
Q5: *What about uncertainty?*

- Investigate sensitivities
  - Uncertainty affecting sensitive factors may indicate risk
- Use Epoch-Era Analysis to understand uncertainties due to discrete changes in contexts and needs
  - Memory intensive, so limit scope
- Use Monte Carlo analysis to understand propagation of uncertainty in performance of subset of designs
  - Computationally intensive, so limit scope



Sensitivities



Monte Carlo-derived uncertainties

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Q6: *How can detailed design be initiated to maximize program success?*

Tradespace exploration appears to have promise in addressing:

- Picking good projects
  - TSE shows what is possible in terms of tradeoffs
  - TSE can be used to identify “favored” designs
- Specifying good requirements
  - TSE shows impact of acceptability ranges on possible utility and cost, including “good” and “bad” constraints on designs
- Understanding risk areas
  - TSE allows for consistent comparison of alternative’s sensitivities and uncertainty propagation tendencies
- Understanding alternatives
  - TSE allows for gaining insights into multiple alternatives simultaneously, creating essential contingency knowledge and design choice justification

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Discussion

- New demonstrated TSE capabilities/insights
  - Multiple cost types
  - Different concepts on same tradespace
  - Systems of systems can be represented, but require more sophisticated modeling/fusion (ongoing research topic)
  - Dynamic issues difficult to analyze/visualize, metrics can be used to screen/filter large datasets (ongoing research topic)
- Structured question-guided tradespace exploration
  - Guided process, with enabling tools, much faster and complete than ad hoc exploration
  - Rapid feedback results in ability to perform additional analysis as well as more “advanced” synthesis
  - Deeper TS exploration into the data and pursuit of more nuanced analysis may require access to data-generators (i.e., “modelers”) as well as preference constructors (i.e., “stakeholders”)
    - Need to understand actual vs. perceived limitations and assumptions
  - TS data demonstrates *correlation*; SMEs needed to determine *causation*

Ultimate goal is knowledge-generation, so trust in the data and tradespace exploration methods is essential

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Tradespace Exploration Benefits

The following strengths of TSE 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, tradespaces give 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

TSE methods highlight and help to focus attention on important trades, possibly overlooked by traditional methods

On-going research is further developing TS visualizations, metrics, and analyses

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