Systems Engineering Advancement Research Initiative

2009 SEAri Annual Research Summit

Research Topic

"Insights from a Multisensory Tradespace Exploration Laboratory for Complex System Selection"

Dr. Adam Ross *(Lead Research Scientist, SEAri)*

October 20, 2009

Cambridge, MA

Massachusetts Institute of Technology

Engineering Systems Division

Tradespace Exploration (TSE)

A method for understanding complex solutions to complex problems

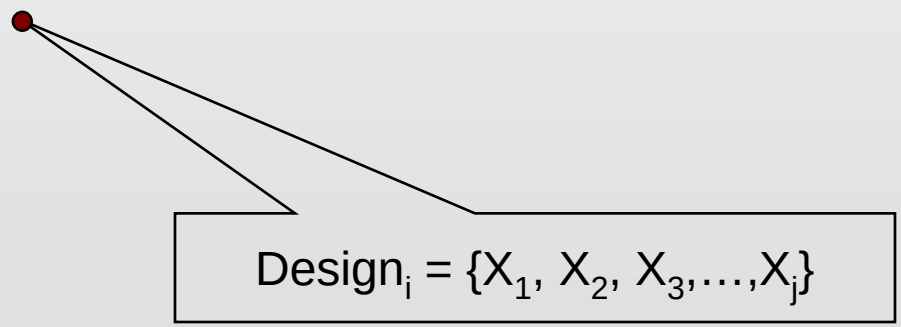
- Model-based, high-level assessment of system capabilities
- Ideally, *many* designs assessed
- Avoids optimized *point solutions* that will not support evolution in environment or user needs
- Provides a basis to explore technical and policy *uncertainties*
- Provides a way to assess the value of *potential*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

Allows informed “upfront” decisions and planning

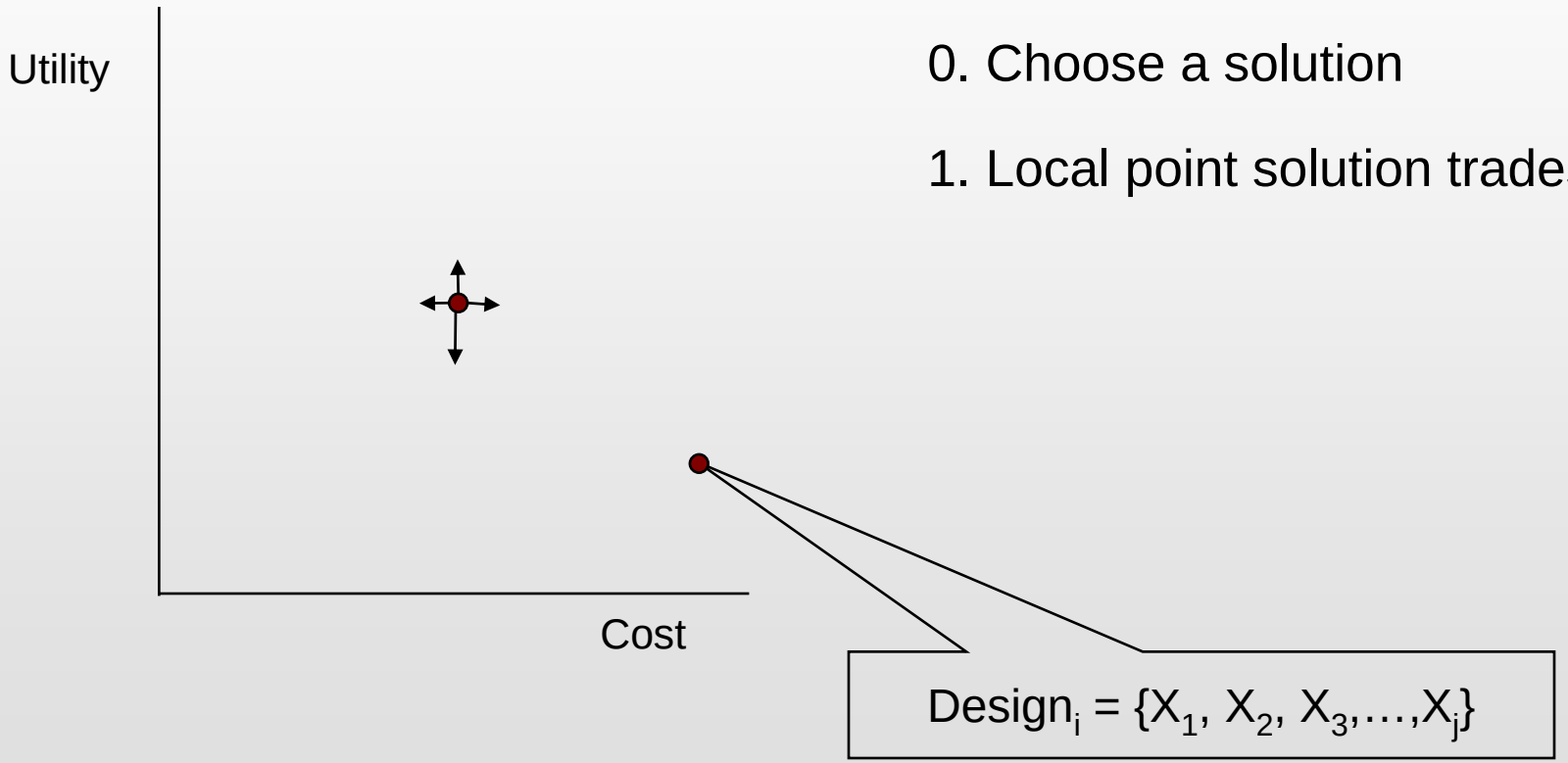
Tradespace Exploration Paradigm: Avoiding Point Designs

<u>Differing types of “trades”</u>

0. Choose a solution



Tradespace Exploration Paradigm: Avoiding Point Designs

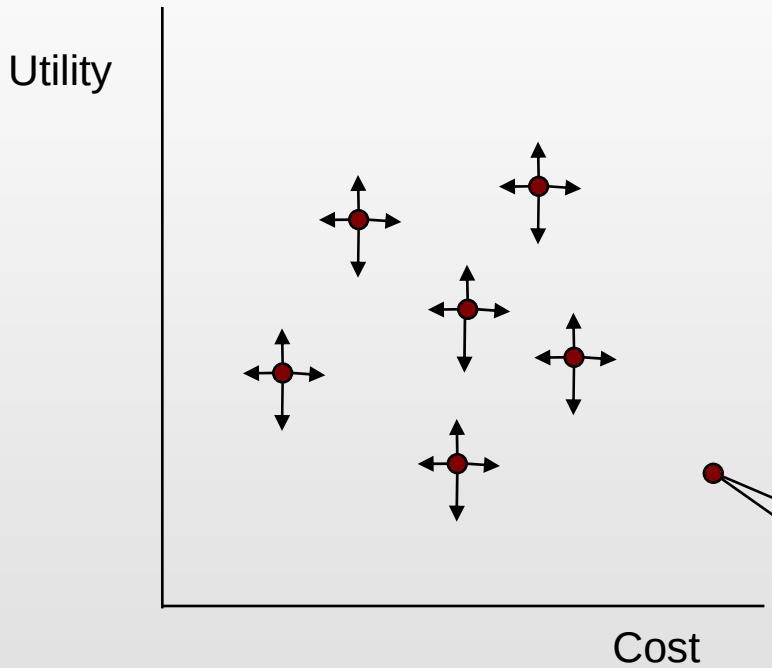


<u>Differing types of "trades"</u>

0. Choose a solution

1. Local point solution trades

Tradespace Exploration Paradigm: Avoiding Point Designs

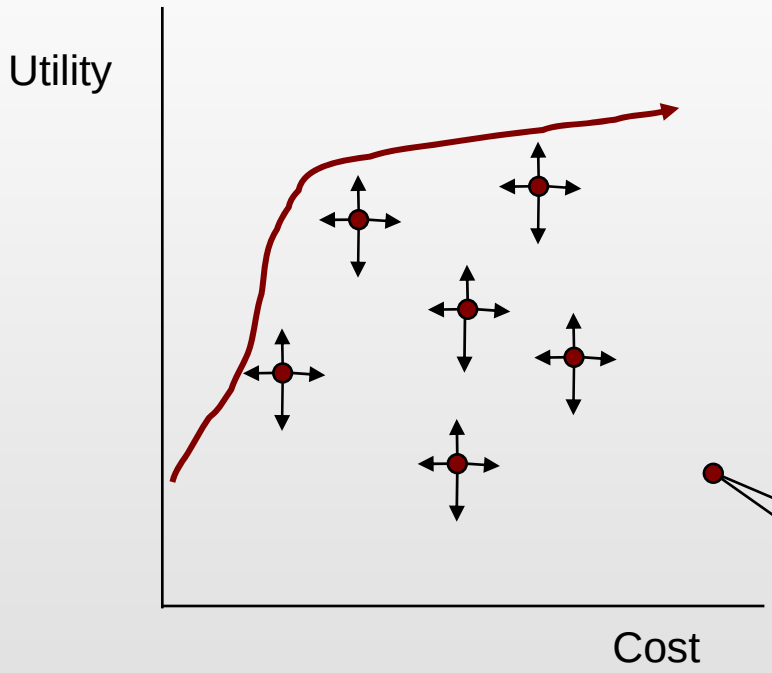


Design$_i$ = {X_1, X_2, X_3,…,X_j}

<u>Differing types of "trades"</u>

0. Choose a solution
1. Local point solution trades
2. Multiple points with trades

Tradespace Exploration Paradigm: Avoiding Point Designs

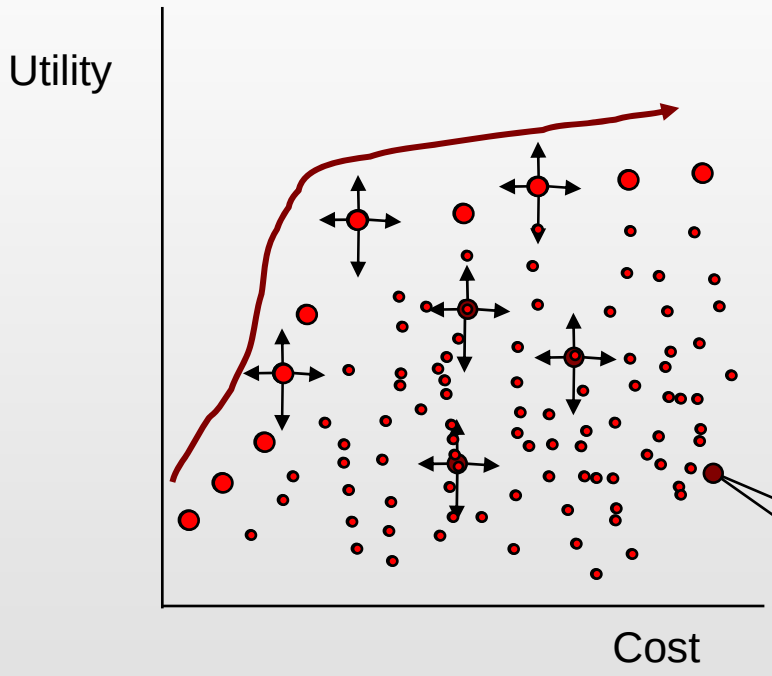


<u>Differing types of "trades"</u>

0. Choose a solution
1. Local point solution trades
2. Multiple points with trades
3. Frontier solution set

$Design_i = \{X_1, X_2, X_3, \ldots, X_j\}$

Tradespace Exploration Paradigm: Avoiding Point Designs



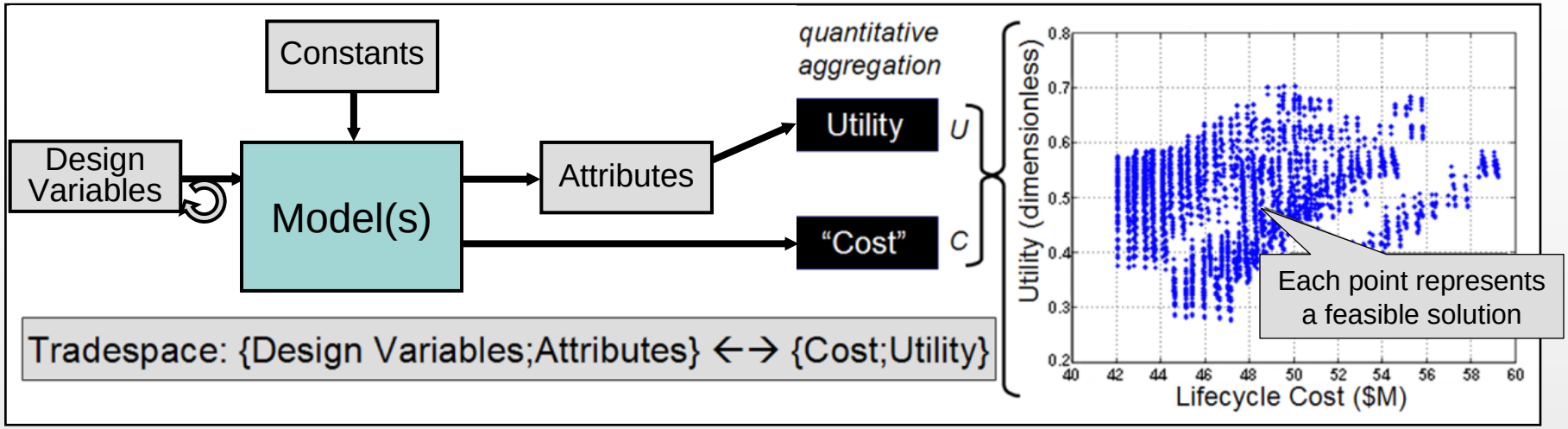
Differing types of "trades"

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 Tradespace Exploration



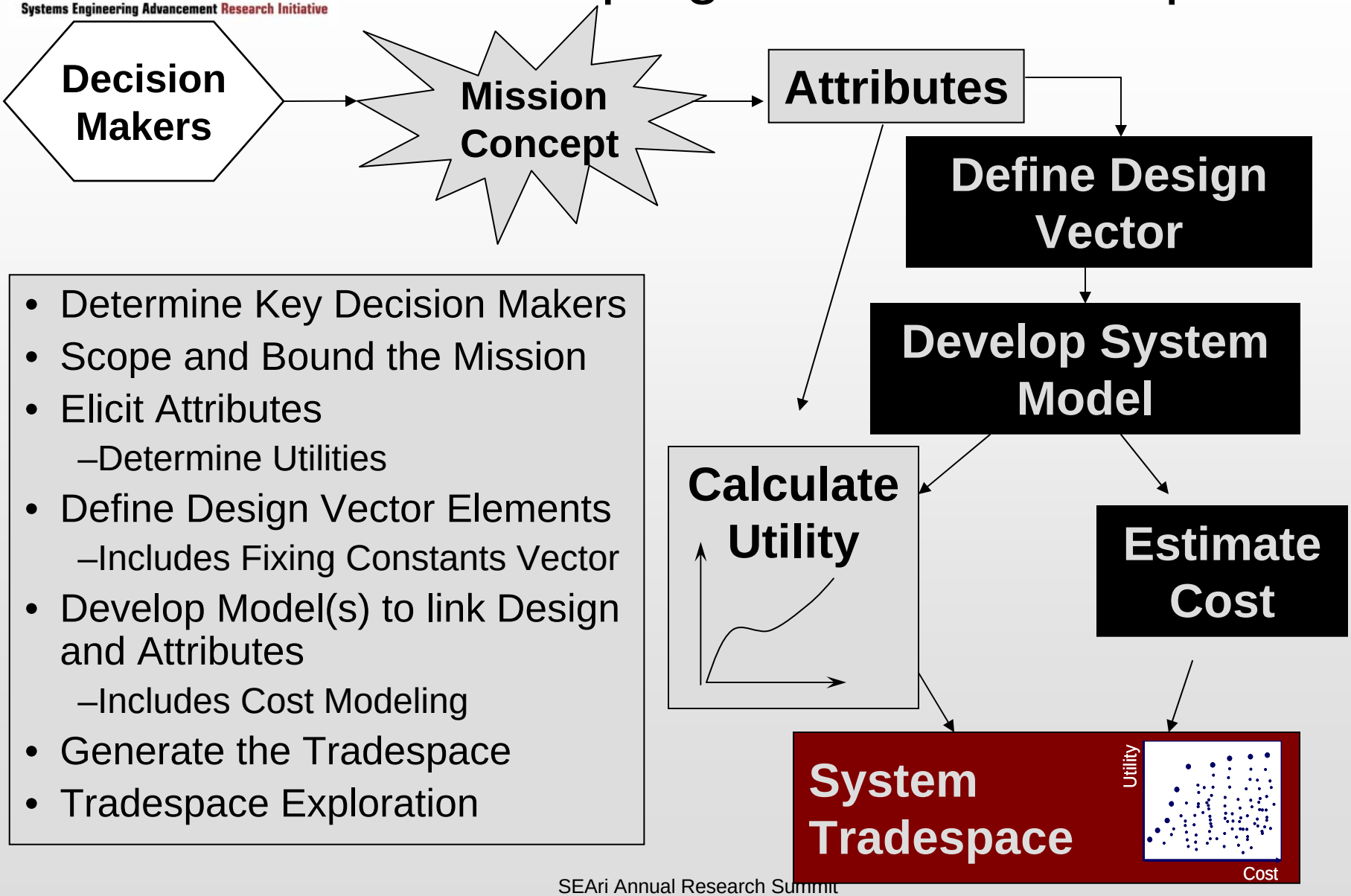
Compares many designs on a common, quantitative basis

- 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)

<u>Typical goal:</u> maximize aggregate benefit (utility) and minimize aggregate cost (lifecycle cost)

Value-based assessments allow for comparison of many different alternatives

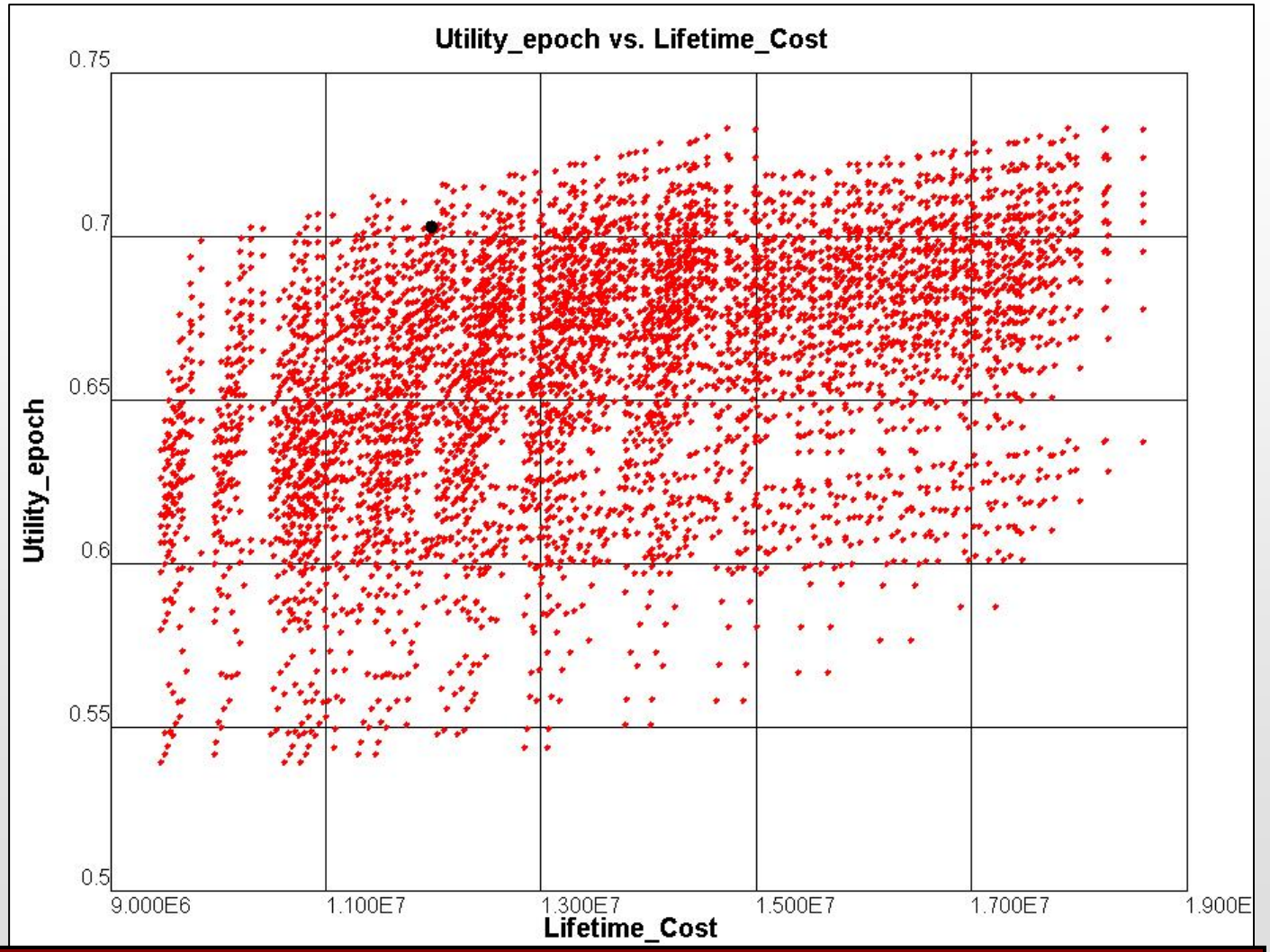
Developing a Static Tradespace



- 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

Tradespace Data Representation

Rich data sets can be explored to reveal complex relationships between design-space and value-space for generating intuition into

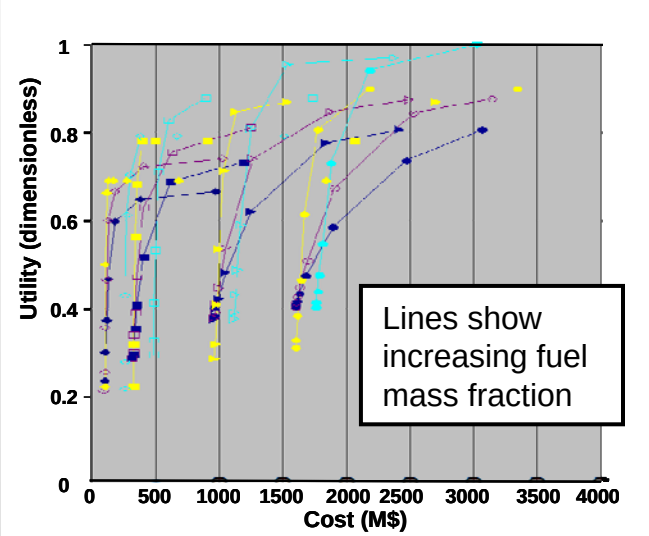


"Explore" tradespace data to develop intuition into complex design-value relationships

Example Tradespace Insights

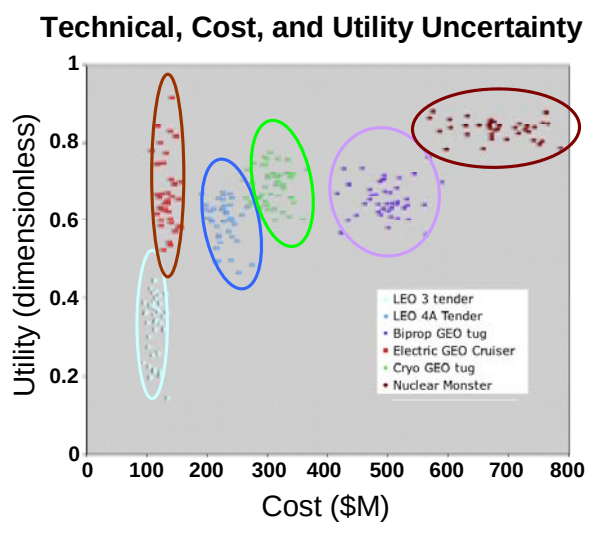
SPACETUG
- General purpose orbit transfer vehicles
- Trades propulsion systems and grappling/observation capabilities

Understanding limiting physical or mission constraints



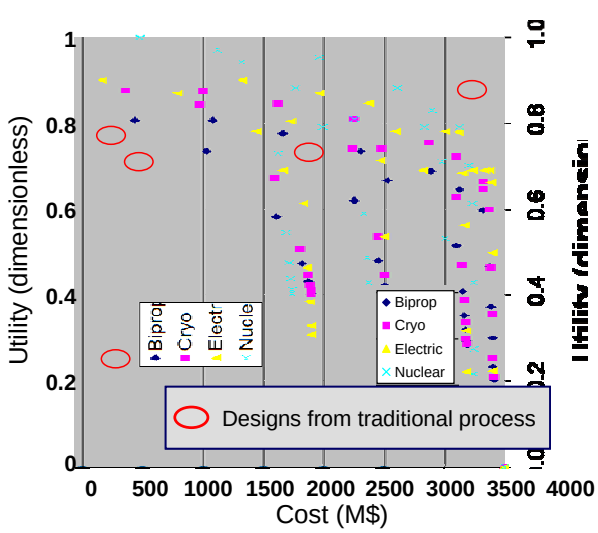
Hits "wall" of either physics (can't change) or utility (can)

Understanding differential uncertainty



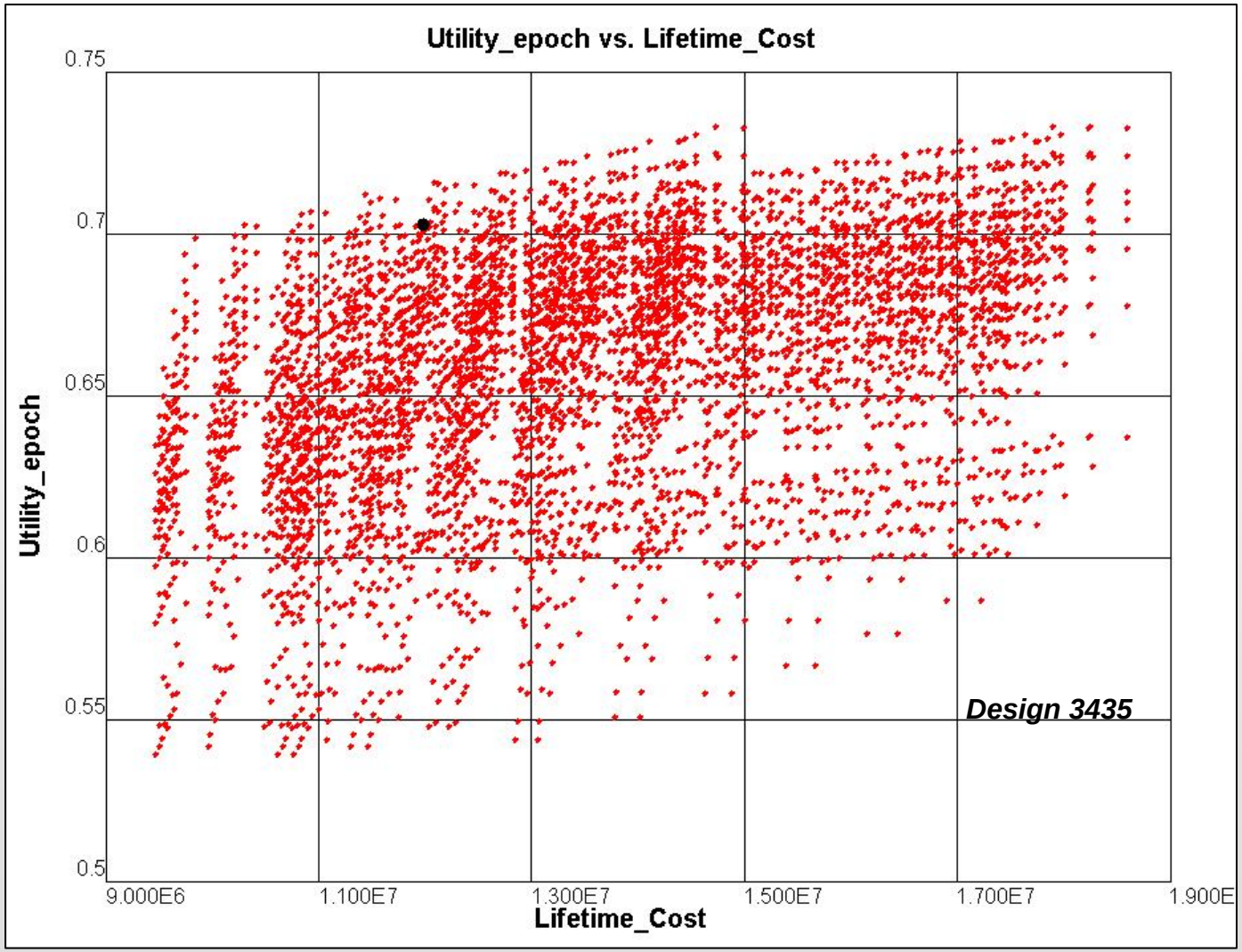
Different designs subject to different risks

Comparing alternatives on common basis

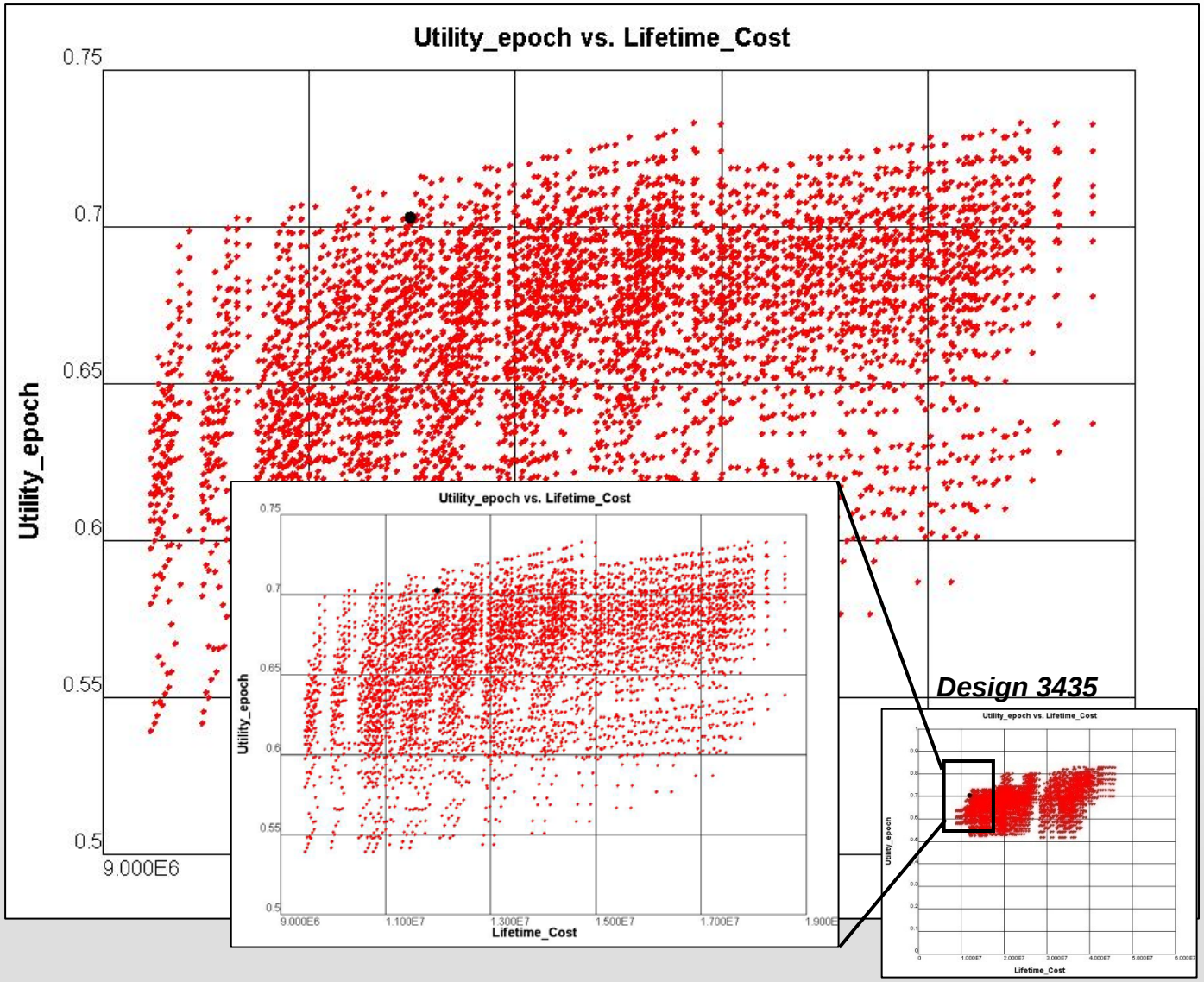


Common "value" definition can compare old and new heterogeneous systems

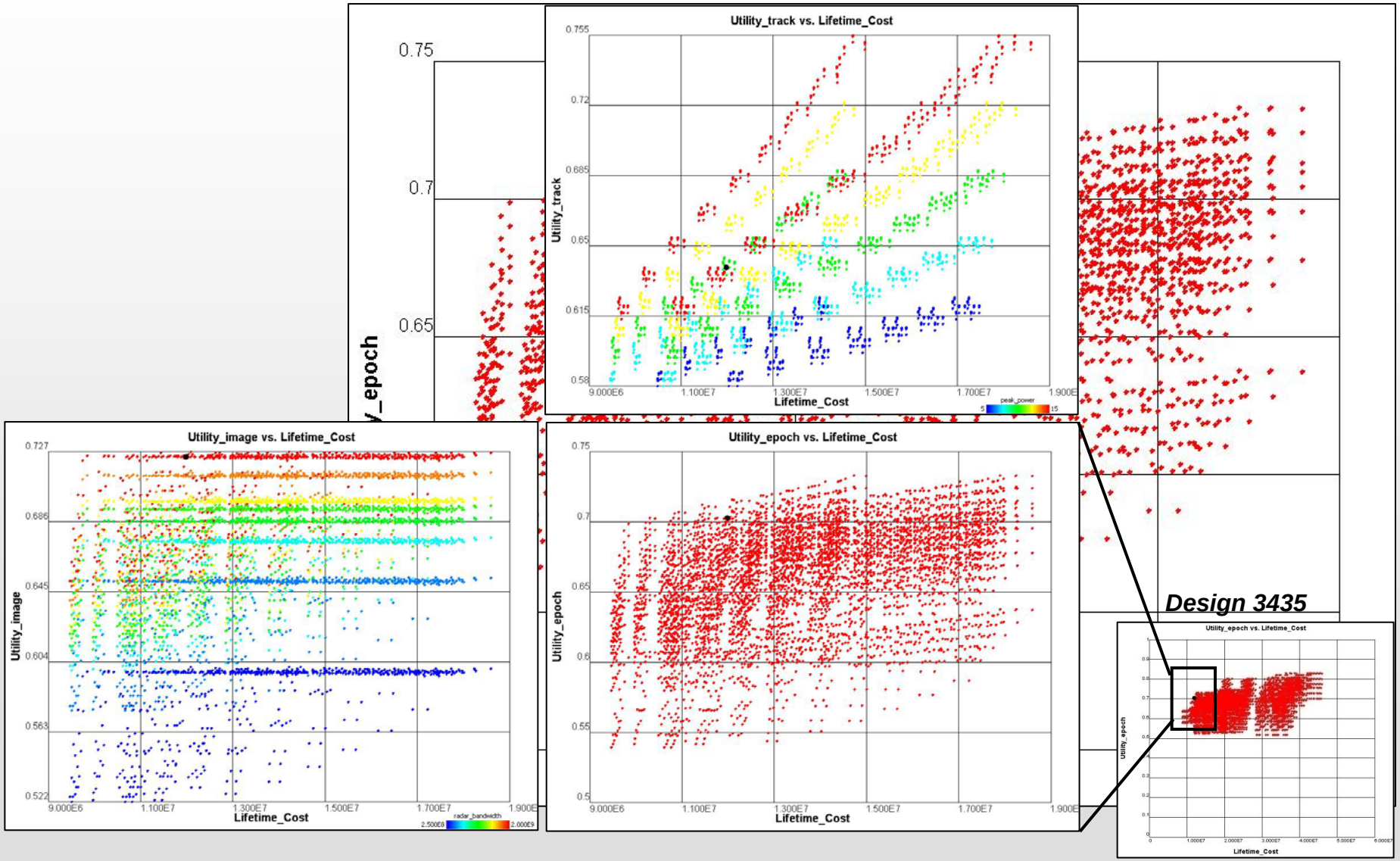
Many Important Dimensions



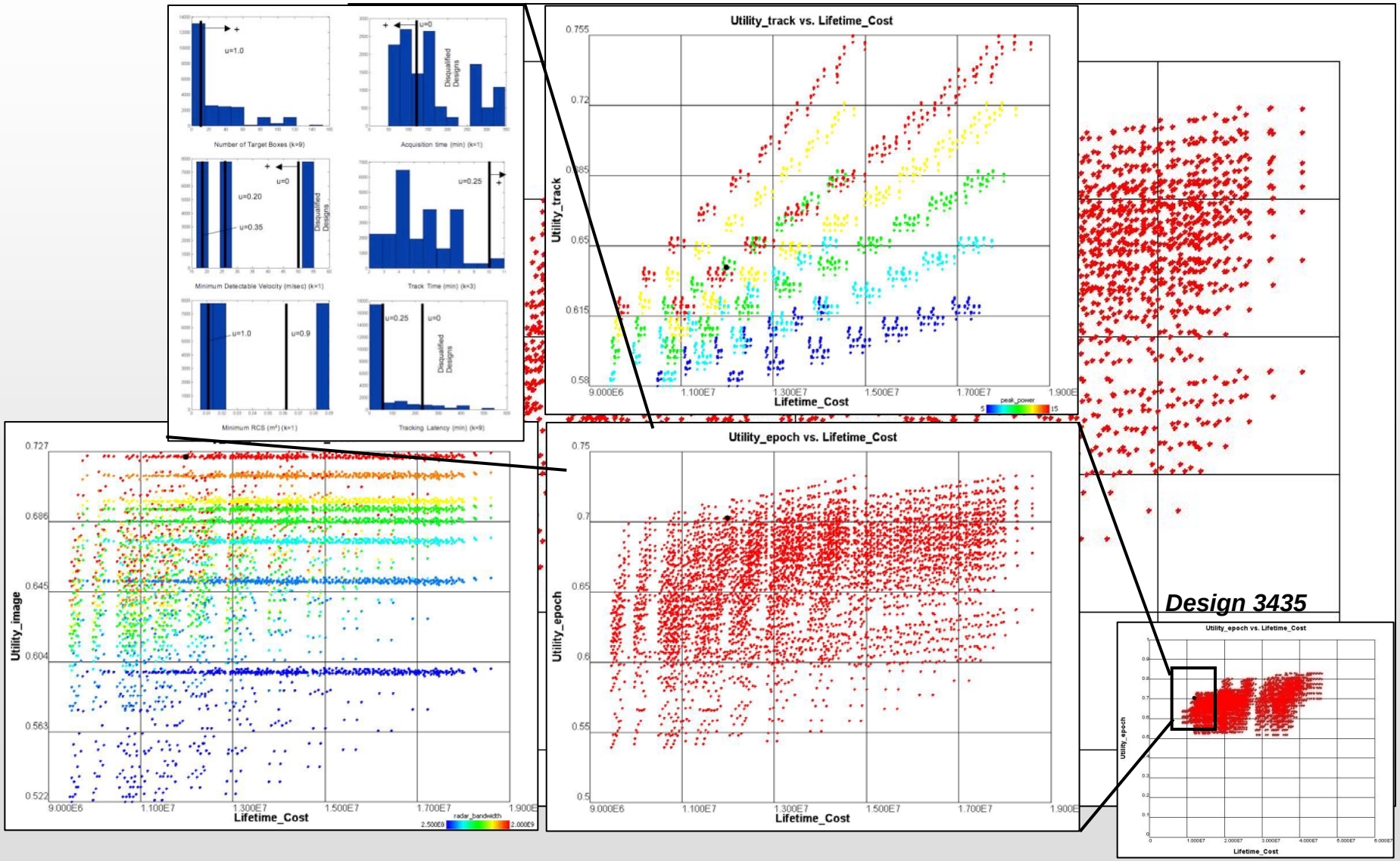
Many Important Dimensions



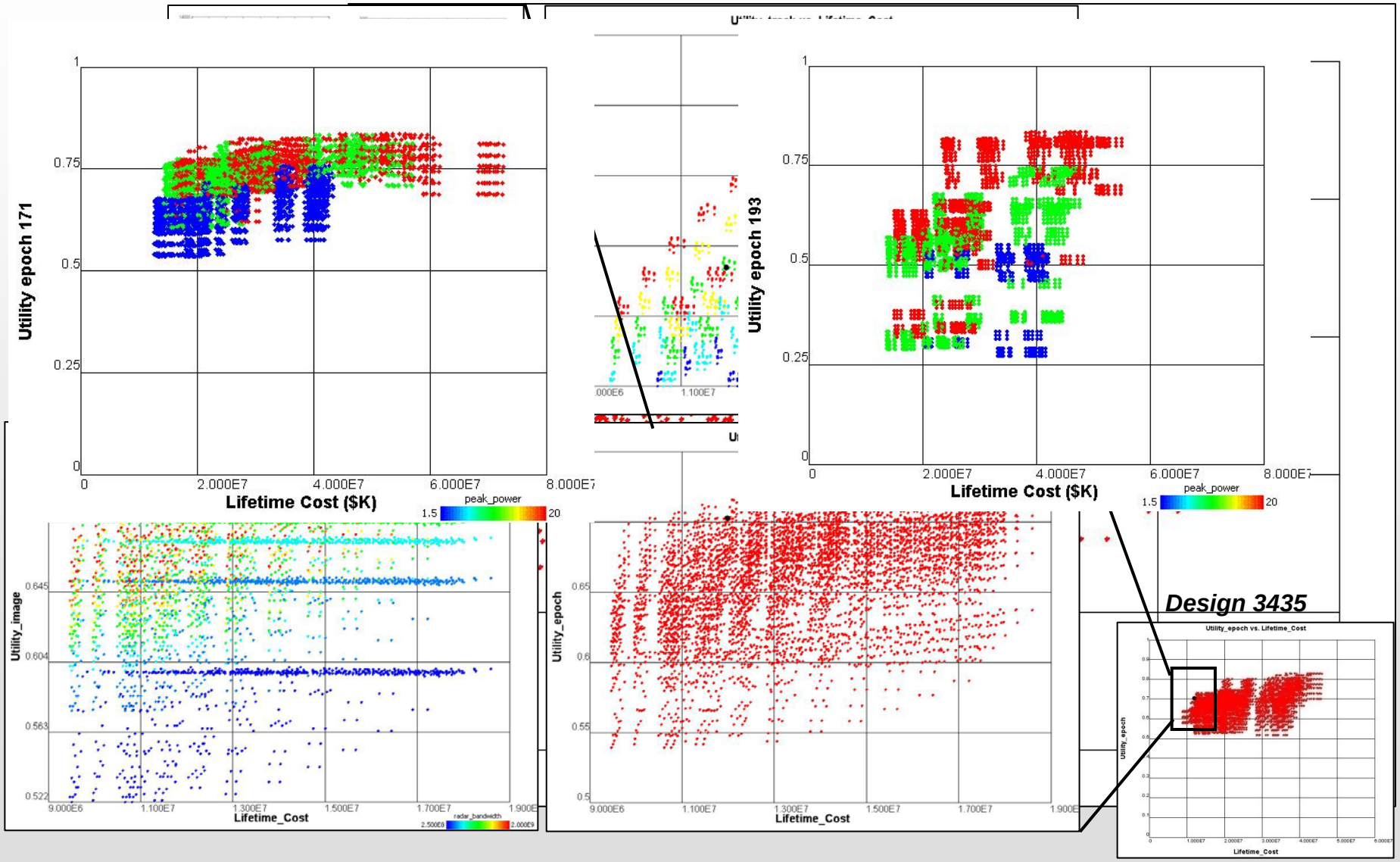
Many Important Dimensions



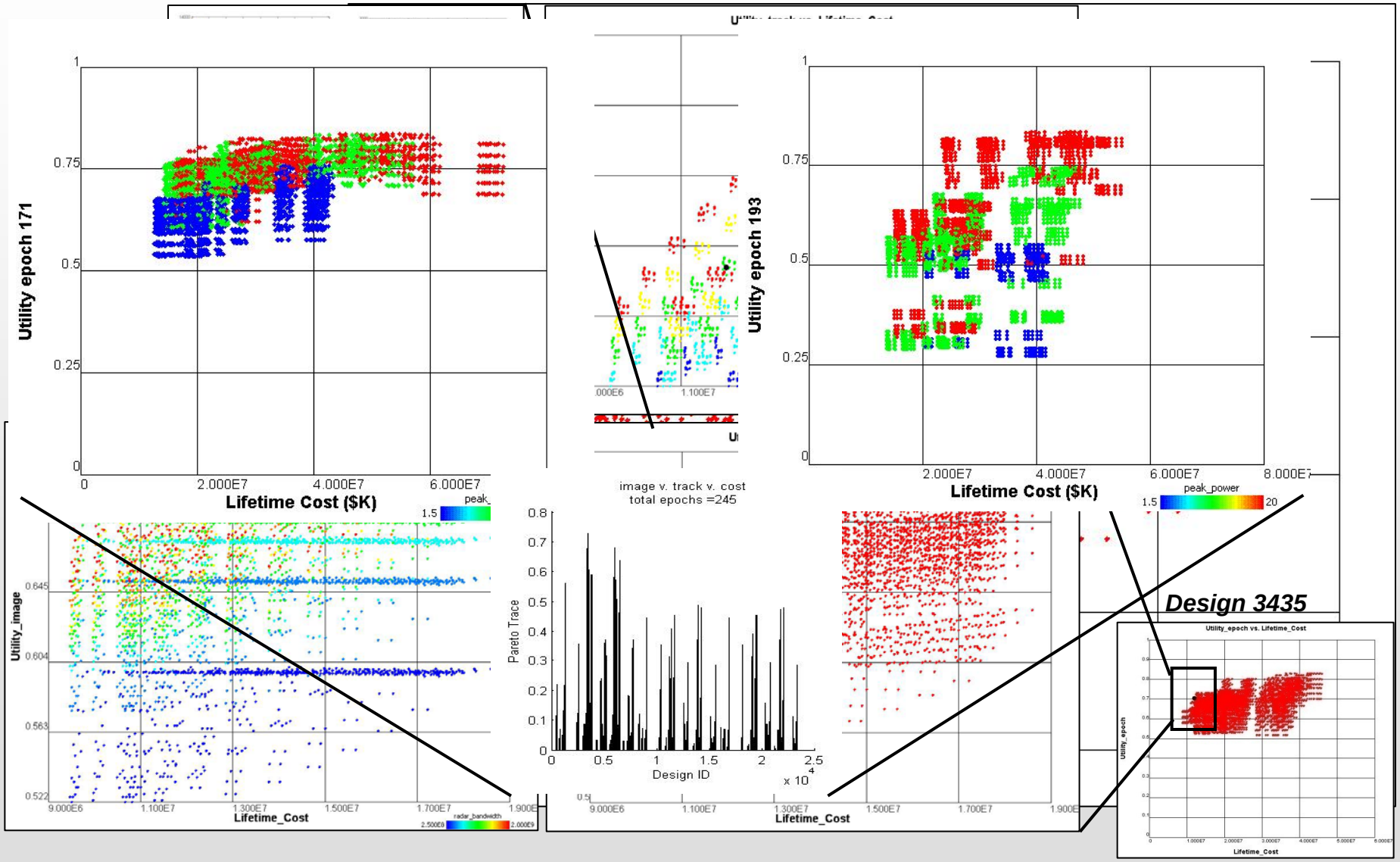
Many Important Dimensions



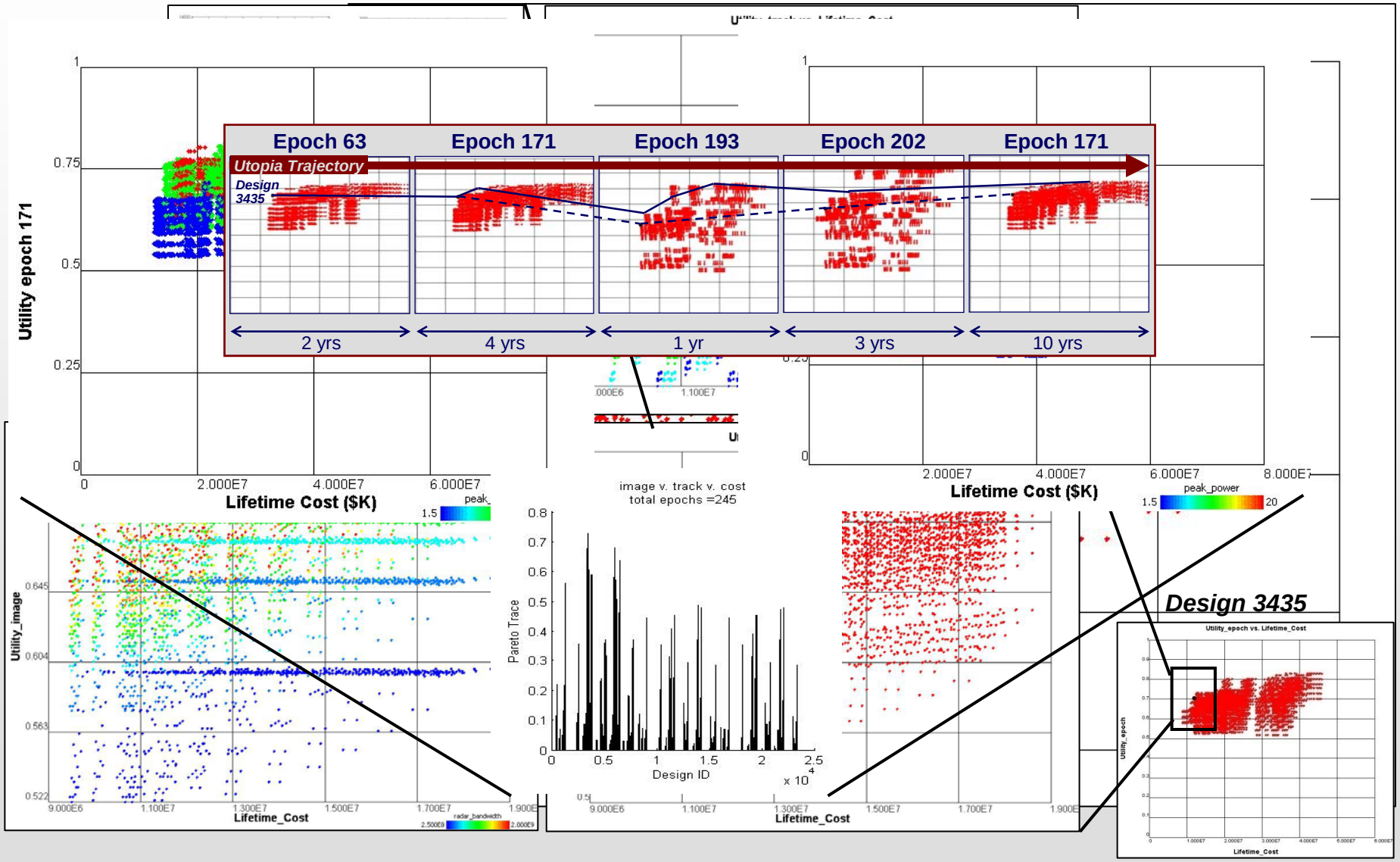
Many Important Dimensions



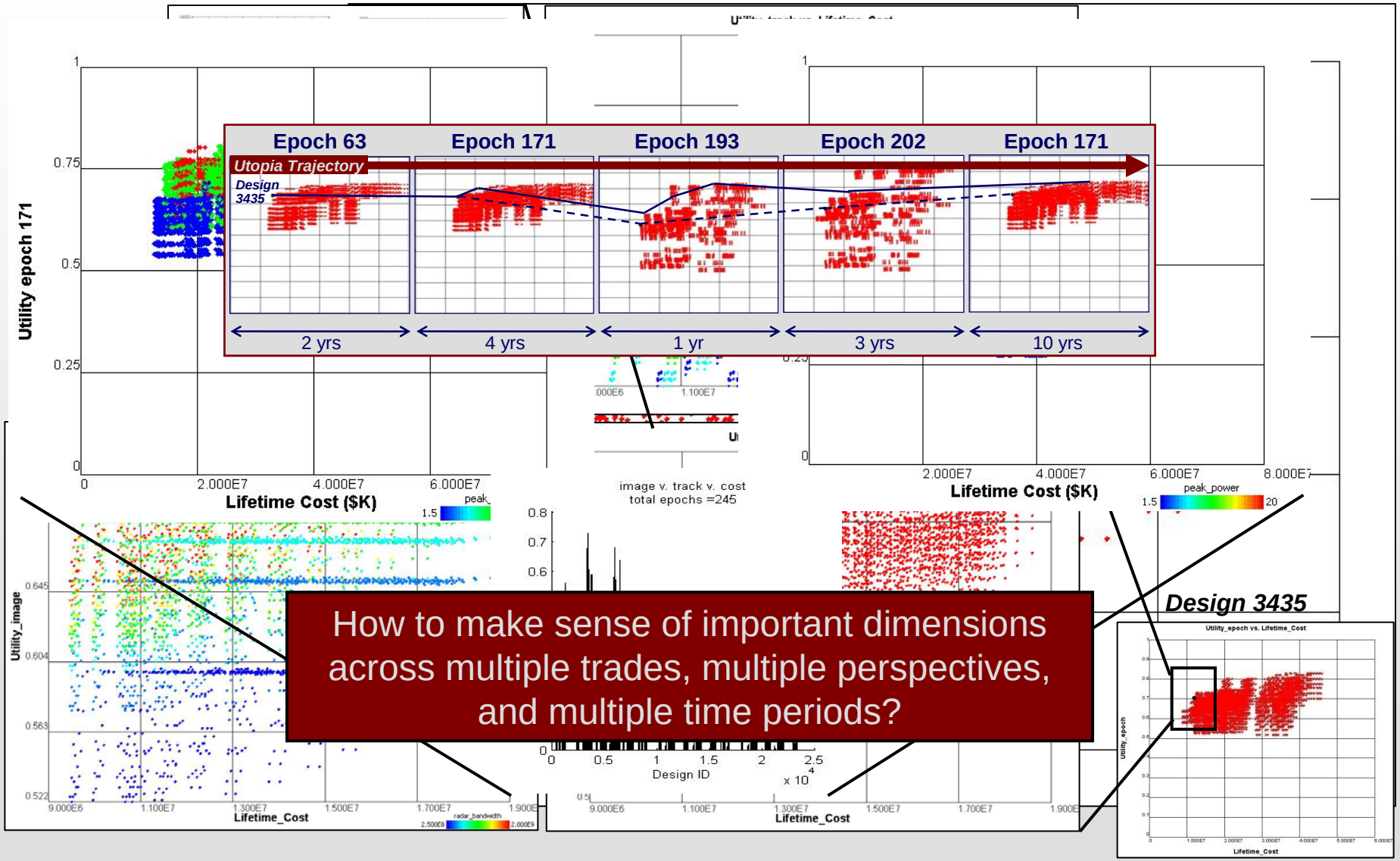
Many Important Dimensions



Many Important Dimensions



Many Important Dimensions



How to make sense of important dimensions across multiple trades, multiple perspectives, and multiple time periods?

Key "Dimensions" for TSE

- Information dimensionality
  - Tradespace has many important variables (e.g. attributes, utilities, design variables, intermediate variables, costs, etc.)
- Multi-perspective
  - Each decision maker has own preferences with sensitivities (e.g. single attribute utilities, weights, multi-attribute utilities, etc.)
- Temporal representations
  - All data have time aspect, both short run and long run (e.g. epochs and eras)
- Depth of detail
  - All data have varying degrees of fidelity/depth (e.g. high level tradespace=many designs, point=one system, details on point=subsystem, point in mission=operations, etc.)

Modern tradespace exploration methods seek to effectively incorporate these dimensions to enable better decision making

Visualization and Communication

- Humans are better at recognition over recall
- According to Tufte (2001)*, graphs should:
  - Show the data
  - Not get in way of message
  - Avoid distortion
  - Present many numbers in a small space
  - Make large data sets coherent
  - Encourage comparison between data
  - Supply both broad overview and fine detail
  - Serve a clear purpose
- Visual displays as domain-independent communication artifact to facilitate learning

*pp 13. Tufte, Edward R. The Visual Display of Quantitative Information. 2001.

Example TSE 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 (e.g. MATE) highlight and help to focus attention on important trades, possibly overlooked by traditional methods

Future State Vision

A concept of operations for creating, using and sharing tradespace data…

2 Key Types of Decision Makers

- Senior technical leadership could explore in-depth in a specialized multi-sensory environment
  - Personnel with deep technical knowledge and contextual understanding
  - Multi-level and multi-dimensional data (terabytes)
  - Goal is holistic understanding of complex system issues

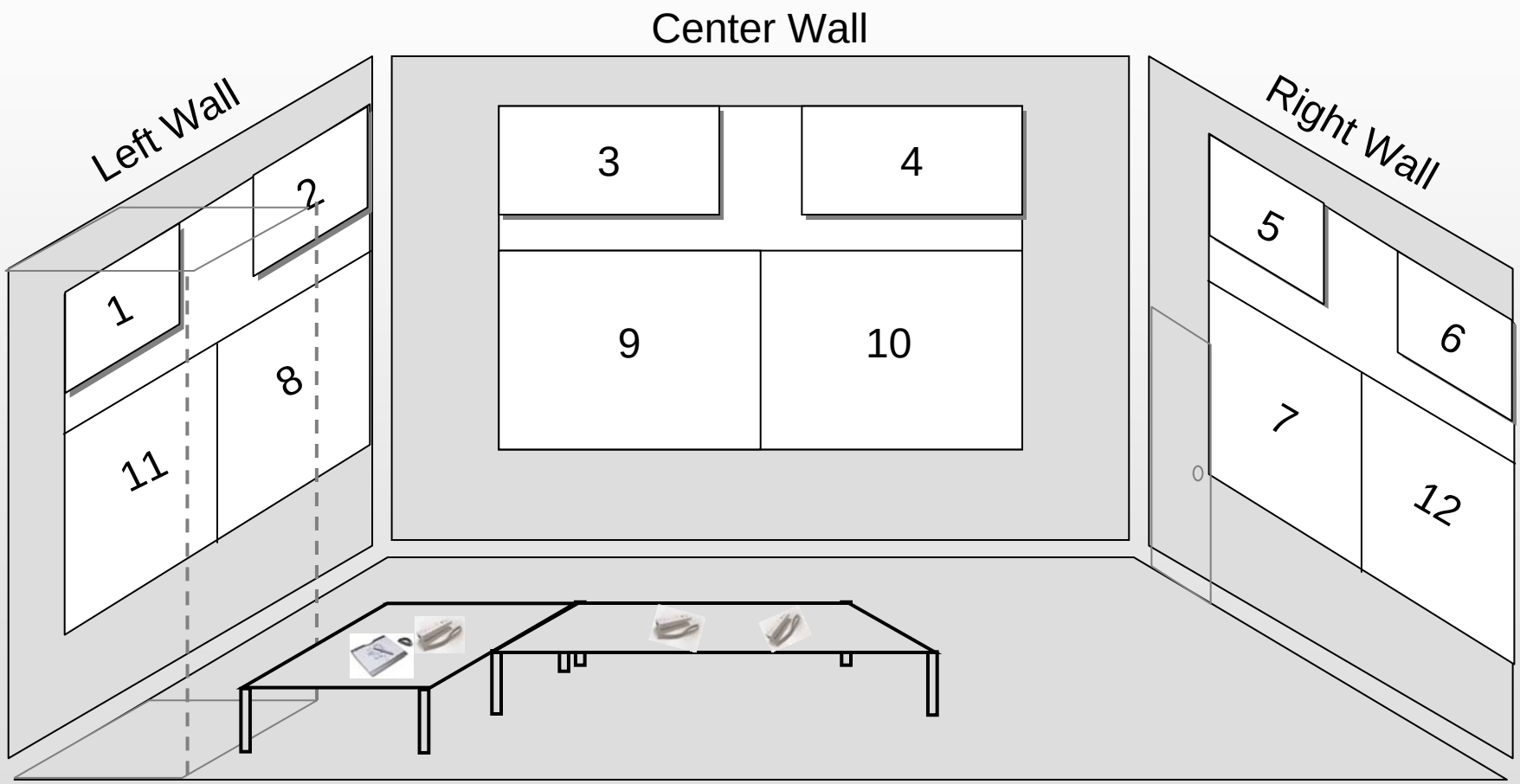
- Policy and financial decision makers could understand results (in their offices) well enough to make better decisions
  - Intelligent but non-technical personnel
  - Explicit messages (static, or linear "storyline")
  - Goal is better cost/benefit, go/no-go, or concept selection choices

…to help make better high consequence, high-payoff decisions

Vision for TSE Lab: Summer Goals

- Rapidly facilitate state of practice for TSE
  - Utility-Cost, SAU-Cost, Attribute-Cost
  - Color by design variable
- Database backend to ensure consistency
  - Linked database to generate consistent plots
  - Minimize code re-run
- Linked representations
  - Baseline setting consistent across analyses
  - Depth and breadth (time, multi-DM) linked
- Intuitive multi-sensory interaction
  - “Touch” and “click”
  - “Drag” and “pull”
  - Using mice, keyboards, stylus, and Wii remote

Tradespace Visualization Lab



Basic, but flexible multi-surface, multi-input facility

Views and “Widgets”

- Views organized around solving types of questions
- Each view has set of associated “widgets”-- modular data “interaction/display” windows
- Widgets can talk to database and can be custom arranged or called up by TSE lab user
- Widgets have *level of analysis* and *level of technical complexity* associated with them
  - Help to categorize widgets for appropriate views and users

Views

Technical complexity: low – high

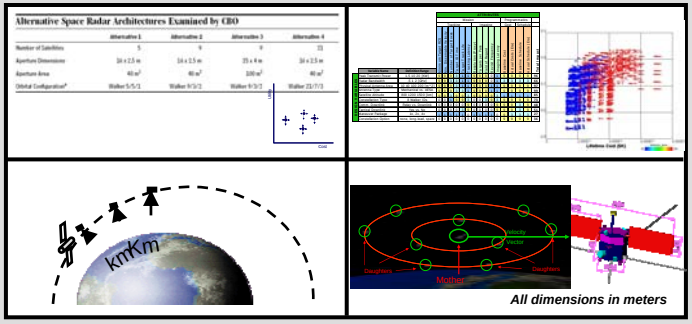
Level of analysis: high – low

- Multi-DM Negotiation
- General TS Exploration
- General Multi-Epoch Analysis
- Lifecycle Path Analyses

Widgets

Technical complexity: low – high

Level of analysis: high – low



Three "Types" of Lab Users

Developing this capability first

- Expert Tradespace Analyst
  - All widgets available by default
  - May tend toward high technical complexity, with both high and low level of analysis
- Senior DM
  - Subset of widgets available by default
  - May tend toward high technical complexity with some low, high and low level of analysis
- Legislative Aid
  - Smallest subset of widgets available by default
  - May tend toward low technical complexity, high level of analysis

Goal: Select "user type" and "question" and lab will pre-select widgets for use (i.e. the "view")

Tradespace Exploration Laboratory

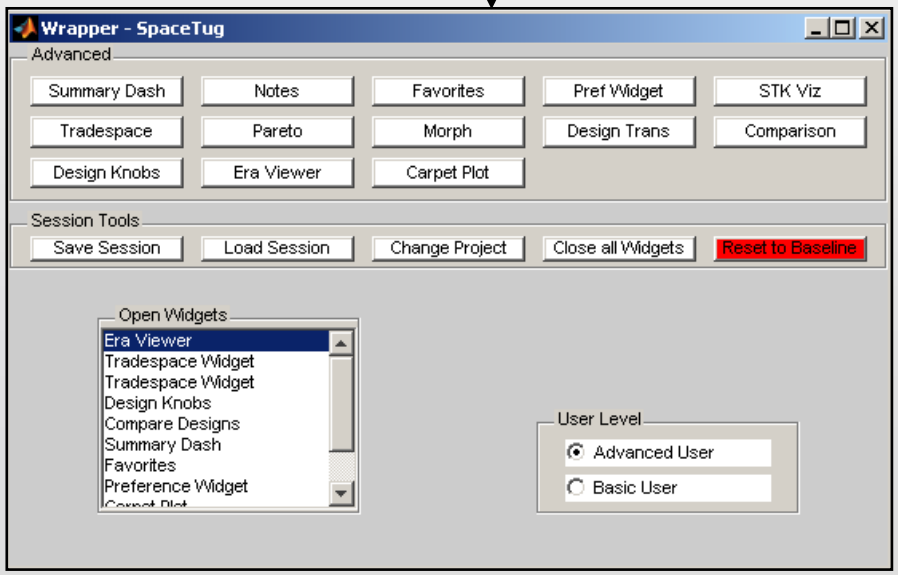
Select project

- Satellite Radar System
- Space Tug
- other

Select "user type"

- Expert analyst
- Senior decision maker
- Policy maker

Database



All current widgets

- Summary Dash
- Notes
- Favorites
- Prefs Explorer
- STK Viz*
- Tradespace Plot
- Pareto Tool
- Morph Tool
- Design Transitions**
- Comparison Tool
- Design Explorer
- Era Constructor
- Carpet Plot Tool**

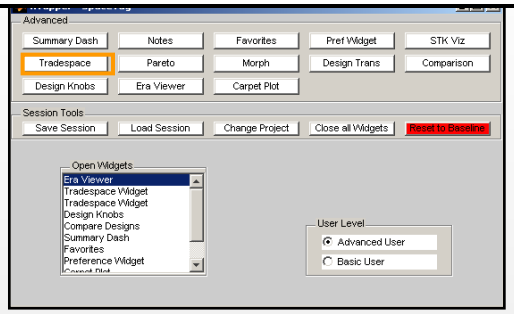
* SRS only

** widget not complete

Note: Widget names and layout are draft

Tradespace Tool

The Tradespace widget generates a scatter plot from DB for a given epoch



"Click on point" capability

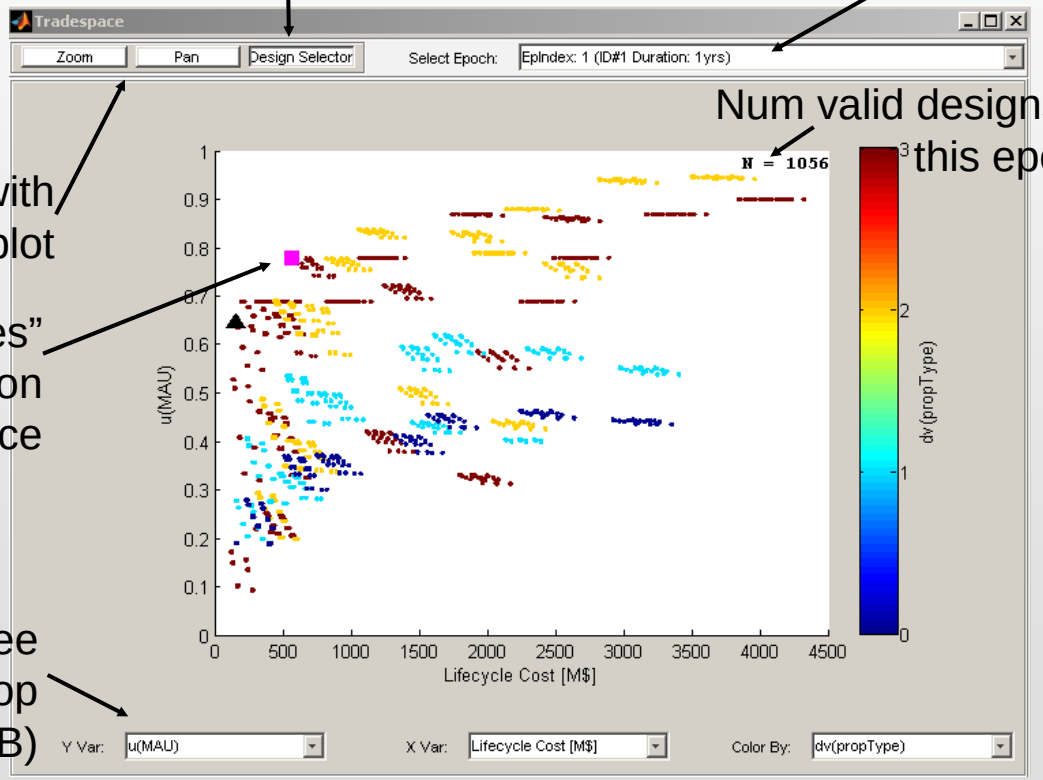
Select current epoch (from Era or other)

Num valid designs in this epoch

Interact with plot

"Favorites" plotted on tradespace

Plot three dimensions (drop downs from DB)

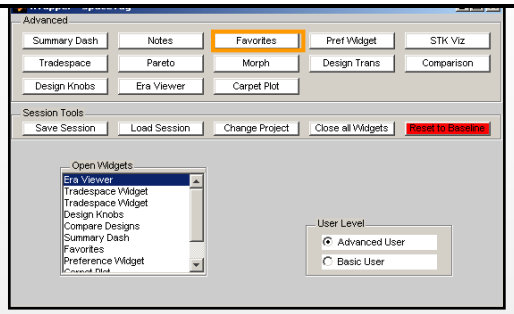


Features

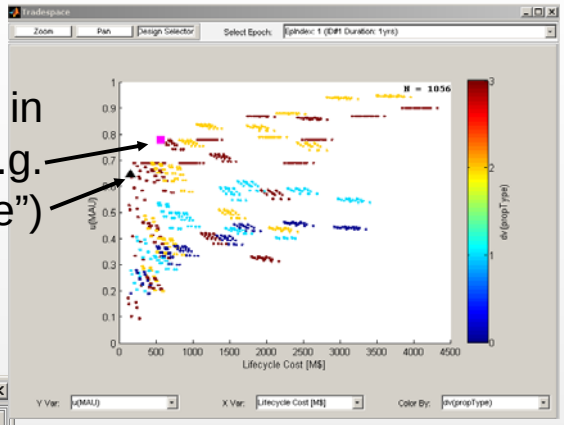
- Multiple tradespace widgets can be open at the same time to allow side-by-side comparisons
- Plots updated in real time by changes made in other widgets

Favorites

The Favorites widget allows a set of designs to be tracked and formatted across widgets



Favorites plotted in other widgets (e.g. "tradespace")



Features

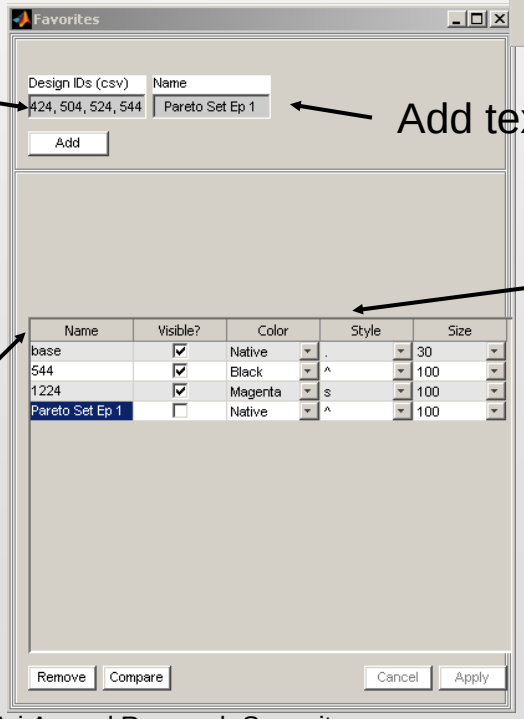
- Single or multiple designs can be grouped as a favorite
- Each favorite can be consistently displayed and formatted across widgets

Enter design ID(s)

Add text label

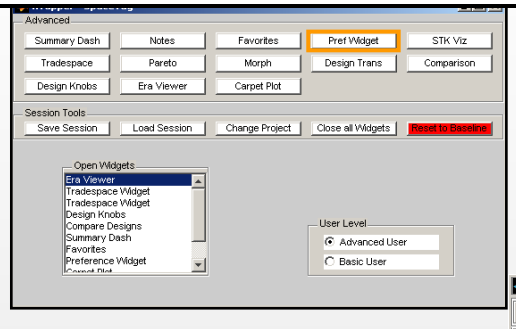
Specify plot formatting for each favorite

List of all favorites

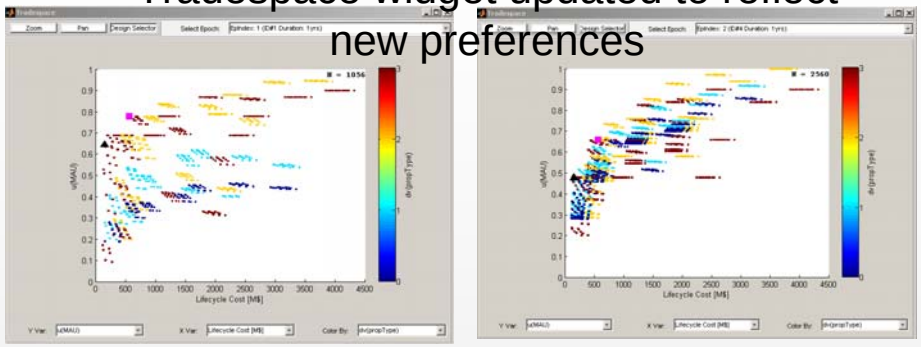


Preferences Explorer

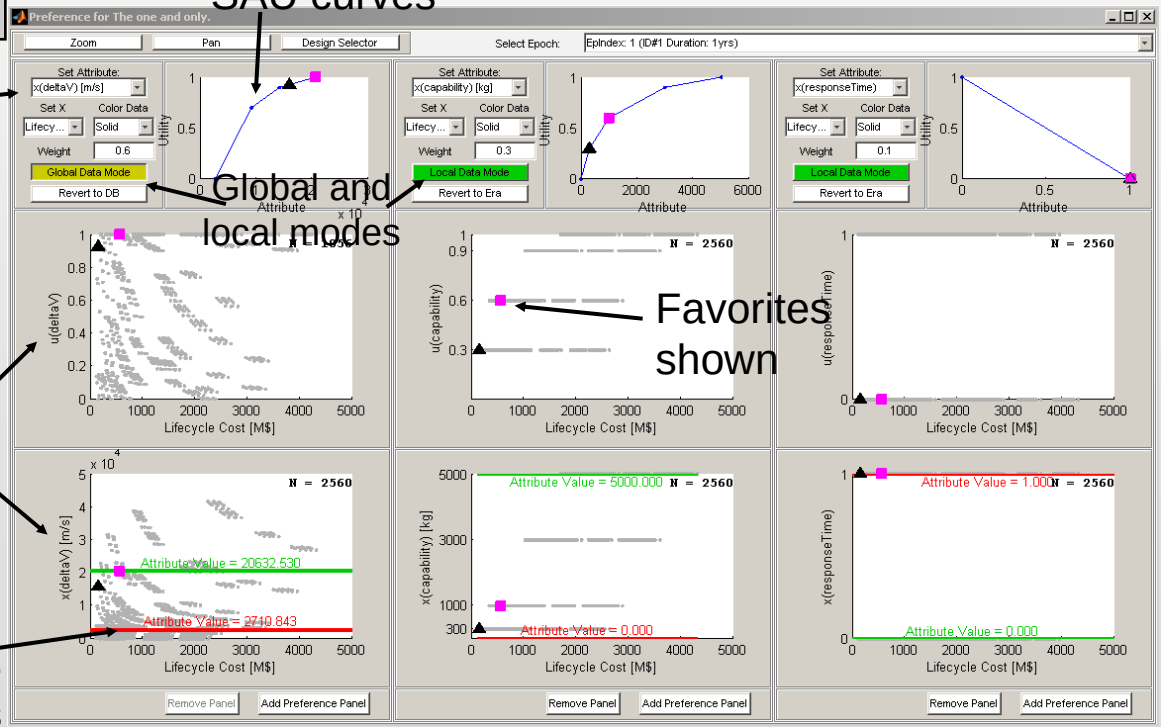
The Preferences widget displays and allows alteration of a decision maker's preferences



Tradespace widget updated to reflect new preferences



SAU curves



Select attribute

Global and local modes

Shows tradespace with SAUs attribute values

Favorites shown

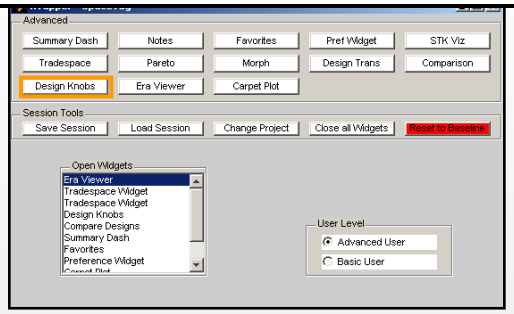
Bars show min acceptable, max desirable attribute levels

Features

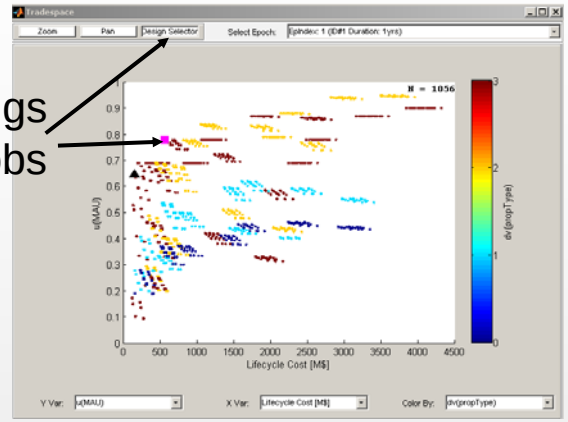
- Preferences can be displayed and edited
- Local mode allows local "playing"; global mode propagates to other widgets
- Favorites can be displayed

Design Explorer

The Design Knobs widget allows (a) design(s) to be specified or looked up from DB



"Click on point" brings up design knobs



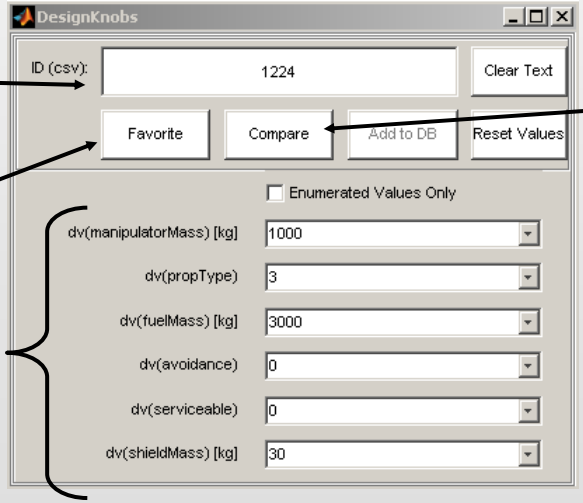
Features

- Single or multiple designs can be specified if entered as ID(s)
- Single or multiple designs can be looked up if entered as dv values
- Linked to "design selector" in tradespace widget

Enter design ID(s) (or look up ID(s)

Set favorite

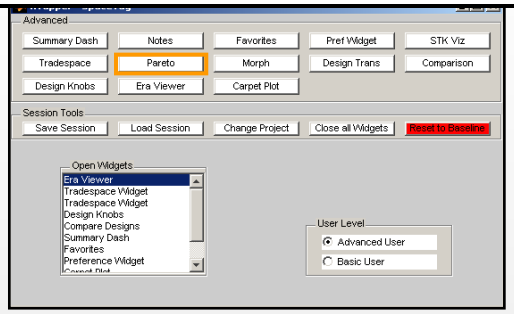
Specify design, or have design described



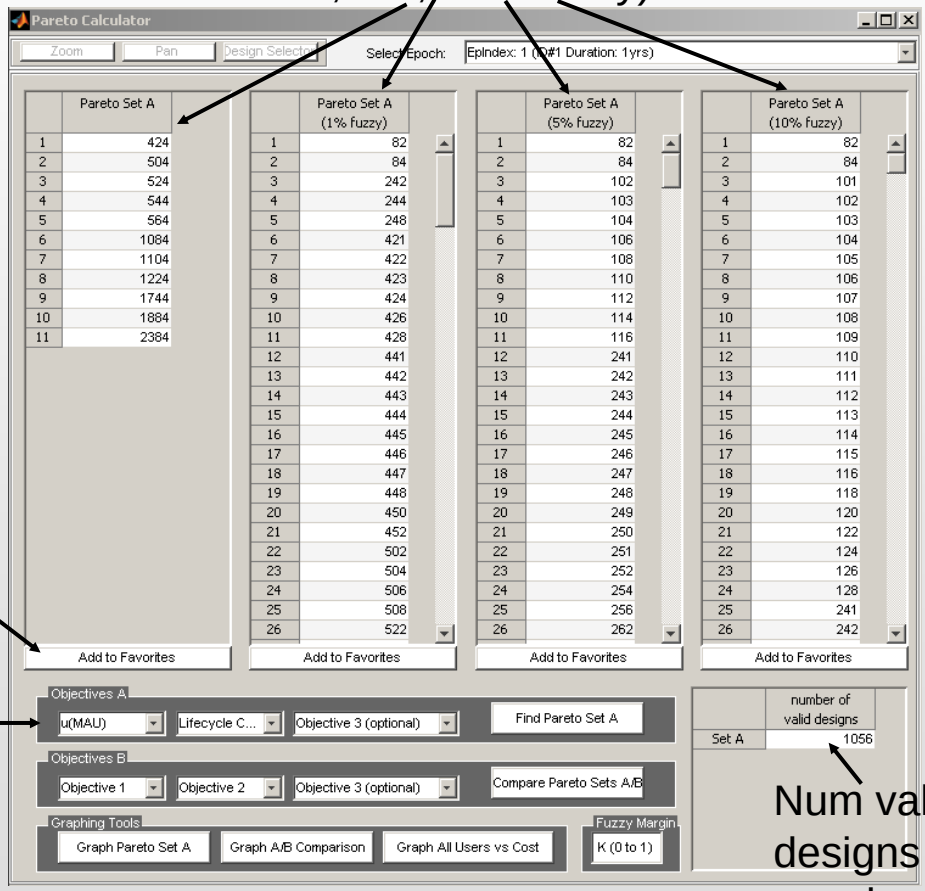
Send to comparison tool

Pareto Tool

The Pareto widget calculates multi-objective fuzzy pareto sets across single or multiple DMs



Find Pareto sets (0%, 1%, 5%, 10% fuzzy)



Quickly add to favorites

Specify objectives

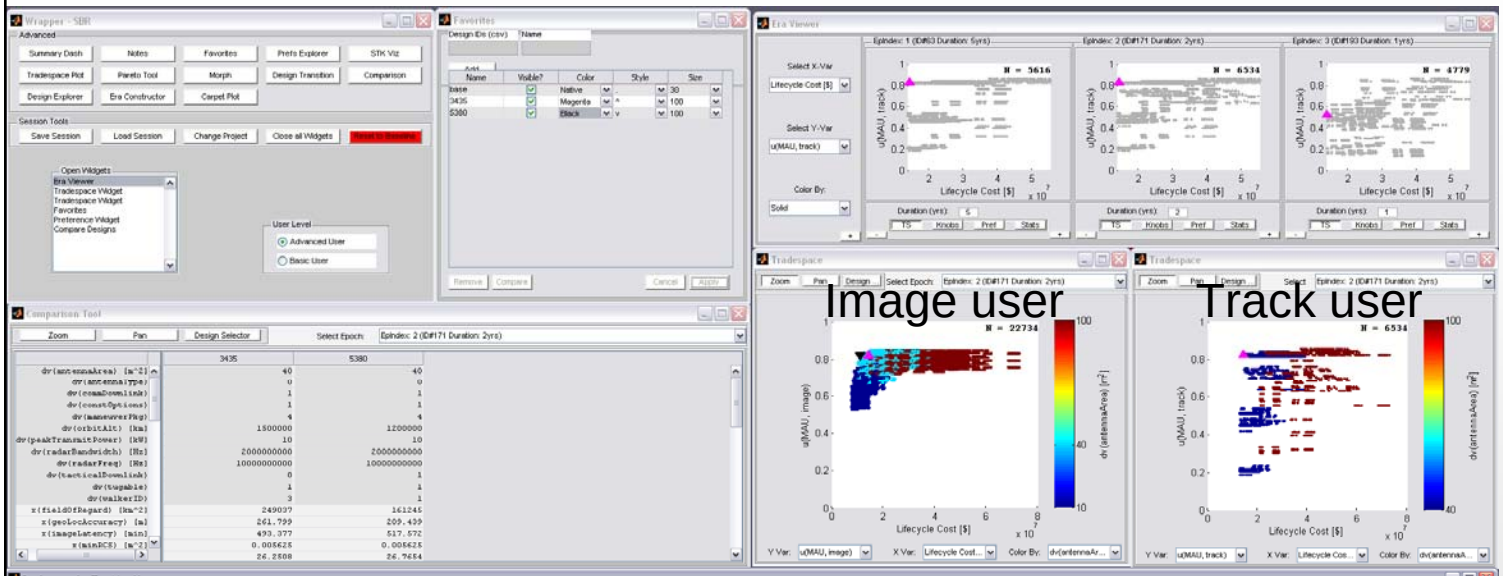
Num valid designs in epoch

Features

- Up to 3 objectives for one or 2 DMs*
- Can specify fuzzy margin for 2 (or more) DMs
- Can bring up specialized graphical comparison across mutiple DMs

* 2 DMs were chosen to demonstrate capability; generalizeable to more DMs, but interface will need to be revised

Example Emergent Insights



Key

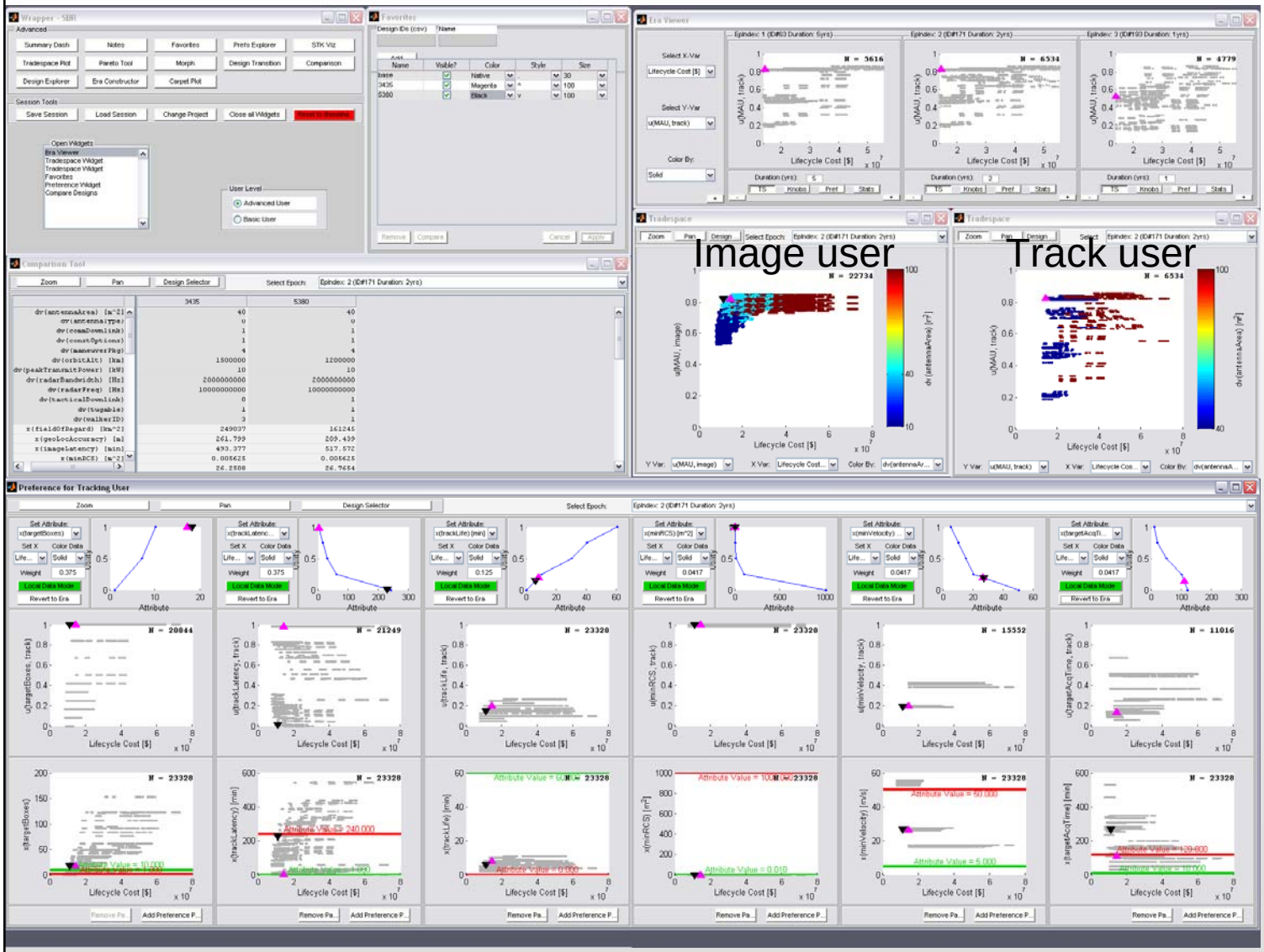
- ▲ Design 3435
- ▼ Design 5380

Design 3435 is good for track user, but only okay for image user.

Design 5380 is better for image user.

Where is design 5380 on track user tradespace?

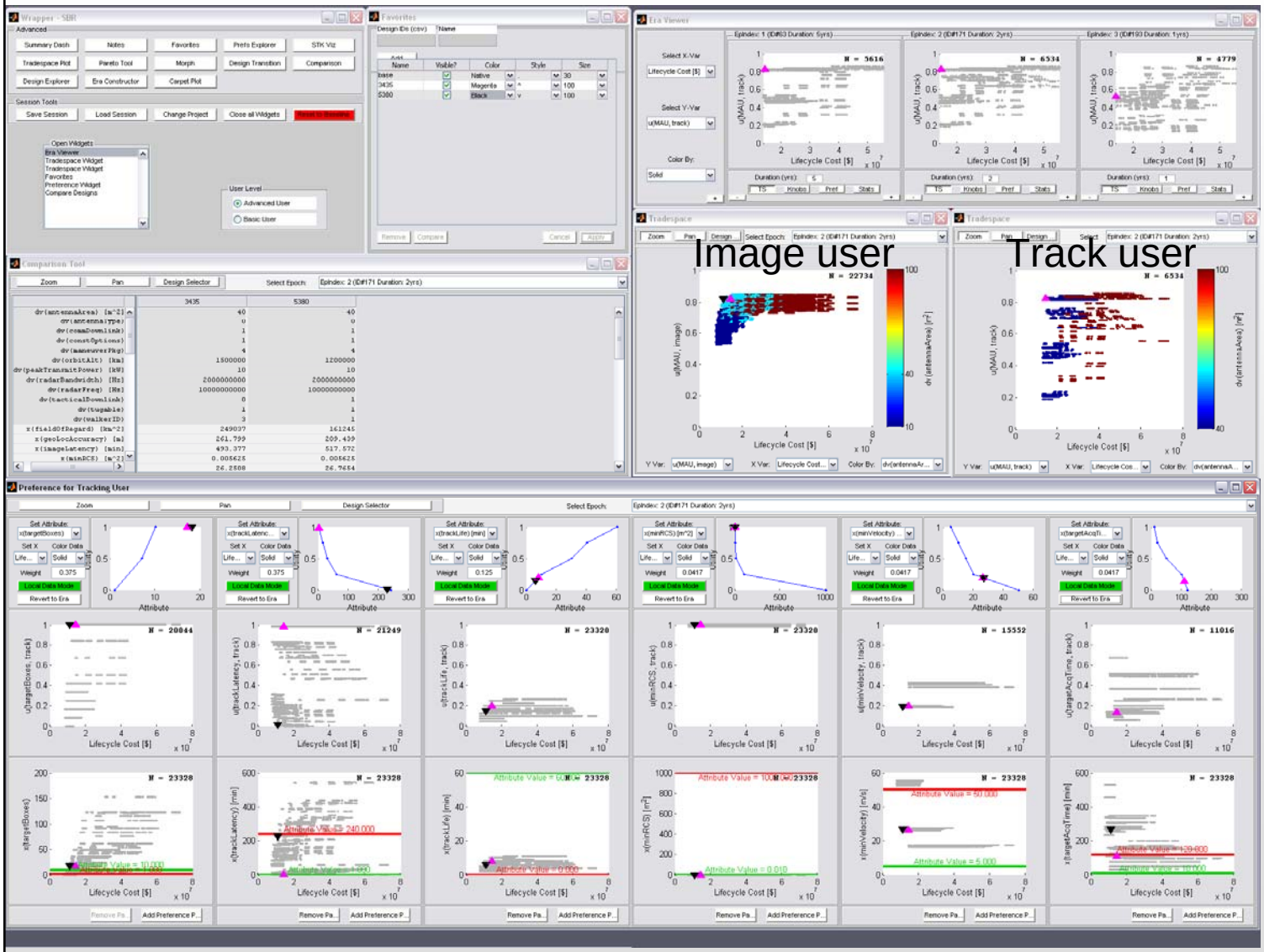
Example Emergent Insights



Key

- ▲ Design 3435
- ▼ Design 5380

Example Emergent Insights

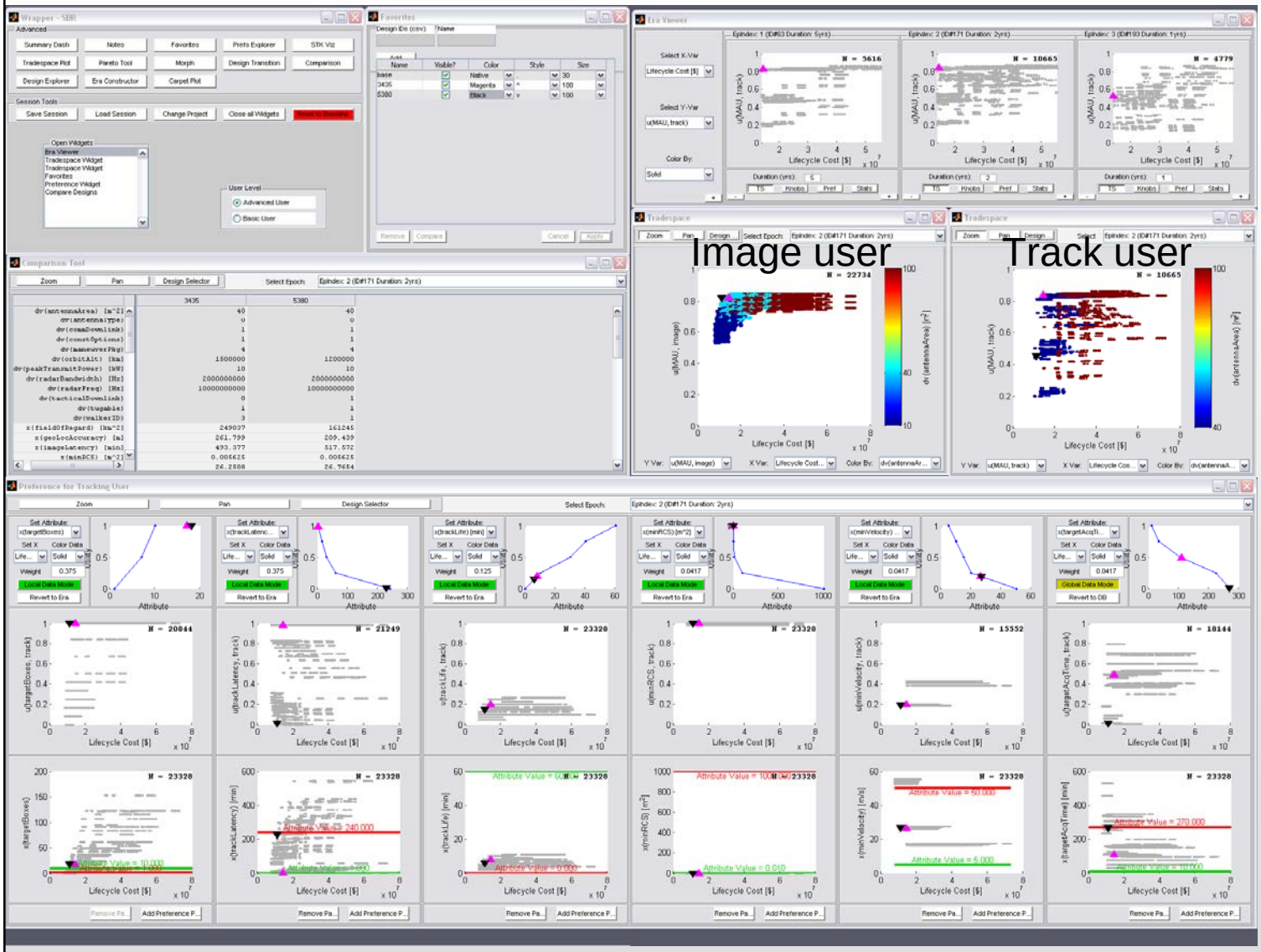


Key

- ▲ Design 3435
- ▼ Design 5380

Find offending constraint

Changing Preferences in Real Time



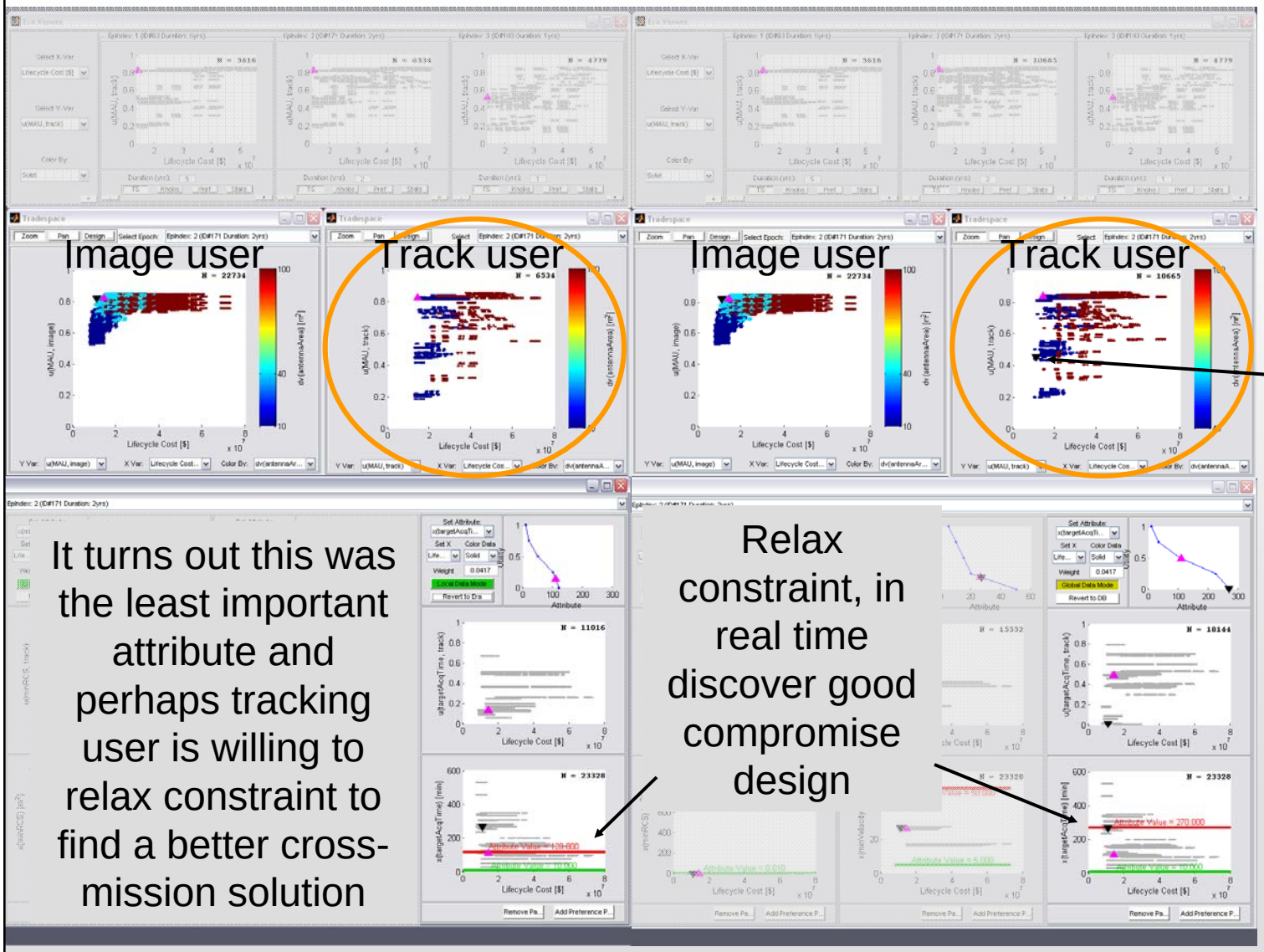
Key

- ▲ Design 3435
- ▼ Design 5380

Find offending constraint

Relax offending constraint

Discovering Compromises



Key

- ▲ Design 3435
- ▼ Design 5380

Design is now valid

It turns out this was the least important attribute and perhaps tracking user is willing to relax constraint to find a better cross-mission solution

Relax constraint, in real time discover good compromise design

Enabling Environment

Enhancing Anticipatory Capacity

Dynamic tradespace exploration performed by multi-disciplinary teams using model-based environments:

- Physical collaboration venue to bring together relevant stakeholders
- Provides computing power and toolsets need to enact anticipation methods
- Enables effective display of complex data sets and analyses to facilitate communication

Anticipatory capacity of an engineering organization will be enhanced by ….

Tradespace exploration laboratories for creating models so that dynamic futures can be elaborated and their implications considered

Plans for Fall

Tradespace Exploration Studies

- Demonstrate at least two additional datasets in lab

Scalability Testing

- Conduct several scalability cases supported by lab

Enhanced Analysis

- Propose and test new metrics, including recent research-proposed
- Develop draft tradespace exploration “handbook”
- Develop algorithms and widgets for supporting the development of system evolution strategies

Enhanced Visualizations

- Develop new, high priority widgets
- Refine interface

Sponsor-based decision makers plan to visit to conduct negotiation role-playing to test the ability of the lab to enhance communication