SEAri Short Course Series

Course: PI.27s Value-driven Tradespace Exploration for System Design

Lecture: Lecture 10: Development of a Tradespace Exploration Laboratory

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Lecture Number: **SC-2010-PI27s-10-1**

Revision Date: July 24, 2010

This course was taught at PI.27s as a part of the MIT Professional Education Short Programs in July 2010 in Cambridge, MA. The lectures are provided to satisfy demand for learning more about Multi-Attribute Tradespace Exploration, Epoch-Era Analysis, and related SEAri-generated methods. The course is intended for self-study only. The materials are provided without instructor support, exercises or "course notebook" contents. Do not separate this cover sheet from the accompanying lecture pages. The copyright of the short course is retained by the Massachusetts Institute of Technology. Reproduction, reuse, and distribution of the course materials are not permitted without permission.

Systems Engineering Advancement Research Initiative

[PI.27s] Value-Driven Tradespace Exploration for System Design

Lecture 10
Development of a Tradespace Exploration Laboratory

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Outline

- Tradespace representations
- Dimensionality of data
- Tradespace exploration facility
- Users, views, and widgets
- Example application

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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

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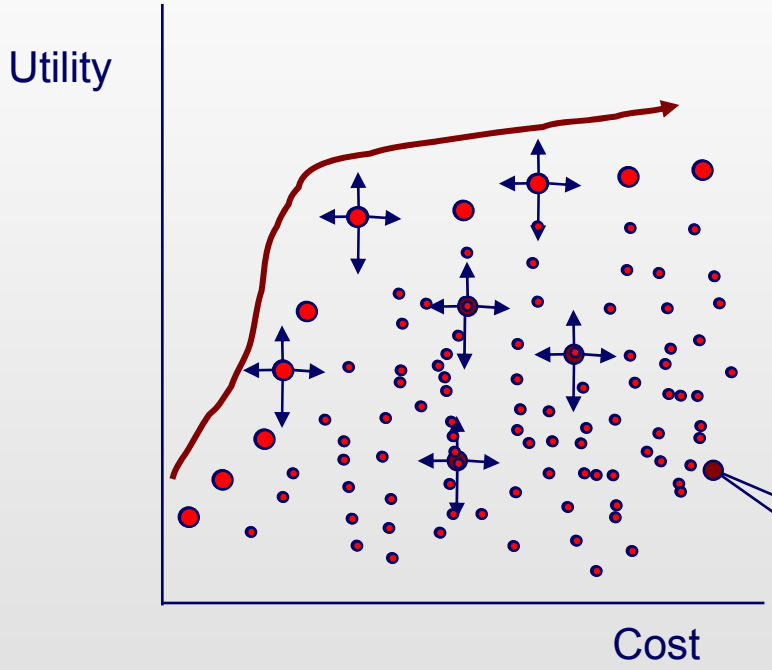
Tradespace Exploration Paradigm: Avoiding Point Designs



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

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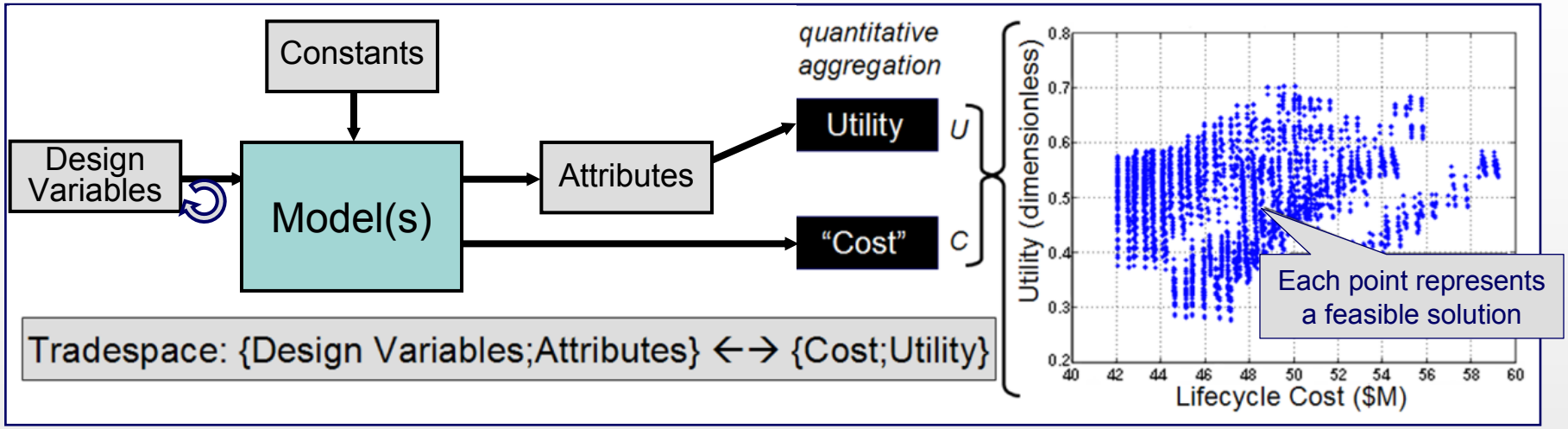
Value-Driven Tradespace Exploration



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)

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

Value-based assessments allow for comparison of many different alternatives

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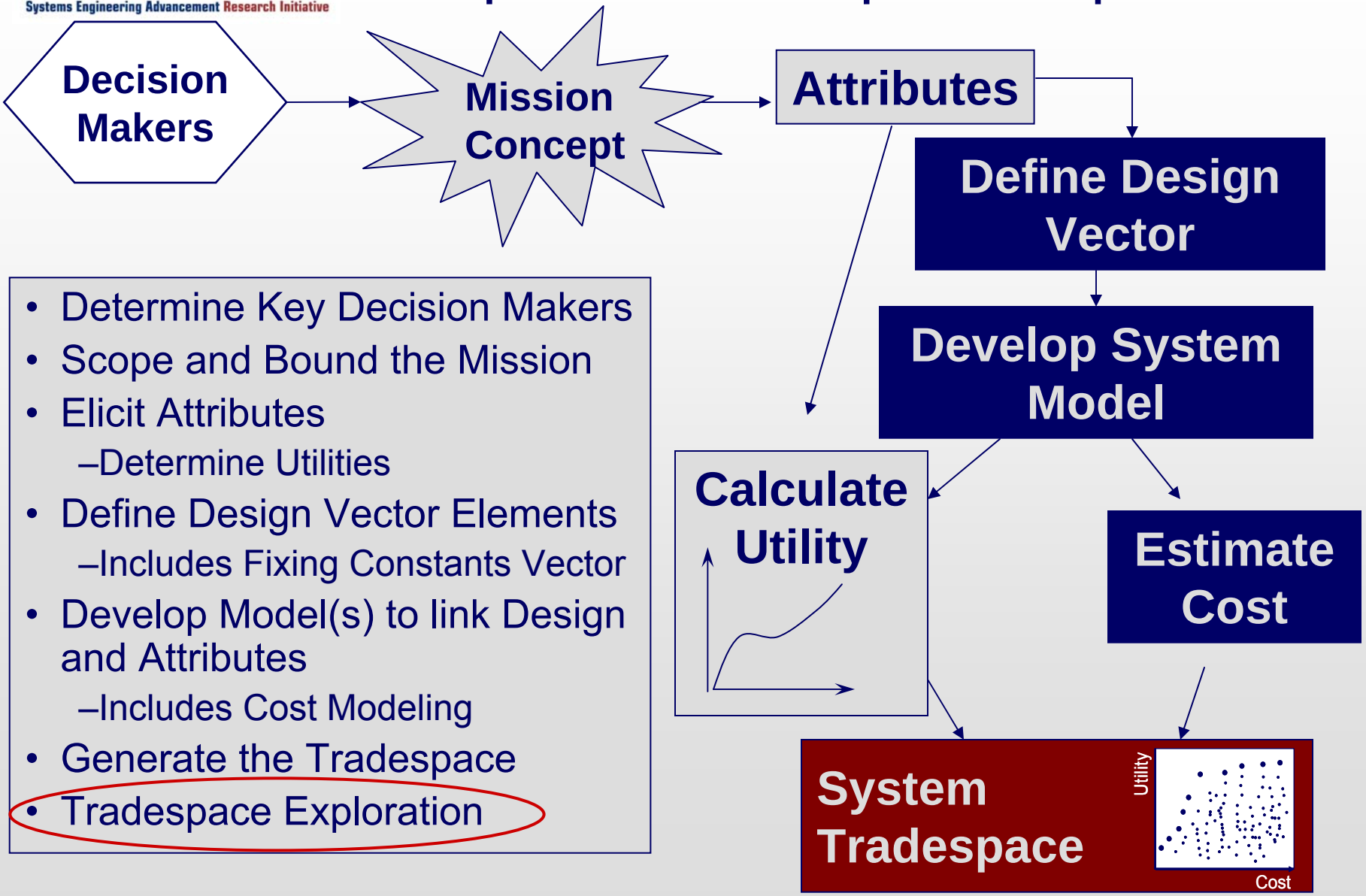
Steps for Tradespace Exploration



- 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

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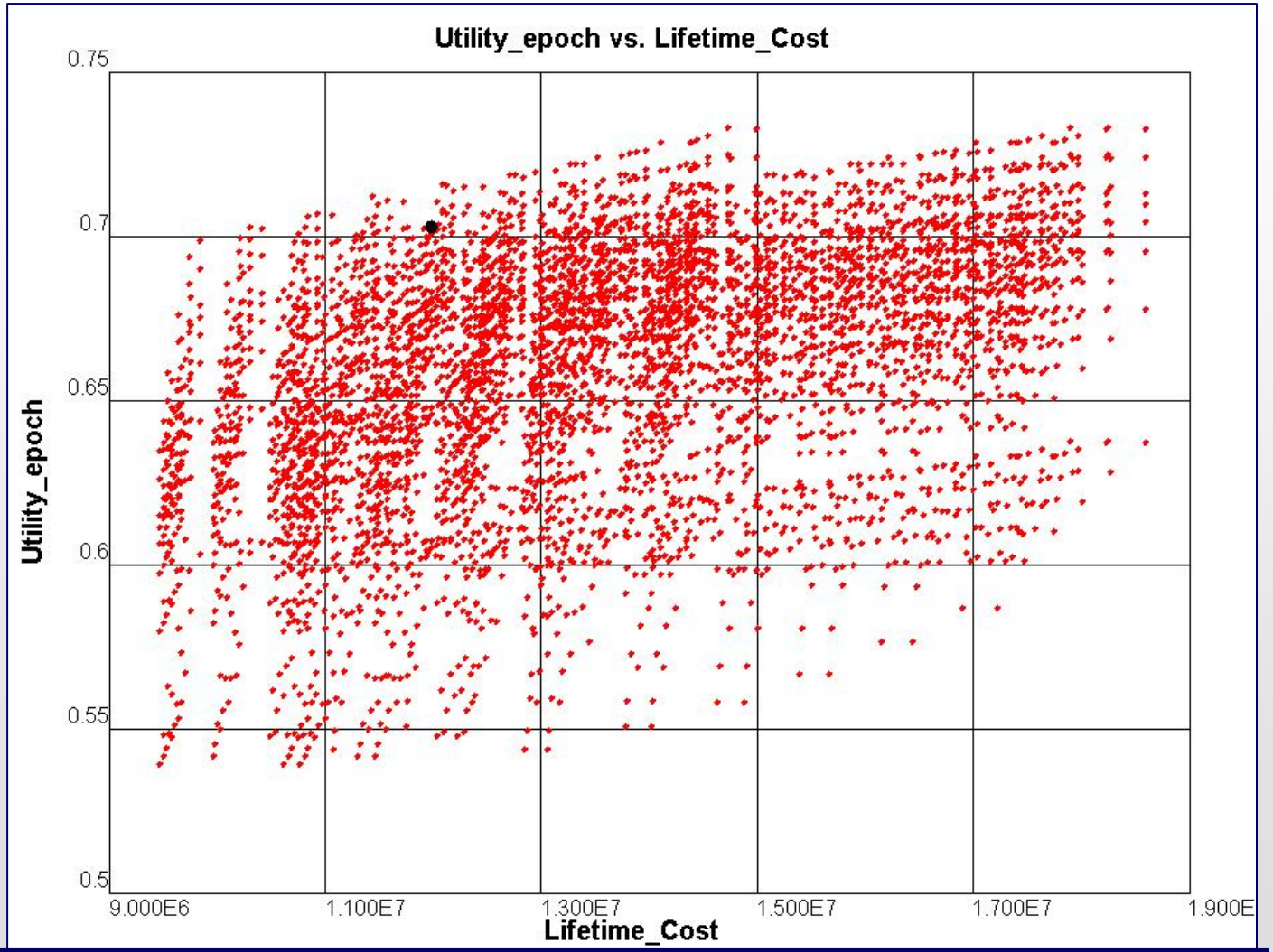
Tradespace Data Representation

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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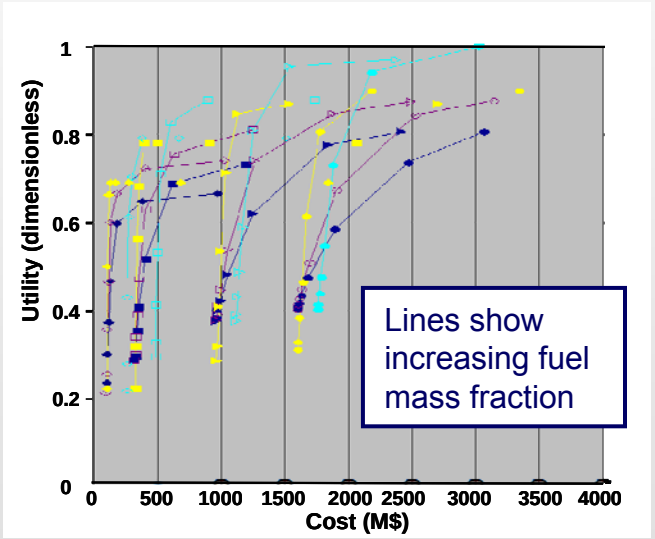
Example Tradespace Insights

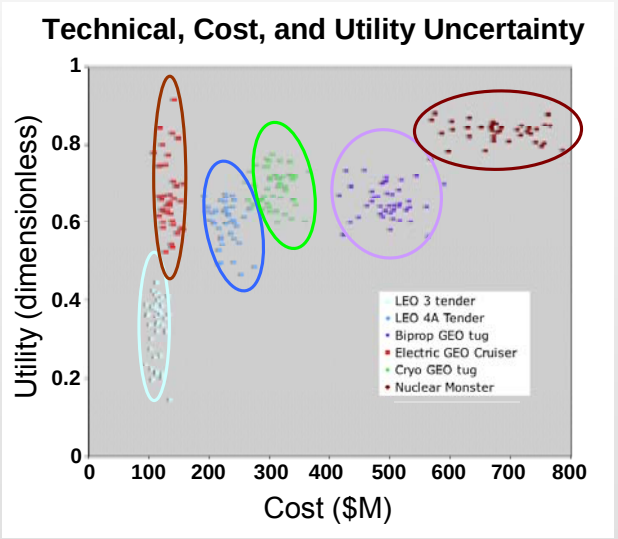
SPACETUG
- General purpose orbit transfer vehicles
- Trades propulsion systems and grappling/observation capabilities

Understanding limiting physical or mission constraints



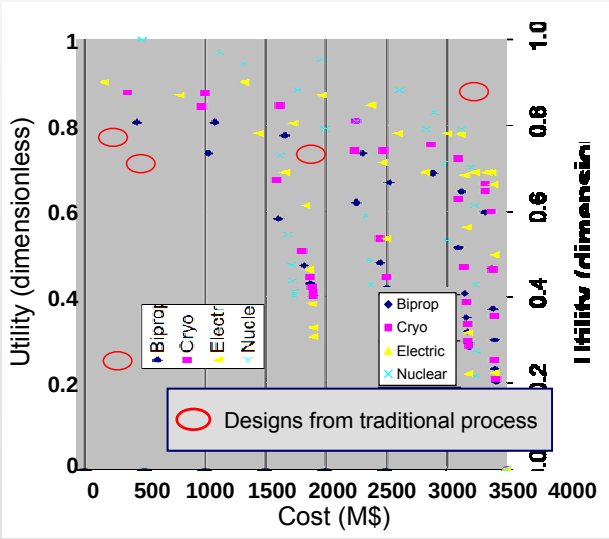
Hits "wall" of either physics (can't change) or utility (can)

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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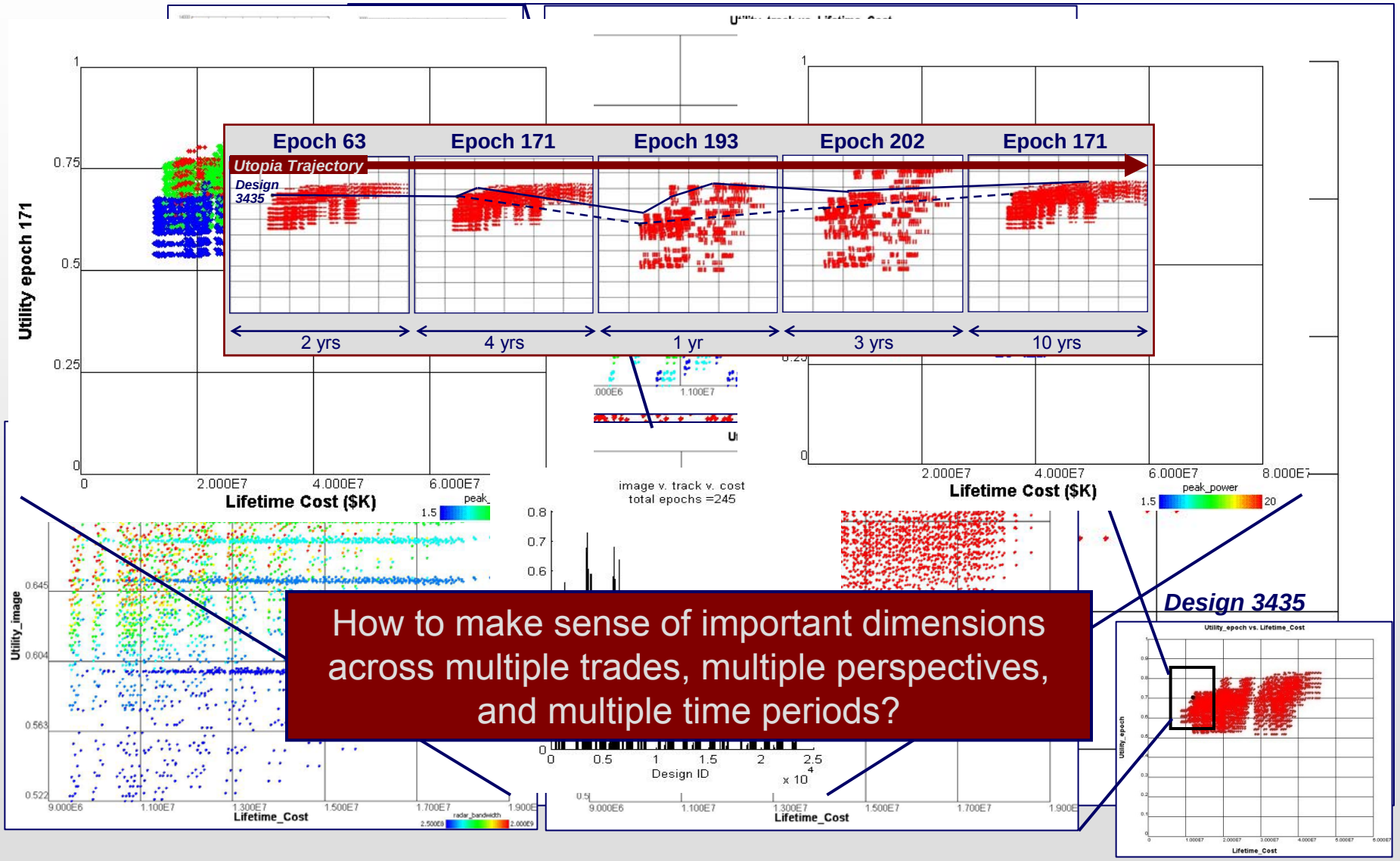
Many Important Dimensions



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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

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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.

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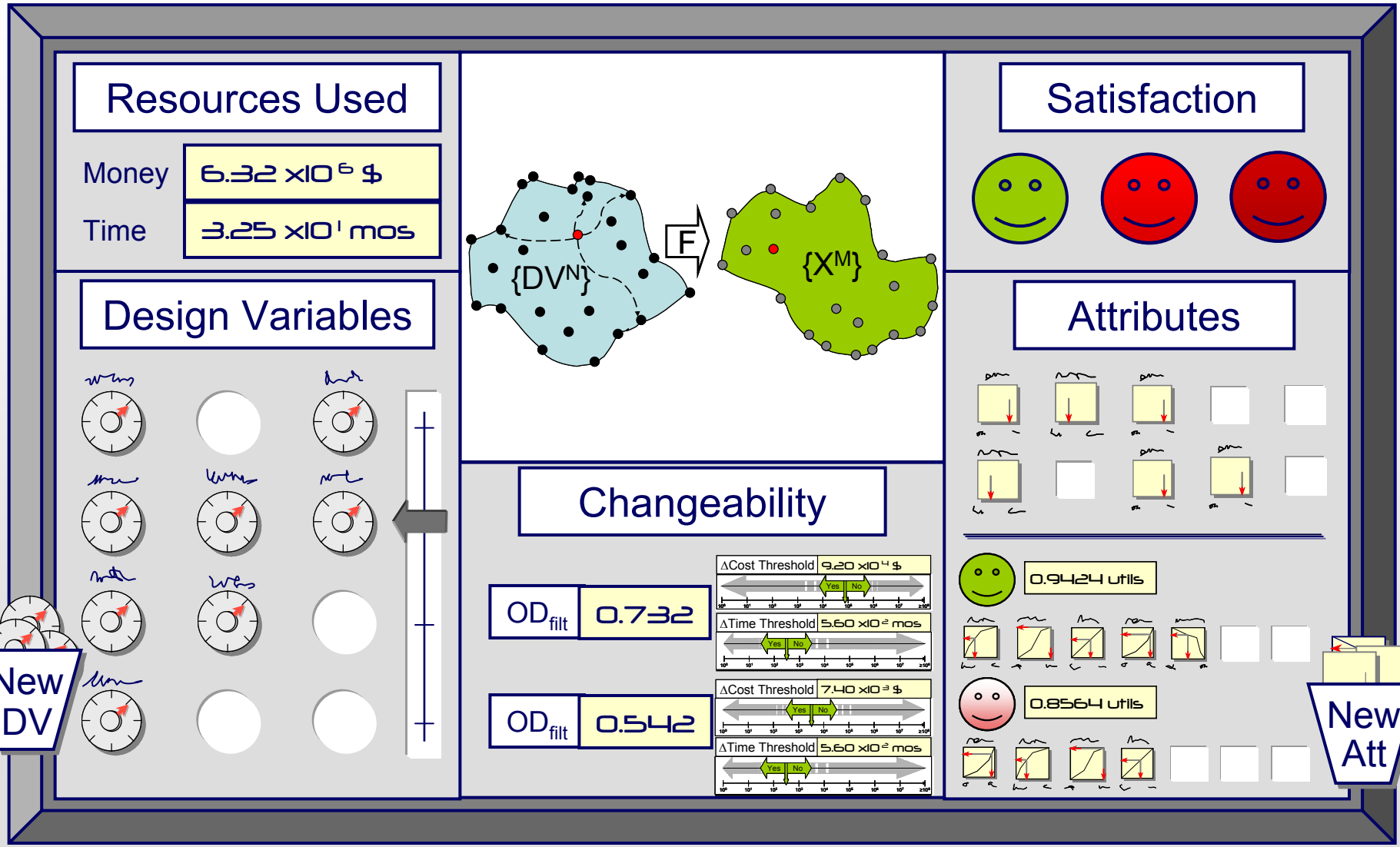
Original Concept: A Design Exploration Console



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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

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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

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Vision for TSE Lab: Summer 2009

- 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

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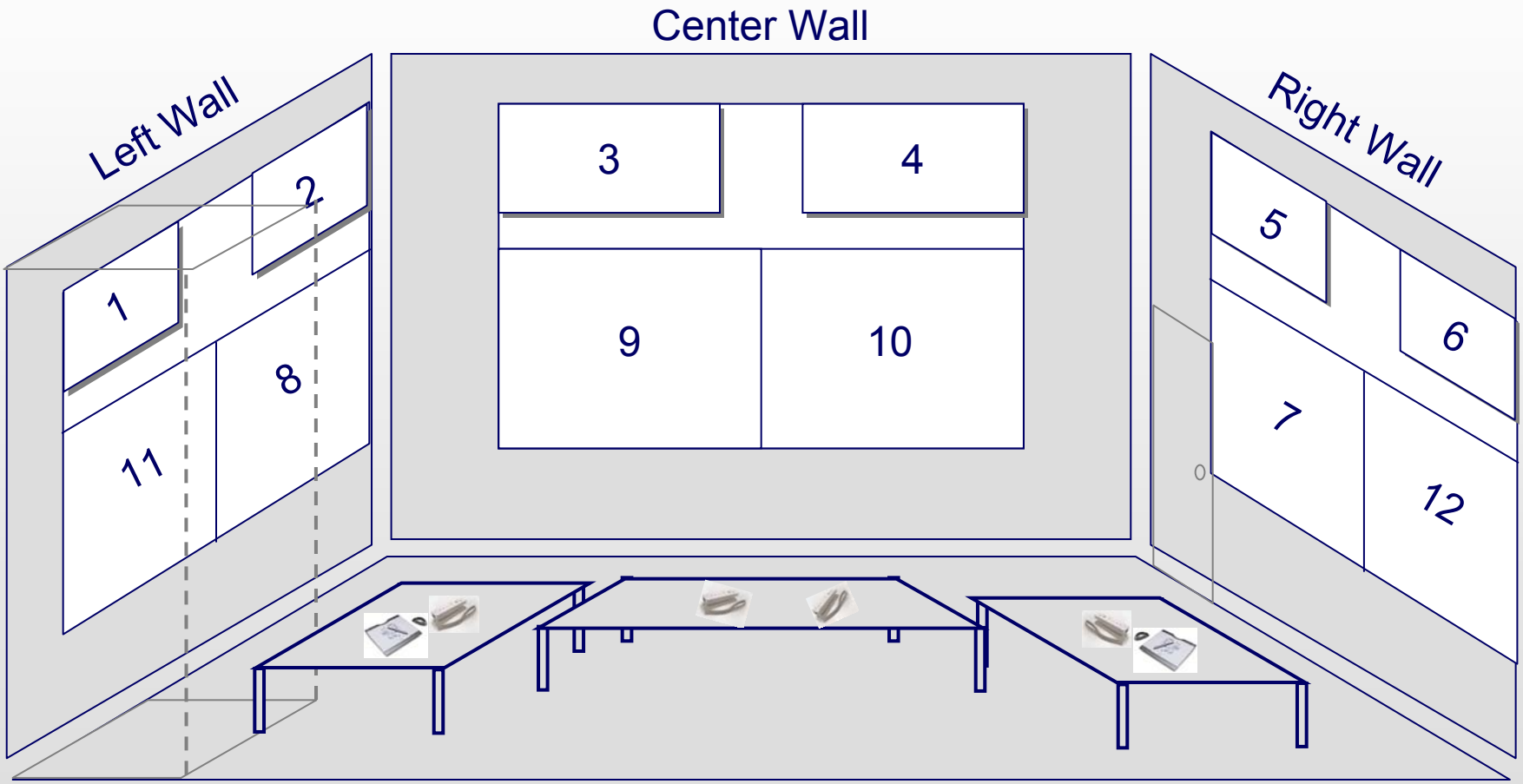
Tradespace Exploration Lab



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

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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

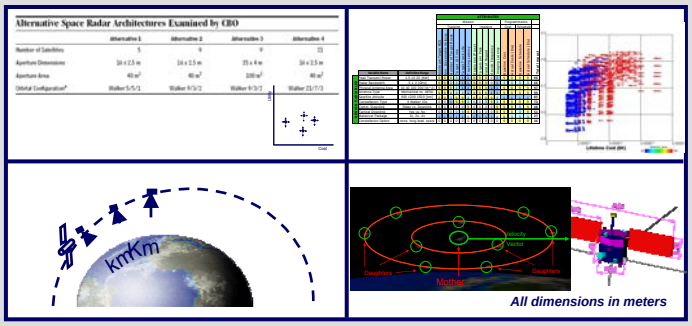
Level of analysis: high / low

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

Widgets

Technical complexity: low — high

Level of analysis: high / low



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Three "Types" of Lab Users

- Expert Tradespace Analyst
  - All widgets available by default
  - May tend toward high technical complexity, with both high and low level of analysis

Developing this capability first

- 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")

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Tradespace Exploration Laboratory

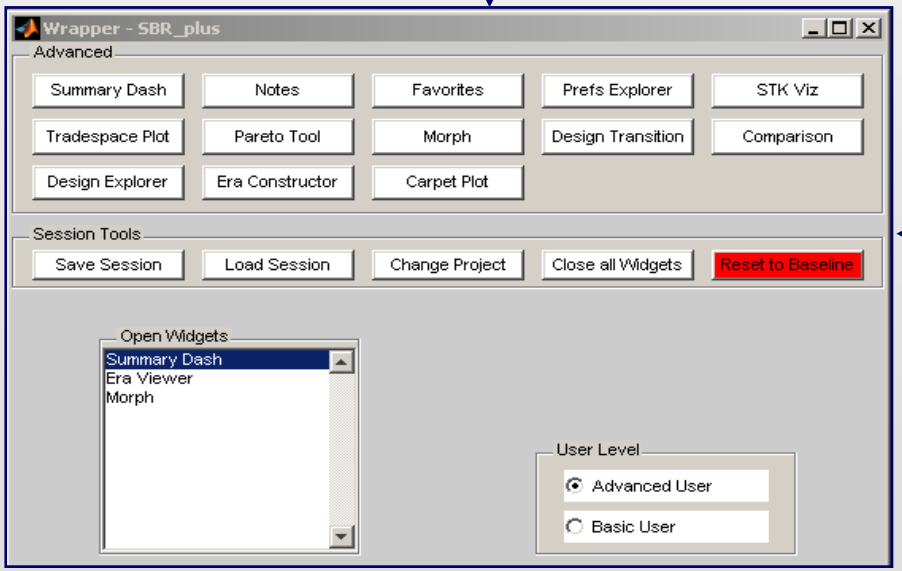
Select project

- 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

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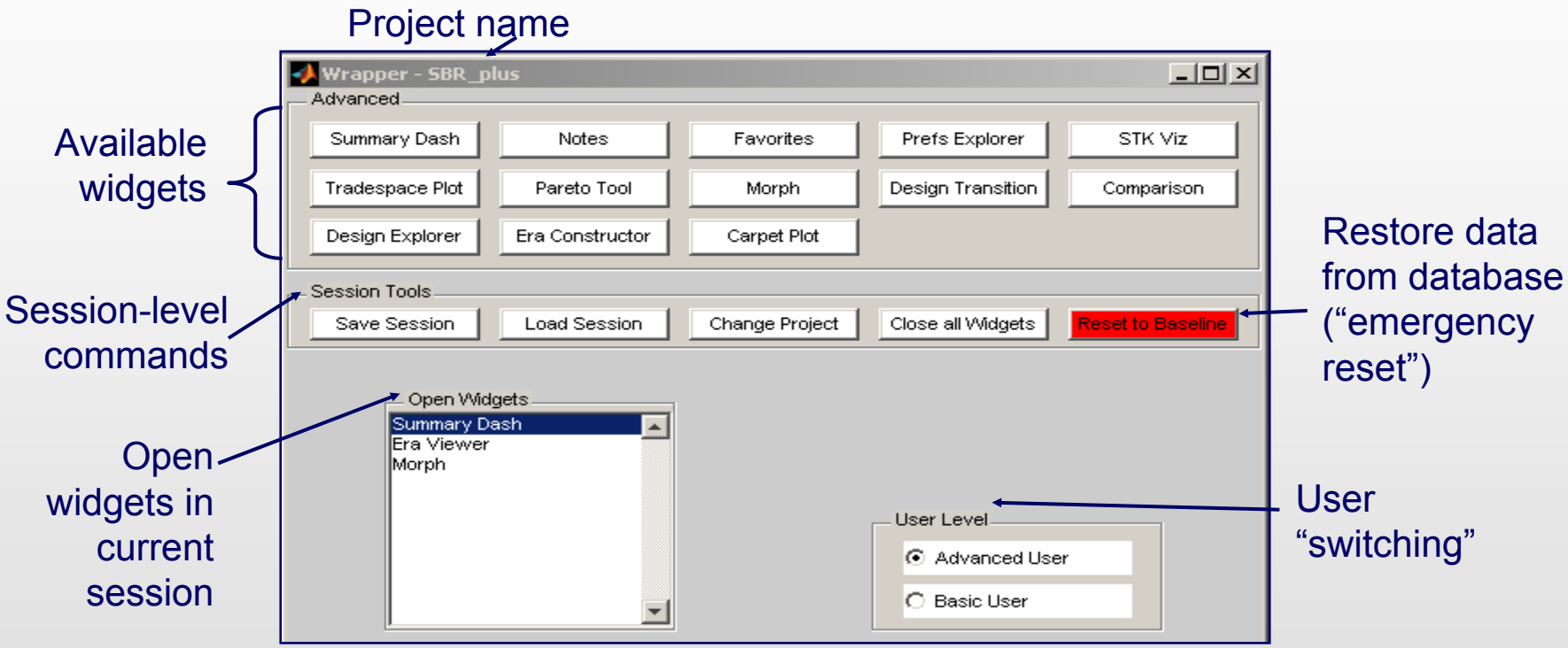
Wrapper

The wrapper is the main control panel for calling widgets



The wrapper layout is for demonstration purposes

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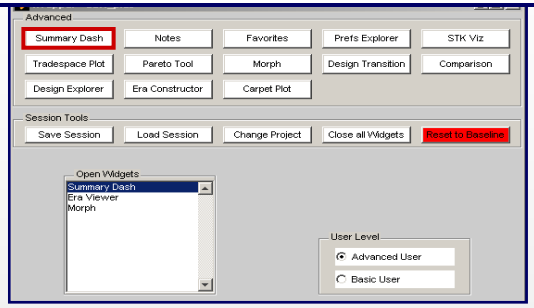
Summary Dash

The Summary Dash gives overall info on DB, tradespace and epoch-space sizes

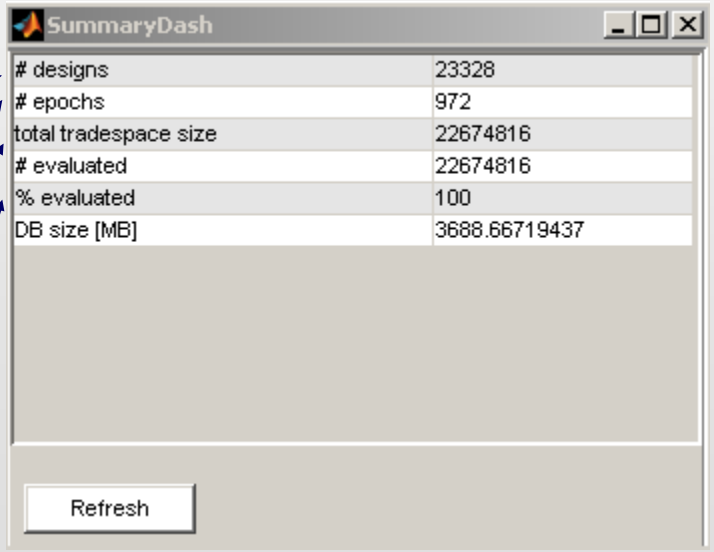


Num designs per tradespace

Num epochs (context var enumeration size)

Num designs across all contexts

Fraction total designs evaluated in DB



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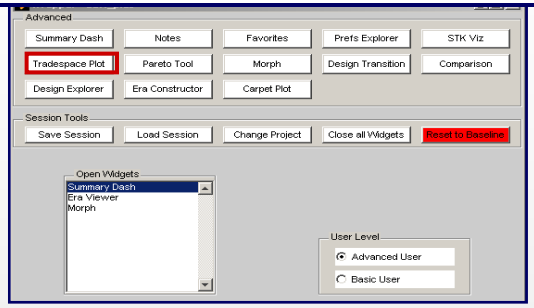
Tradespace Plot

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



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

"Click on point" capability

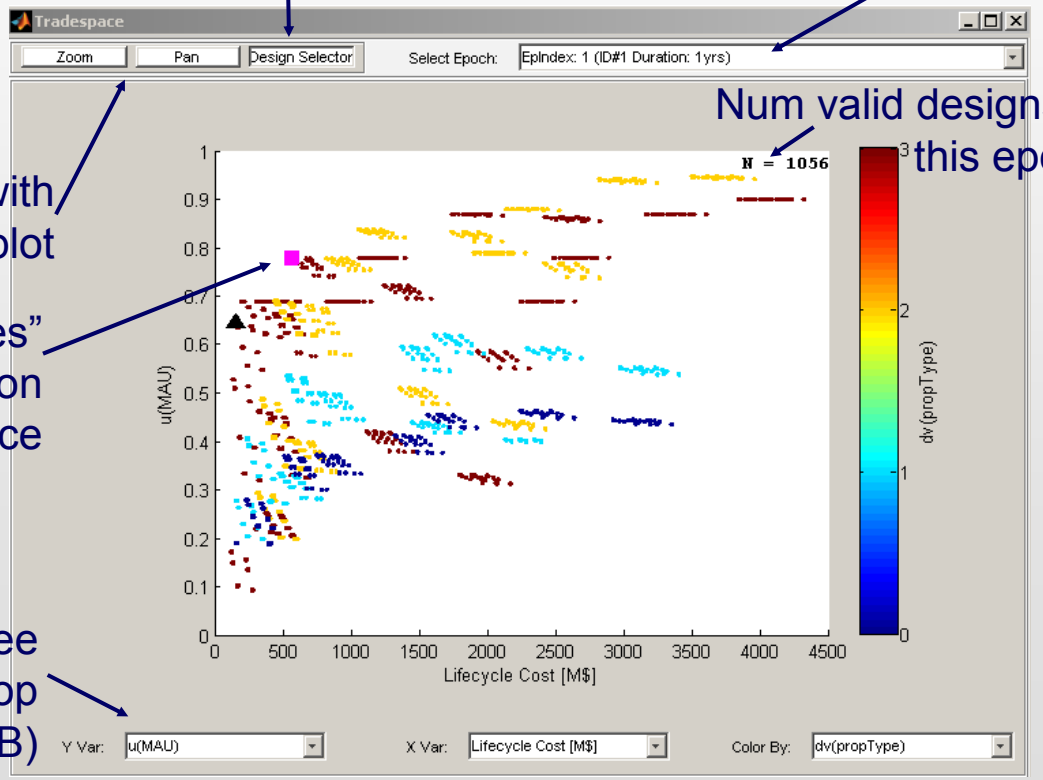
Select current epoch (from Era or other)

Num valid designs in this epoch

Interact with plot

"Favorites" plotted on tradespace

Plot three dimensions (drop downs from DB)



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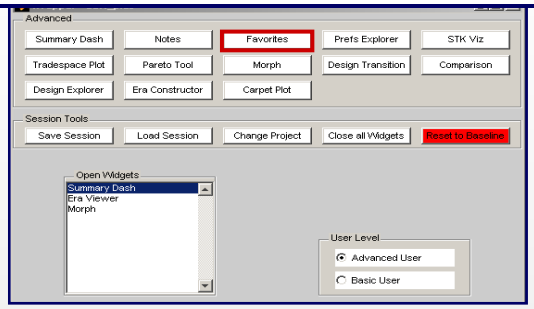
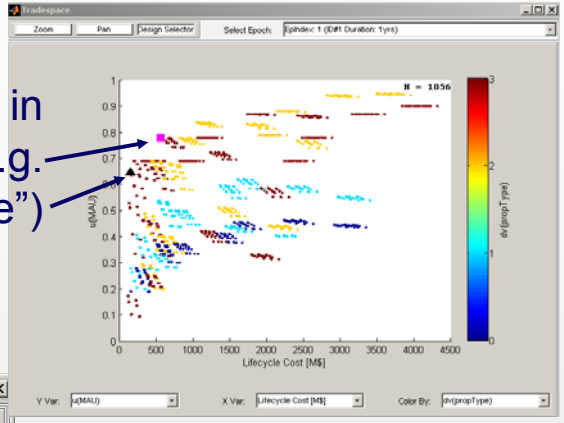
Favorites

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



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



Features

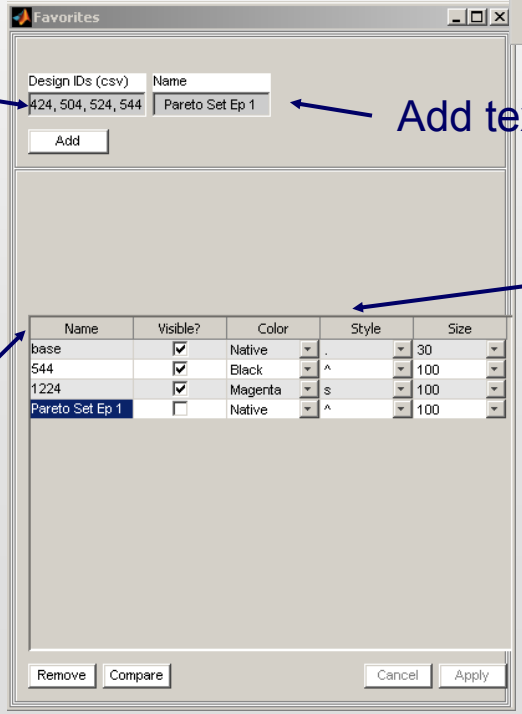
- Single or multiple designs can be grouped as a favorite
- Each favorite can be consistently displayed and formatted across widgets

Enter design ID(s)

Add text label

Specify plot formatting for each favorite

List of all favorites



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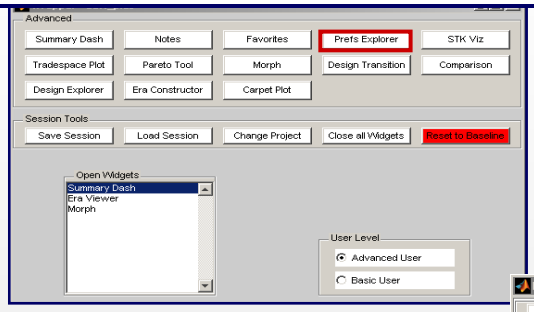
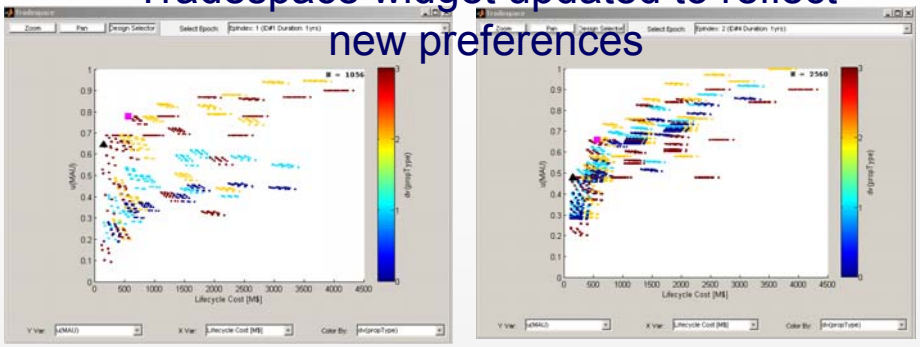
Preferences Explorer

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



Tradespace widget updated to reflect new preferences



SAU curves

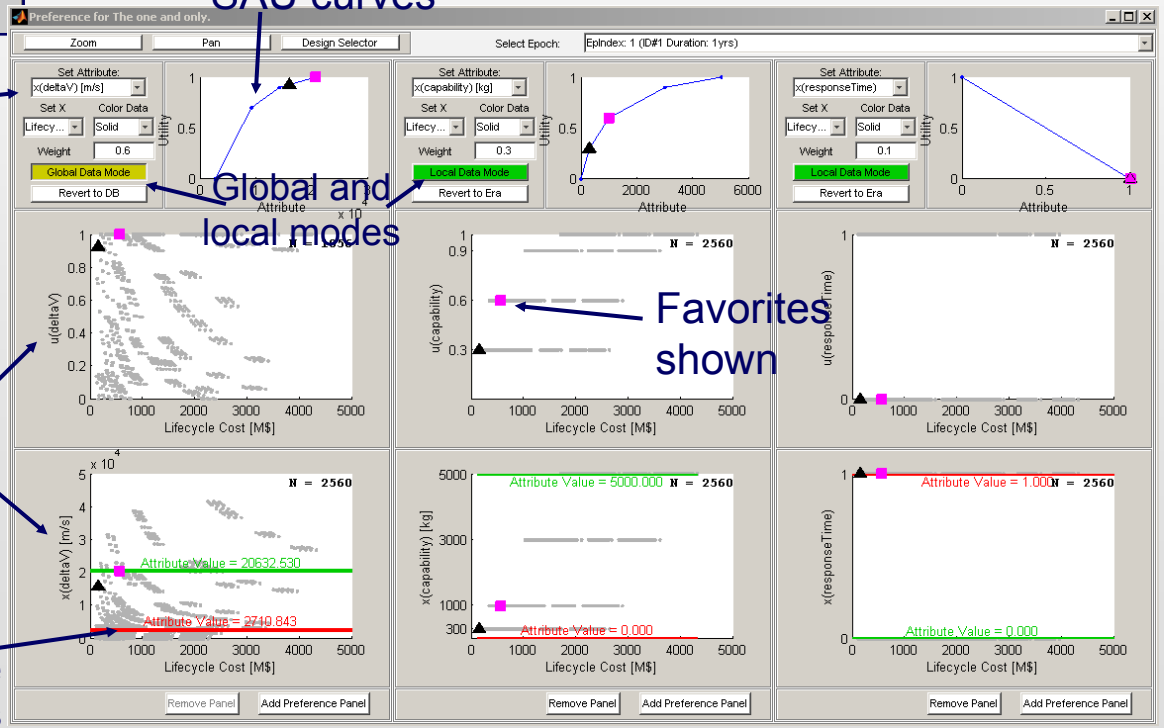
Select attribute

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

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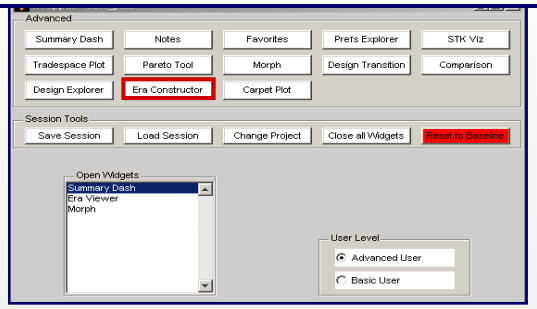
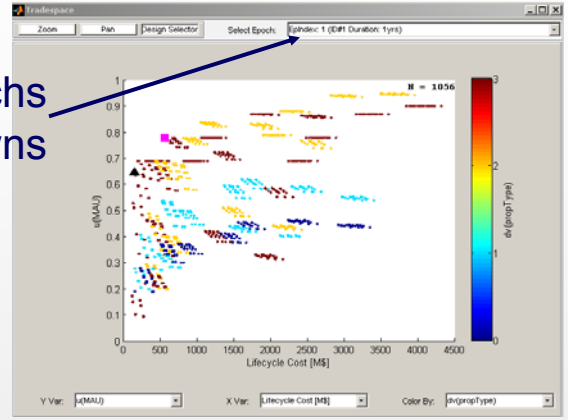
Era Constructor

The Era Constructor displays and allows to be edited the current set of epochs in the era



Determines epochs for dropdowns



Features

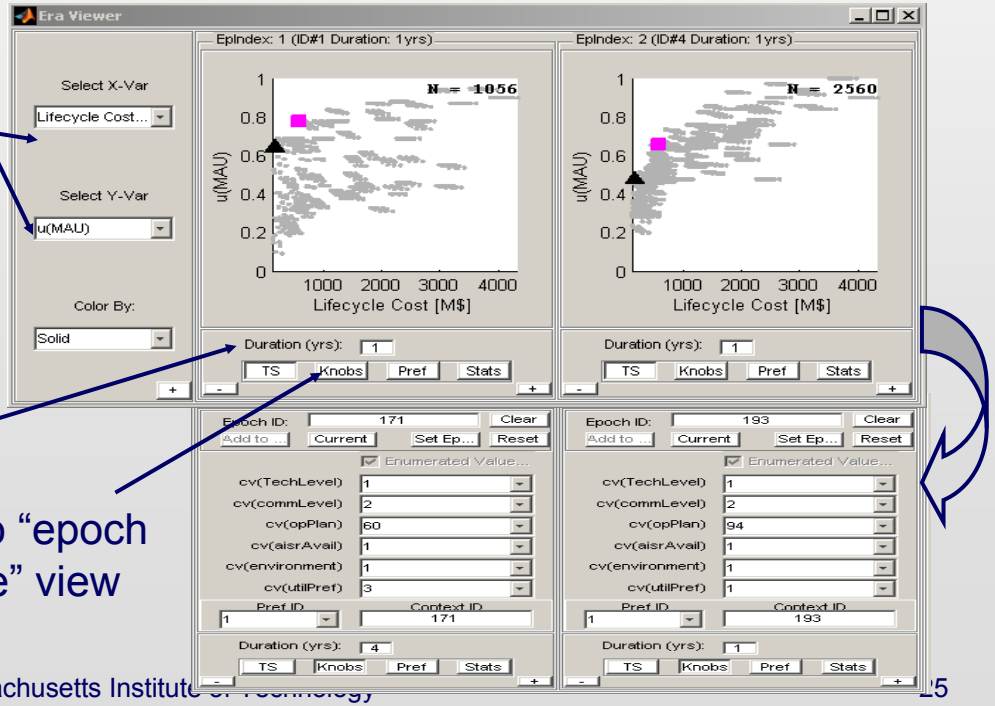
- Specify epochs (context and prefs) in current era
- Each epoch context variables and preferences can be reviewed*

*mini pref viewer under development

Select plot variables

Specify duration

Switch to “epoch variable” view



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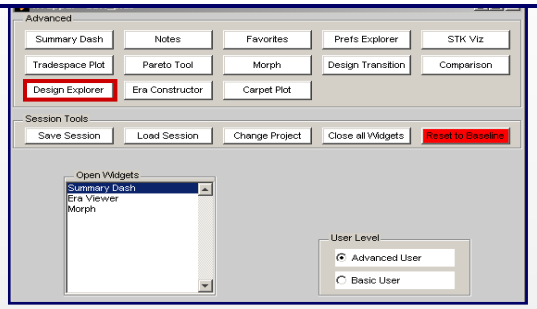
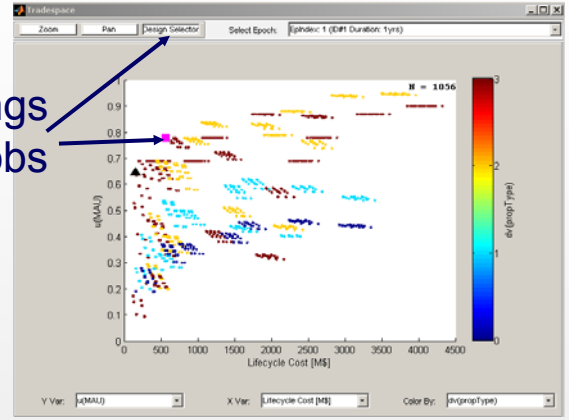
Design Explorer

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



"Click on point" brings up design knobs



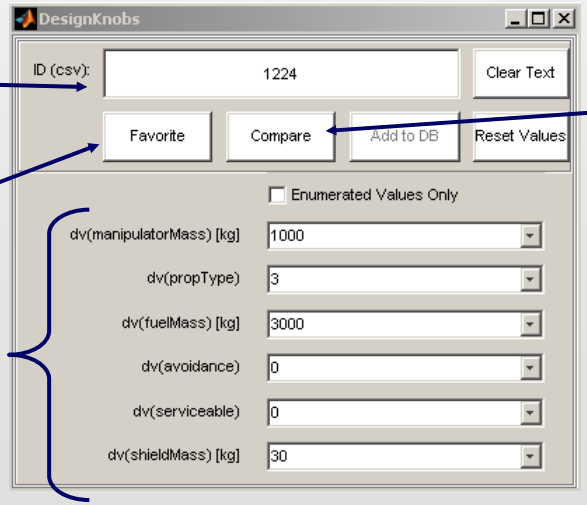
Features

- 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

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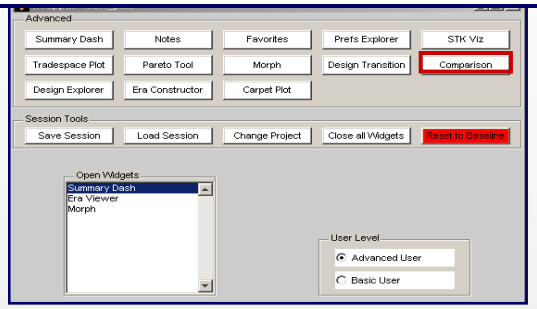
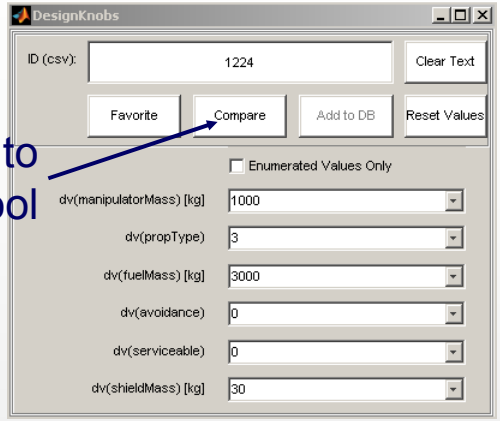
Comparison Tool

The Comparison Tool shows DB info in table for selected designs to compare details



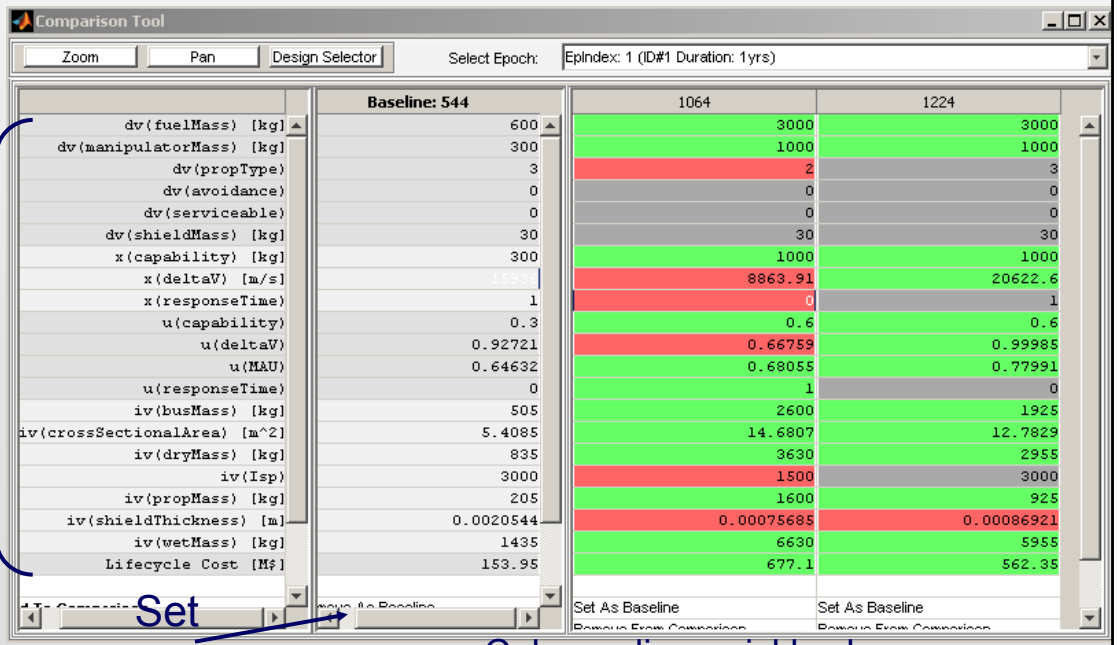
Send to comparison tool



Features

- Shows DB info for designs in tabular form
- Single or multiple designs can be compared
- Simple color coding highlights differences from specified baseline

DB info for "compared" designs



Set baseline

Color coding quickly shows differences from baseline (green ~ >, red ~ <, gray ~ =)

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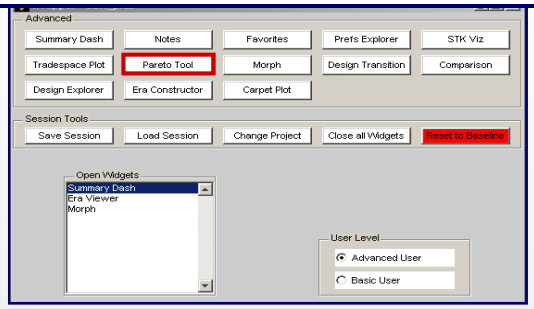
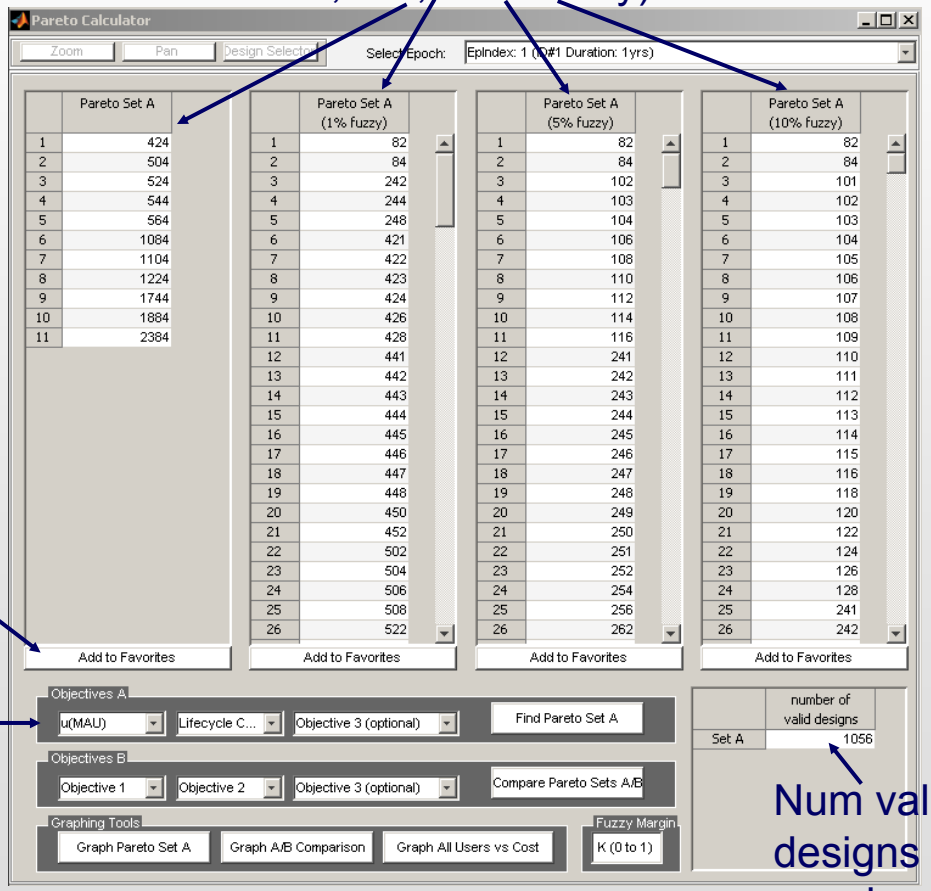
Pareto Tool

The Pareto Tool 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

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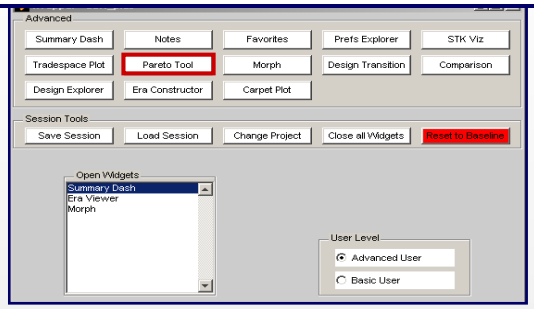
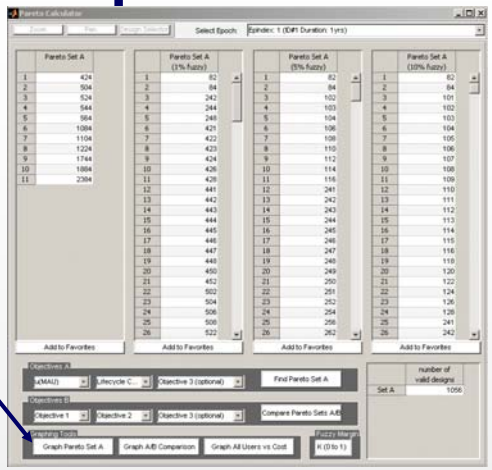
Pareto Graph

The Pareto widget graphs single or multiple DM pareto sets, with fuzziness

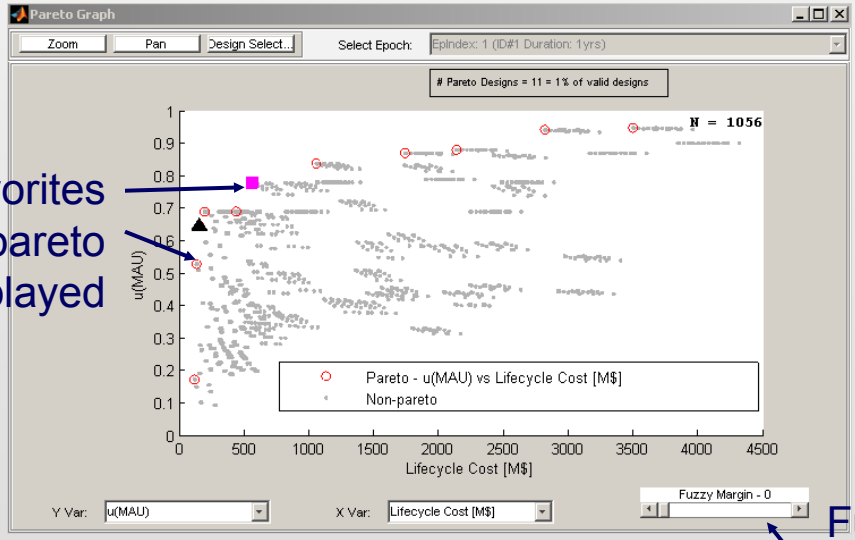




Call from Pareto Tool

Features

- Real time fuzziness control
- Size of pareto set and location in tradespace updated



Favorites and pareto displayed

Fuzziness margin can be changed in real-time

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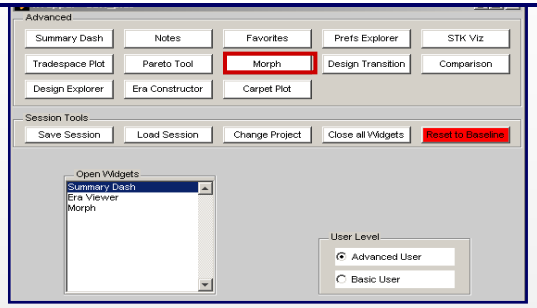
Morph Tool

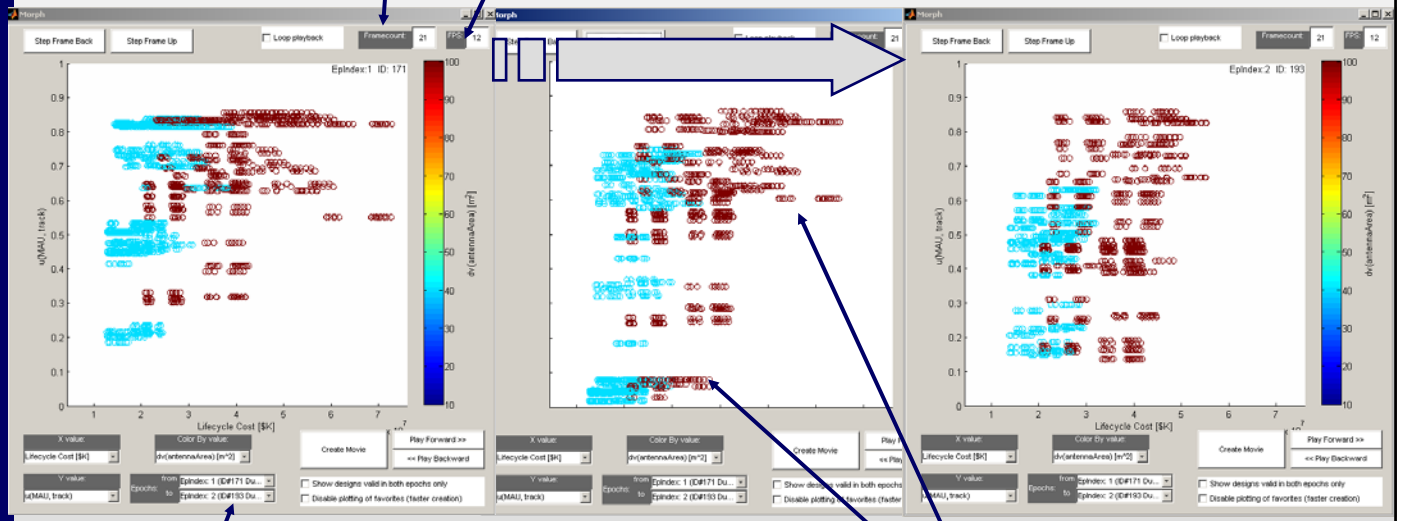
The Morph widget animates the transition between two epochs in the era



Specify framecount and frames per second (FPS)

Features

- Linear interpolates trajectories of designs across two epochs
- Can customize steps size and speed of animation
- Can step through animation and play backwards



Specify start and end epochs

Spot differential "motion" of designs

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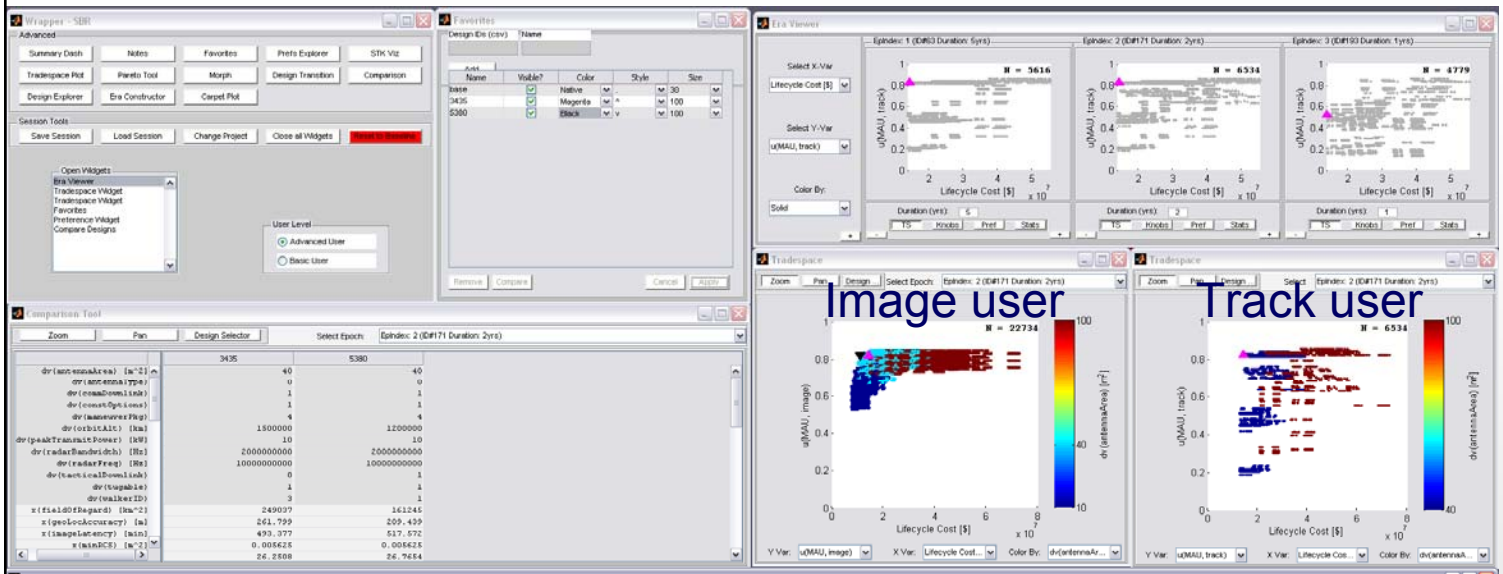
Example Emergent Insights



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?

Find offending constraint

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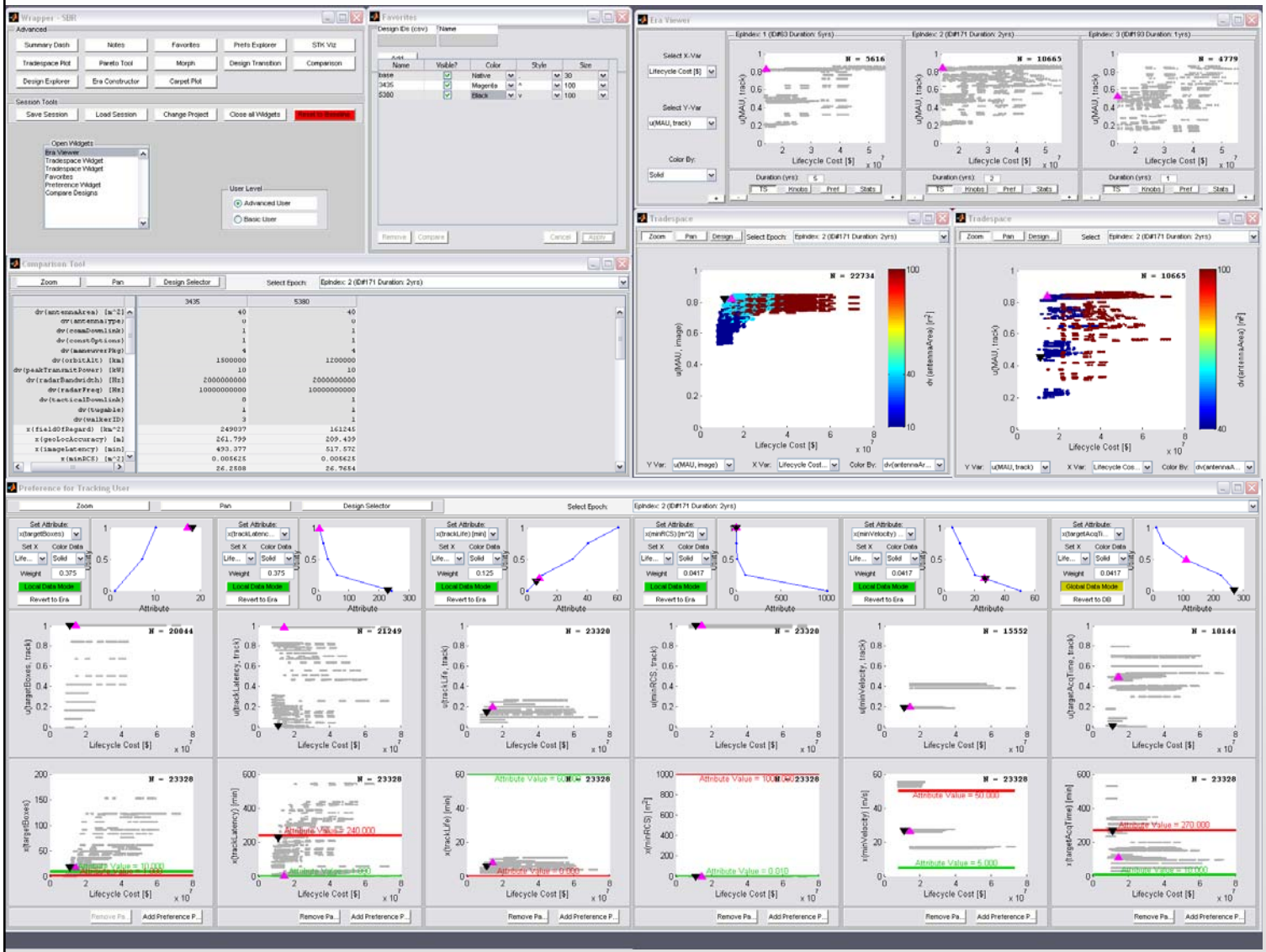
Changing Preferences in Real Time



Key
▲ Design 3435
▼ Design 5380

Find offending constraint

Relax offending constraint

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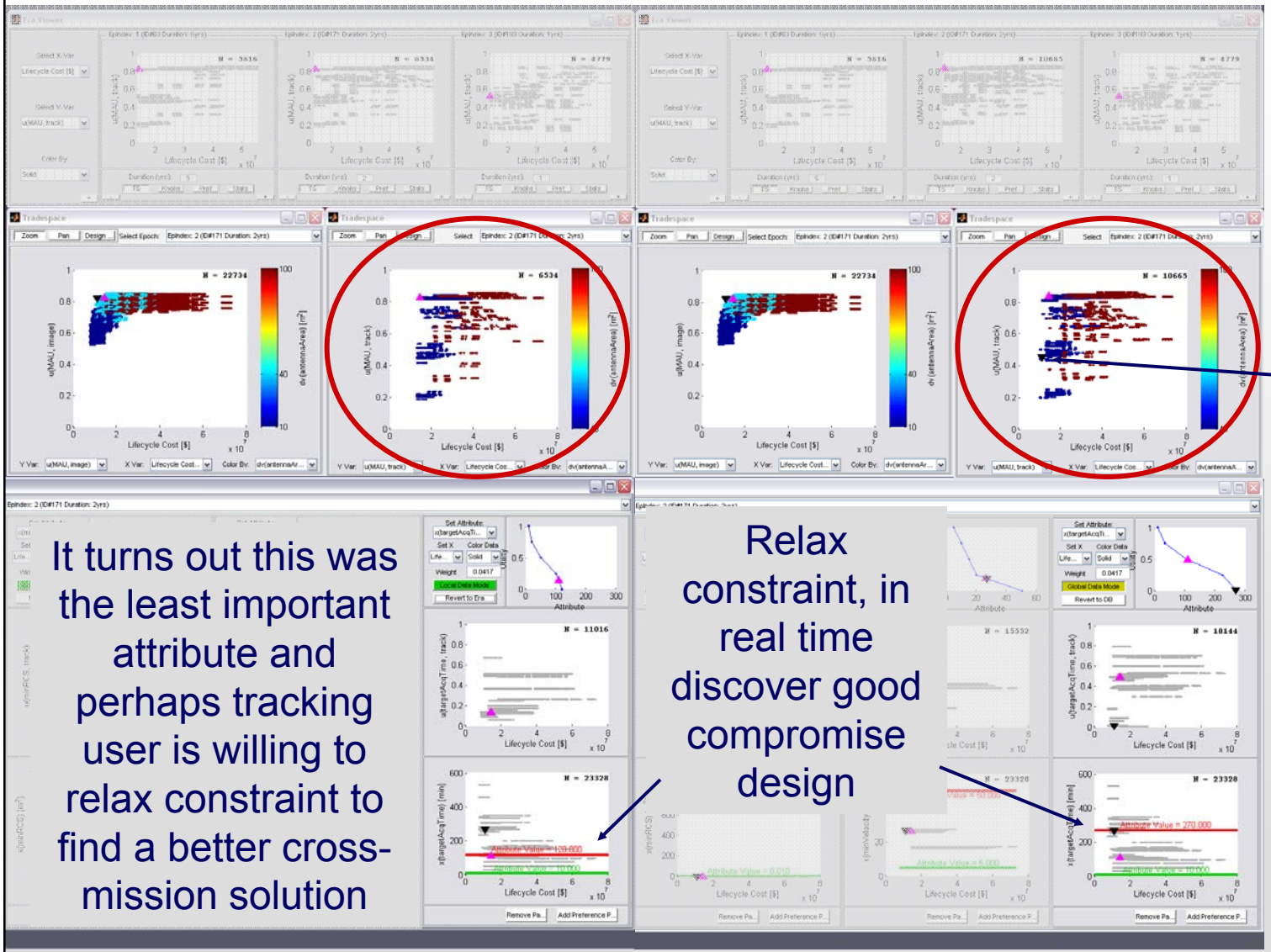
Discovering Compromises



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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

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