Research Topic
“Insights from a Multisensory Tradespace Exploration Laboratory for Complex System Selection”

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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
Tradespace Exploration Paradigm: Avoiding Point Designs

Differing types of “trades”

0. Choose a solution

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

\[ \text{Design}_i = \{X_1, X_2, X_3, \ldots, X_j\} \]
Tradespace Exploration Paradigm: Avoiding Point Designs

Differing types of “trades”

0. Choose a solution

1. Local point solution trades

2. Multiple points with trades

Design$_i$ = \{X$_1$, X$_2$, X$_3$, ..., 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

\[ \text{Design}_i = \{X_1, X_2, X_3, \ldots, X_j\} \]
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

\[ \text{Design}_i = \{ X_1, X_2, X_3, \ldots, X_j \} \]

TradeSpace exploration enables big picture understanding
Value-Driven Tradespace Exploration

**Value-based assessments allow for comparison of many different alternatives**

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

- 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)

Tradespace: \{Design Variables; Attributes\} \leftrightarrow \{Cost; Utility\}
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

Decision Makers → Mission Concept → Attributes

- Define Design Vector
- Develop System Model

Calculate Utility

- Estimate Cost

System Tradespace

Mission Concept

Attributes

Define Design Vector

Develop System Model

Calculate Utility

Estimate Cost

System Tradespace

Cost

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

“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**

**Understanding differential uncertainty**

**Comparing alternatives on common basis**

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

**Different designs subject to different risks**

**Common “value” definition can compare old and new heterogeneous systems**
Many Important Dimensions

Utility_epoch vs. Lifetime_Cost

Design 3435
Many Important Dimensions
Many Important Dimensions
Many Important Dimensions
Many Important Dimensions

Design 3435
Many Important Dimensions
Many Important Dimensions

Design 3435

Epochs:
- Epoch 63
- Epoch 171
- Epoch 193
- Epoch 202
- Epoch 171

2 yrs 4 yrs 1 yr 3 yrs 10 yrs

Utopia Trajectory

Design 3435
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

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
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

<table>
<thead>
<tr>
<th>Views</th>
<th>Technical complexity</th>
<th>Widgets</th>
<th>Technical complexity</th>
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</thead>
<tbody>
<tr>
<td>Level of analysis</td>
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<td>low</td>
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<td>high</td>
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<td>Multi-DM Negotiation</td>
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<td>General TS Exploration</td>
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<td>General Multi-Epoch Analysis</td>
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<td>Lifecycle Path Analyses</td>
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- All dimensions in meters

- Cost
  - Peak Transmit Power: 1.5, 10, 20 [KW]
  - Radar Bandwidth: .5, 1, 2 [GHz]
  - Physical Antenna Area: 10, 40, 100, 200 [m²]
  - Antenna Type: Mechanical vs. AESA
  - Satellite Altitude: 800, 1200, 1500 [km]
  - Constellation Type: 8 Walker IDs
  - Comm. Downlink Relay vs. Downlink
  - Tactical Downlink: Yes vs. No
  - Maneuver Package: 1x, 2x, 4x
  - Constellation Option: none, long-lead, spare

- Baseline Schedule
  - Actual Schedule (Era)

<table>
<thead>
<tr>
<th>ATTRIBUTES</th>
<th>Schedule</th>
<th>Programmatic</th>
<th>Cost</th>
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<tr>
<td>Baseline Schedule</td>
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<tr>
<td>Actual Schedule</td>
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<tr>
<td>Total Impact</td>
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- Imaging Latency
  - Minimum Target RCS

- DESIGN VARIABLES
  - Baseline Cost
  - Actual Costs (Era)
  - Imaging Latency
  - Resolution (Proxy)
  - Targets per Pass
  - Field of Regard
  - Revisit Frequency

- Daughters
  - Mother

- Velocity Vector
  - Daughters
  - Mother
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

- 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”)
Select project
- Satellite Radar System
- Space Tug
- other

Select “user type”
- Expert analyst
- Senior decision maker
- Policy maker

All current widgets
- Summary Dash
- Notes
- Favorites
- Pref 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
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.

Interact with plot:
- "Click on point" capability
- "Favorites" plotted on tradespace

Plot three dimensions (drop downs from DB):
- Select current epoch (from Era or other)
- Num valid designs in this epoch

"Favorites" plotted on tradespace.
The Favorites widget allows a set of designs to be tracked and formatted across widgets.

**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)

List of all favorites

Favorites plotted in other widgets (e.g. “tradespace”)

Add text label

Specify plot formatting for each favorite
The Preferences widget displays and allows alteration of a decision maker’s preferences.

**Features**
- Preferences can be displayed and edited
- Local mode allows local “playing”; global mode propagates to other widgets
- Favorites can be displayed

**Select attribute**
- Shows tradespace with SAUs attribute values
- Bars show min acceptable, max desirable attribute levels

**SAU curves**
- Global and local modes

**Favorites shown**
- Tradespace widget updated to reflect new preferences
Design Explorer

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

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

“Click on point” brings up design knobs

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

Set favorite

Specify design, or have design described

Send to comparison tool
The Pareto widget calculates multi-objective fuzzy pareto sets across single or multiple DMs.

**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 multiple DMs

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

Quickly add to favorites
Specify objectives

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

Num valid designs in epoch

Add to Favorites

Pareto Tool
Example Emergent Insights

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

Find offending constraint

Key
▲ Design 3435
▼ Design 5380
Changing Preferences in Real Time

Key

▲ Design 3435
▼ Design 5380

Find offending constraint
Relax offending constraint
Discovering Compromises

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.

Design is now valid.

Key
- Design 3435
- Design 5380
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