Session 7: CONCEPT DESIGN and TRADESPACE EXPLORATION

2 JULY 2009

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ESD.33 Systems Engineering
SEAr is positioned within the Engineering Systems Division at MIT

Mission

Advance the theories, methods, and effective practice of systems engineering applied to complex socio-technical systems through collaborative research

Current Sponsors:

292 Main Street
E38-575
Focus of Lecture

• One of the key contemporary challenges in developing successful systems is to be able to make effective architectural design choices in the face of complexity and a changing world.

• This lecture will highlight a new method for tradespace exploration based on a value driven perspective, allowing designers to better understand and meet both present and future stakeholder needs and expectations.

• The Multi-Attribute Tradespace Exploration (MATE) methodology was developed for exploring tradespaces of possible designs rather than settling quickly on an optimum.
The Design Knowledge Gap

Value is primarily determined at the beginning of a program

Adapted from Fabrycky and Blanchard 1991

How can we make good decisions?
Three Keys to Good Upfront Decisions

• Structured program selection process
  – Choosing the programs that are right for the organization’s stakeholders

• Systems Engineering
  – Determining stakeholder needs and translating them into functional requirements

• Conceptual design practices
  – Finding the right form to maximize stakeholder value over the product (or product family) lifetime
Design Paradigm: Linear Program Lifecycle

- Linear progression from User Need to End of Life
- Formalized with schedule milestones, gates, reviews
- Many variations on the theme

Phases of System Lifecycle

From ISO/IEC 15288

NASA Handbook 2007
NASA, ESA, DoD Versions (from SMAD)
Investing “up-front” Pays Off


Honour, Value of SE Report, 2004

SE Effort = SE Quality * SE Cost/Actual Cost
Traditional Trade Studies

...focus on a few alternatives or variations on point designs
Possible Pitfalls: When Iteration Used to Add Detail

- Coarse decisions (the important ones!) made and implemented first
- Further refinement may be adding detail to the wrong concept
- Lack of formal process may make this good idea ineffective - “Spiral of Doom”

NASA Handbook, 1995
Critique of Concept Design Methods Has Informed Research

• *A priori* design selections without analysis/consideration of other options
• Inadequate technical feasibility studies in the early stages of design
• Insufficient regard for preferences of key decision makers
• Disconnects between perceived and actual decision maker preferences
• Pursuit of a detailed design without understanding the effects on the larger system
• Limited incorporation of interdisciplinary expert opinion and diverse stakeholder interest.

Design Tradespace Exploration

A process for understanding complex solutions to complex problems

- Model-based high-level assessment of system capability
- 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 value of *potential* capabilities

Allows informed “upfront” decisions and planning
Design Decision Making
The Scope of Upfront Decisions

Conceptual Design is a high leverage phase in system development

Key Phase Activities

- Needs Captured
- Resources Scoped
- Concept(s) Selected

After Fabrycky and Blanchard 1991

Concept(s) Selected

vs.

In Situ

Top-side sounder

~66%

~66%

Management Leverage

Cost Committed

Knowledge

Cost Incurred

Concept Development

Detail Design

Production

Use

After Fabrycky and Blanchard 1991
The Scope of Upfront Decisions

Conceptual Design is a high leverage phase in system development

Reliance upon BOGGSAT could have large consequences

How can we make better decisions?

Key Phase Activities

Needs Captured

Resources Scoped

Concept(s) Selected

After Fabrycky and Blanchard 1991
Three keys to good upfront decisions

- Structured program selection process
  - Choosing the programs that are right for the organization’s stakeholders
- Systems engineering
  - Determining stakeholder needs, generating concept of operations, and deriving requirements
- Conceptual design practices
  - Finding the right form to maximize stakeholder value over the product (or product family) lifetime

“Good” system decisions must both answer the right questions as well as answer the questions right

What is involved in getting the right questions?
Decision Maker defined objectives

What is involved in getting the questions right?
Rigorous decision and analytic methods
Determining “Value” Proposition

Create a system that fulfills some need while efficiently utilizing resources within some context.

There may be many stakeholders, but…

Decision makers are a subset that have significant influence/control over the driving need and/or resources… so focus on satisfying decision makers.
Framework for Identifying Key Decision Makers

Definition of Levels
Level 2 – Close connection to System
Level 1 – Distant connection to System
Level 0 – Little or no connection to System
Define the Mission

• Understand the mission
• Create a list of attributes
• Interview the decision maker(s)
• Create utility curves

Decision Makers

Mission Objectives

Attributes

(Selection rule: maximize “utility”)

Utility

(Goals)
In order to ensure a successful mission, the implied value proposition must be fulfilled. Each system stakeholder has a value proposition—what they want to “get out” of the mission. Decision makers are stakeholders with influence over the mission objectives for needs and/or resources. Meeting the objectives for each decision maker can be assessed in terms of “attributes.” An alternative that scores well in a set of attributes gives a decision maker value, or “utility.” The goal for the selection of a good alternative is to maximize the utility for individuals and groups.
Defining Attributes

- Decision criteria used by decision makers for selecting an alternative from among a set of alternatives
- Should obey, to the extent possible, perceived independence and other rules
- Set of 3-7 attributes “best” per individual DM
- For each attribute, must define:
  - Units: “natural” or “artificial”
  - Range: from lowest acceptable value, to highest meaningful value
- In practice, iteration may be necessary
Utilities as Selection Criteria

- “What the attributes are WORTH to the decision makers”
- Single Attribute utility maps attribute to utility
- Multi-attribute utility maps multiple attributes (as expressed by an alternative) to utility

```
1 --> Good

Single Attribute Utility function

Attribute
```

```
1 --> Good

Multi-Attribute Utility Analysis

Alternatives
```
Example Single Attribute Utility

![Graph showing data collection altitude (km) vs utility]

- **Utility** axis ranges from 0 to 1.
- **Data Collection Altitude (km)** axis ranges from 150 to 950.

The graph illustrates a decreasing utility with increasing altitude, indicating a negative relationship between the two variables.
Single Attribute Utility

- Postulate a dimensionless metric that is a function of attribute $X$: $U_i = U_i(X)$
- Set $U_i = 0$ at the least desirable, but still acceptable value of $X$
- Set $U_i = 1$ at the highest (most desirable) value of $X$
- $U_i$, the “single attribute utility,” can be used to express the relative desirability of values of $X$

Working with Utilities

• Useful as selection criteria: contains complete ordering preferences
• Superior to pair-wise or other
• Determination methods:
  – Sketching
  – Analogy
  – Interviewing
Determining Single Attribute Utility

Sketching - imprecise but easy

- a) linear
- b) diminishing returns
- c) increasing returns
- d) threshold
- e) non-monotonic

- Each curve shows “more is better”
- A curve could also be reversed (i.e., “less is better”)

Beware: sketches are somewhat arbitrary; their use may result in “bad” decisions
Aggregating Utility for Single Decision Maker

• Single attribute may not be enough; multiple attributes must be aggregated for use in ranking

• Benefit:
  – Simplify analysis
  – Simplify communication

• Drawback:
  – Obscure trades
  – Misrepresent actual preferences
  – Impose preferences and biases

• Examples to follow
Example Utility Aggregation Functions

• Combine multiple single-attribute utilities $U_i$ into a single metric $U$
• May not be possible
• May be simple
  – Weighted sum $U = \sum_{i=1}^{n} k_i U_i$
  – Multiplicative function $U = \prod_{i=1}^{n} U_i$
  – Inverse multiplicative function $1 - U = \prod_{i=1}^{n} (1 - U_i)$
• Generalized form - Keeney-Raiffa function
  $$KU + 1 = \prod_{i=1}^{n} (Kk_i U_i + 1)$$
Aggregating Utility Across Multiple Decision Makers

• Diversity across stakeholders
  – No absolute scale, so necessarily cannot compare numbers (no “anchor”)
  – Using utilities to rank options
  – Comparing rank as “absolute” measure
  – But what about “relative” weight of stakeholders?

Separate decision maker utilities should be kept separate; any combining of decision maker utilities will introduce assumptions and bias
Simple Multi-Attribute Methods

- **Lexicographic**
  - Rank attributes
  - Score alternatives with natural units; (normalize scores)
  - Alternative with highest score in most important attribute is selected; if tied, tie-break with second most important attribute score, etc.

- **Pugh**
  - Choose baseline alternative
  - Determine comparison of each alternative’s criteria to baseline: +/S/-
  - Sum +/S/- for each alternative; clear best alternative ranked first, etc.

- **QFD**
  - Rank attributes
  - Score alternatives with 1,3,9;
  - Alternative with highest score summed across attributes is selected

- **Modified decision matrix**
  - Rank attributes
  - Score alternatives with natural units; normalize scores
  - Alternative with highest weighted sum across normalized attribute scores is selected

- **MAU**
  - Elicit single attribute utility curves
  - Elicit multi-attribute utility attribute weights;
  - Score alternatives with single attribute utility curves
  - Alternative with highest multi-attribute utility is selected
Buying a Car

http://www.carpictures.com/

vs.
Lexicographic (Decision Matrix) Method

- Rank attributes
- Score alternatives with natural units; (normalize scores)
- Alternative with highest score in most important attribute is selected; if tied, tie-break with second most important attribute score, etc.

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<tr>
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</table>

### Alternatives Ranking

- **Kia** (Rank 1)
- **Toyota** (Rank 2)
- **Volvo** (Rank 3)
- **Porsche** (Rank 4)

### Normalized units: 0-1, 1 is better
### Pugh (Controlled Convergence) Method

- Choose baseline alternative
- Determine comparison of each alternative’s criteria to baseline: +/S/-
- Sum +/S/- for each alternative; clear best alternative ranked first, etc.

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**Natural units**

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**Alternatives Ranking**

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<td>2</td>
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<tr>
<td>2</td>
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QFD Method

- Rank attributes
- Score alternatives with 1,3,9;
- Alternative with highest score summed across attributes is selected

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<tr>
<td>4</td>
<td>Volvo</td>
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Qualitative units: 1=bad, 3=okay, 9=great
Modified Decision Matrix Method

- Rank attributes
- Score alternatives with natural units; normalize scores
- Alternative with highest weighted sum across normalized attribute scores is selected

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Normalized units: 0-1, 1 is better

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<td>4</td>
<td>Porsche</td>
</tr>
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</table>
MAU Method

- Elicit single attribute utility curves
- Elicit multi-attribute utility attribute weights;
- Score alternatives with single attribute utility curves
- Alternative with highest multi-attribute utility is selected

\[ U = \sum_{i=1}^{n} k_i U_i \]

### Weight: 0.3 0.2 0.4 0.1

<table>
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<tr>
<th>Criterion</th>
<th>Volcano</th>
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<tr>
<td>MPG</td>
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### Natural units

- \( U_{\text{Accel}} = 105 \)
- \( U_{\text{Comfort}} = 110 \)
- \( U_{\text{Price}} = 100 \)
- \( U_{\text{MPG}} = 1545 \)

### Alternatives Ranking

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<td>4</td>
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Utility units: 0-1, 1 is better

Rank | Car
1    | Toyota
2    | Volvo
3    | Kia
4    | Porsche
Comparison of MA methods

Answering the question right…

… requires understanding the limits of the method used

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Lexicographic | Pugh | QFD | Modified DM | MAU

More effort to rank

MAU is *axiomatically* based and helps for answering the right question as well as answering the question right

Among only four alternatives, each method resulted in a *different* ranking!
MATE Method
for Tradespace Exploration
What is a Tradespace?

Attributes
– Delta-V
– Capability
– Response time

Design Space
> Manipulator Mass
  – Low (300kg)
  – Medium (1000kg)
  – High (3000 kg)
  – Extreme (5000 kg)

> Propulsion Type
  – Storable bi-prop
  – Cryogenic bi-prop
  – Electric (NSTAR)
  – Nuclear Thermal

> Fuel Load - 8 levels

> Simple performance model
  – Delta-V calculated from rocket equation
  – Binary response time (electric propulsion slow)
  – Capability solely dependent on manipulator mass
  – Cost calculated from vehicle wet and dry mass

Assessment of the utility and cost of a large space of possible system designs
Steps for Multi-Attribute 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

Mission Concept

Attributes

Define Design Vector

Develop System Model

Calculate Utility

Estimate Cost

System Tradespace
Decision Makers and Mission Concept

• Choose Decision Makers that you have to satisfy - *they will define the utility*
• Choose Mission Concept(s) - the basic framework you will use to define the design vector
  – Open enough so that creative solutions are not excluded
  – Defined enough to be tractable

Space Tug Example:
• (potential) Stakeholder need is for infrastructure to maintain on-orbit assets
• Mission concept is vehicle that can rendezvous with and interact with on-orbit assets
• Project Mission is to assess how potential systems could satisfy potential stakeholders
Choose finite (but as open as possible) set of potential solutions

Choose the parts of the overall system that you will design
Define Attributes

- **Defined by the decision maker**, with designer assistance
- Define units, lowest acceptable value, highest meaningful value
- Set of 3-7 attributes should obey, to the extent possible, perceived independence and other rules
- Ideally:
  - Reflect what the decision maker cares about
  - Computable
  - Sensitive to design decisions

You will probably have to iterate

Space Tug Example:

1) **Delta-V**: How much velocity can the vehicle impart on itself and/or the target? (km/sec) \[0 \rightarrow 12\]

2) **Interaction Capability**: What can the vehicle do to the target? (kg of equipment carried) \[0 \rightarrow 5000\]

3) **Speed**: Can the Space Tug change orbits in days? Months? (binary) \[0 \rightarrow 1\]
Defining Utilities

- Each attribute (worst to best value) monotonically maps to utility (0 to 1)
- Need rule for under/over values

Space Tug Example:

Delta-V vs. Utility

- Diminishing returns, with breakpoints at targets

Capability vs. Utility

- Diminishing returns, discrete levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Capacity (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>300</td>
</tr>
<tr>
<td>Medium</td>
<td>1000</td>
</tr>
<tr>
<td>High</td>
<td>3000</td>
</tr>
<tr>
<td>Extreme</td>
<td>5000</td>
</tr>
</tbody>
</table>
Aggregating Utilities

Diminishing returns, with breakpoints at targets

Single attribute utilities

\[ KU(X) + 1 = \prod_{i=1}^{N} (Kk_i U(X_i) + 1) \]

Aggregating Function

- If possible, define an aggregating function
  - Weighted sum often used (iff \( \Sigma k_i = 1! \))
  - MAUT Keeney-Raiffa function best
  - Weights defined by decision maker

Weighting factors

Diminishing returns, discrete levels
Defining the Design Vector

- The design vector defines the space of designs that will be considered - a key step!
- Define units, range to be considered, sampling levels
- Good design vector elements (DV)
  - Capture the range of possible solutions
  - Are realistic, physically or in terms of available technology or components
  - Are under the direct control of the designer
  - Impact the attributes
- Steps:
  - Brainstorm individually & in groups, consider how to best affect the attributes
  - Use a DVM to map DV to attributes to screen out unnecessary DV and to motivate creation of more DV if attributes are not affected

Space Tug Example:
- Manipulator Mass (=Capability)
  - Low (300kg), Medium (1000kg), High (3000 kg), Extreme (5000 kg)
- Propulsion Type
  - Storable bi-prop, Cryogenic bi-prop, Electric (NSTAR), Nuclear Thermal
- Fuel/Reaction Mass Load
  - 8 levels, geometric progression (30 to 30000kg)
The Constants Vector

- To keep modeling general and adaptable to later changes, do not “hardwire” assumptions into code
- Instead, keep list (data structure) of “constants”
- Five types (at least):
  - True constants \((g, \pi)\), value may change if your units change…
  - Constraints (policies, standards…)
  - Modeling assumptions (\$/kg, W/GHz, Margins…)
  - Quantities associated with design vector choices
  - Potential design vector elements (things under designers control) that have been fixed - record reason

Space Tug Example:

<table>
<thead>
<tr>
<th>Propulsion System</th>
<th>(I_{sp}) (sec)</th>
<th>Base Mass (m_{p0}) (kg)</th>
<th>Mass Fract. (m_{pf})</th>
<th>High Impulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storable biprop</td>
<td>300</td>
<td>0</td>
<td>0.12</td>
<td>Y</td>
</tr>
<tr>
<td>Cryo</td>
<td>450</td>
<td>0</td>
<td>0.13</td>
<td>Y</td>
</tr>
<tr>
<td>Electric</td>
<td>3000</td>
<td>25</td>
<td>0.30</td>
<td>N</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1500</td>
<td>1000</td>
<td>0.20</td>
<td>Y</td>
</tr>
</tbody>
</table>

- True constants
  - \(g\) Acceleration due to gravity (9.8 m/sec\(^2\))
- Modeling assumptions
  - \(c_d\) Dry mass cost coefficient (\$/kg)
  - \(c_w\) Wet mass cost coefficient (\$/kg)
  - \(m_{bf}\) Bus mass fraction coefficient
- Quantities associated with design vector choices
  - \(I_{sp}\) Specific impulse (sec)
  - \(m_{p0}\) Propulsion system base mass (kg)
  - \(m_{bf}\) Propulsion system mass fraction coefficient
- Potential design vector elements (things under designer’s control) that have been fixed - record why
  - (examples) Launch cost and time, operations cost
    - mostly scope and resources
Modeling

- Calculate Costs & Attributes from Design Vector & Constants Vector
- Approaches:
  - Tabulation - car example from previous lecture
  - Explicit calculation - Attributes = f(DV, CV)
  - Implicit or iterative calculations
    - May involve local optimizations
  - Simulations/Scenarios
- Calculate single- and multi-attribute Utilities
- All but the simplest models will involve important Intermediate Variables (e.g. system mass, power) which should be explicitly calculated and tracked
Motivating the Model: Space Tug

- Very simple, explicit, physics-based model
- Intermediate Variables (masses):

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Propulsion System Mass</th>
<th>Bus Mass</th>
<th>Dry Mass</th>
<th>Wet Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta-V</td>
<td>( M_p = m_{p0} + m_{pf} M_f )</td>
<td>( M_b = M_p + m_{bd} M_c )</td>
<td>( M_d = M_b + M_c )</td>
<td>( M_w = M_d + M_f )</td>
</tr>
<tr>
<td>Speed</td>
<td>( \Delta v = g \ I_{sp} \ln(M_w / M_d) )</td>
<td>( \text{Table lookup} )</td>
<td>( \text{Table lookup} )</td>
<td>( \text{Table lookup} )</td>
</tr>
</tbody>
</table>

DVM can also be used to motivate and identify relationships for models

Purpose of model: Calculate “performance” of each design in terms of attributes, costs, and utilities
Cost Modeling

• Need cost estimates for each design
  – For decision making, *not budget planning*
  – Order of magnitude costs for concepts
  – Relative costs of various concepts

• Many approaches and tools available

• Fidelity will be low in early design (this is OK)
  – Expect +/- 30% error, even in simple stuff

• Need to keep track of limits and weaknesses of cost (and other) models (ROM uncertainties)

Space Tug Example:
• Very very simple parametric model
• Appropriate to broad survey
• Important to understand what is *not* modeled
  – Software
  – Launch
  – Technology Development

\[ C = c_w M_w + c_d M_d \]
Baseline Study: Space Tug

- Existing MATE* study of space tug tradespace
  - Three attributes
    - Delta-V
    - Capability
    - Response time
  - Three design variables

Design Space
- Manipulator Mass
  - Low (300kg)
  - Medium (1000kg)
  - High (3000 kg)
  - Extreme (5000 kg)
- Propulsion Type
  - Storable bi-prop
  - Cryogenic bi-prop
  - Electric (NSTAR)
  - Nuclear Thermal
- Fuel Load - 8 levels

> Simple performance model
  - Delta-V calculated from rocket equation
  - Binary response time (electric propulsion slow)
  - Capability solely dependent on manipulator mass
  - Cost calculated from vehicle wet and dry mass

* MATE: Multi-Attribute Tradespace Exploration; see McManus, H., and Schuman, T., “Understanding the Orbital Transfer Vehicle Tradespace,” AIAA-2003-6370, Sept. 2003...
The Tradespace

• Now have a lot of information:
  – Design Vector (many possible designs)
  – Constants Vector
  – Attributes (for each design)
  – Utilities (for each design)
  – Cost (for each design)

• This is, collectively, the tradespace

Need to distill this information into knowledge useful to decision makers
Space Tug Tradespace
Aggregated Utility vs. Cost

Each point is a complete design
The Pareto Front

Points on the front give best Utility for Cost
Other points are dominated - better utility for same cost or same utility for less cost available
Understanding Design Choices

- Propulsion system identified by color
- Different parts of the Pareto front favor different propulsion systems

Identifying design choices by color identifies good/bad choices, sensitivities
Understanding Design Choices: Example II

- Interface system capability identified by color
- More capability costs more money
- Low capability (=small) designs dominate low cost/utility systems
- Only a meaningful choice at the high utility end

Interdependency of choices a sign of a “rich” tradespace
Physical phenomena create patterns; must look at full data set to find root causes

Understanding Design Choices: Example III

- Line represents a set of designs differing only by fuel/reaction mass load
- More fuel, more utility but very non-linear
- At high end, hit “walls”
  - some are physics (rocket equation)
  - some utility (electric vehicles can “max out” the utility functions)
Tradespace Reveals Promising Designs

- Small, light, cheap vehicles with low-mid \( \Delta V \) capability (tenders)
- Small, slow, high-\( \Delta V \) electric propulsion vehicles (cruisers)
- Big, fast vehicles require nuclear power (expensive)

Sets of “good” designs share features/architectures

*Often insight is emergent - the tradespace can reveal good design concepts*
## MATE Applications

<table>
<thead>
<tr>
<th>Name</th>
<th>Num DV</th>
<th>Num Att</th>
<th>Size Tradespace</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-TOS</td>
<td>7</td>
<td>2</td>
<td>1380</td>
</tr>
<tr>
<td>B-TOS</td>
<td>6</td>
<td>5</td>
<td>4033</td>
</tr>
<tr>
<td>C-TOS</td>
<td>NA</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>X-TOS</td>
<td>9</td>
<td>5</td>
<td>50488</td>
</tr>
<tr>
<td>SDB</td>
<td>5</td>
<td>2-4</td>
<td>8700+8700+35000</td>
</tr>
<tr>
<td>SBR</td>
<td>5</td>
<td>7</td>
<td>1872</td>
</tr>
<tr>
<td>Space Tug</td>
<td>3</td>
<td>3</td>
<td>137</td>
</tr>
<tr>
<td>TPF</td>
<td>8-10</td>
<td>4-6, 2-3</td>
<td>10611</td>
</tr>
<tr>
<td>JDAM</td>
<td>8-11</td>
<td>5-8, 1-3</td>
<td>7151</td>
</tr>
<tr>
<td>RDSS</td>
<td>5,7</td>
<td>10</td>
<td>2340+8640</td>
</tr>
<tr>
<td>SRS</td>
<td>10</td>
<td>5,5,5</td>
<td>23328x245</td>
</tr>
<tr>
<td>ORS</td>
<td>6</td>
<td>6</td>
<td>1100+1100+1100</td>
</tr>
<tr>
<td>HSR</td>
<td>15</td>
<td>20</td>
<td>TBD</td>
</tr>
</tbody>
</table>

There have been 13 case studies as of June 2009
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, tradespace gives 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

MATE highlights and helps to focus attention on important trades, possibly overlooked by traditional methods
Summary

• MATE includes an ordered set of steps for creating an information-rich Tradespace:
  – Scoping and Bounding the Mission
  – Choosing Attributes
  – Choosing Design Vector Elements
  – Modeling Concepts
  – Creating the Tradespace
  – Tradespace Exploration

Goal is the extraction of knowledge that decision makers can use
Increased knowledge (including understanding of uncertainties) allows better decisions
Resources for Learning
More about Our Research
Backup
In Situ Ionospheric Measurements

**A-TOS**

Swarm making in-situ ionosphere measurements

**DESIGN VARIABLES (7)**

- **Bulk Orbit Variables**
  - Swarm inclination (deg) 63.4
  - Swarm perigee altitude (km) 200 – 800
  - Swarm apogee altitude (km) 200 – 800
  - Swarm argument of perigee (deg) 0
  - Number of orbit planes 1
  - Swarms per plane 1

- **Swarm Orbit Variables**
  - Subsats per swarm 1 – 26
  - Number of subplanes in each swarm 1 – 2
  - Number of suborbits in each subplane 1 – 4
  - Yaw angle of subplanes (deg: vector) ±60
  - Maximum satellite separation (km) 0.001 – 200

- **Non-orbit Variables**
  - Mothership (yes/no)

**ATTRIBUTES (2)**

- “Value” in Low latitude mission, “Value” in High latitude mission

---

**Number of Designs Explored: 1380**

---

**Life Cycle Cost vs. Total Value (N=1380)**

- **Life Cycle Cost** vs. **Total Value** (N=1380)

---

**Color scale:** Life Cycle Cost, 1380 data points, grid: 75x75, density: 0.08

---

- **Increasing utility**
- **Cost $100M**
B-TOS
Hills swarm making ionosphere soundings

DESIGN VARIABLES (6)

- **Large Scale Arch**
  - Circular orbit altitude (km) 1100, 1300
  - Number of Planes 1, 2, 3, 4, 5

- **Swarm Arch**
  - Number of Swarms/Plane 1, 2, 3, 4, 5
  - Number of Satellites/Swarm 4, 7, 10, 13
  - Radius of Swarm (km) 0.18, 1.5, 8.75, 50

- **Vehicle Arch**
  - 5 Configuration Studies Trades payload, communication, and processing capability

ATTRIBUTES (5)

- Spatial Resolution (deg²), Revisit Time (min), Latency (min), Accuracy (deg), Inst. Global Coverage (%)

Number of Designs Explored: 4033
C-TOS
ICE design of B-TOS like vehicles*

Number of Designs Explored: 1

*Design similar to “D” from B-TOS
X-TOS
Single-Vehicle *in-situ* density measurements

**DESIGN VARIABLES (9)**

- **Mission Design**
  - Scenario
    - 1 sat, single launch
    - 2 sats, sequential launch
    - 2 sats, parallel launch

- **Orbital Parameters**
  - Apogee altitude (km) 200-2000
  - Perigee altitude (km) 150-350
  - Orbit inclination (deg) 0, 30, 60, 90

- **Physical Spacecraft Parameters**
  - Antenna gain low, high
  - Communication architecture TDRSS, AFSCN
  - Propulsion type electric, chemical
  - Power type solar, fuel cell
  - Delta_v (m/s) 200-1000

**ATTRIBUTES (5)**

- Data lifespan (mos), Sample altitude (km), Latitude diversity (deg), Equatorial time (hr/day), Latency (hrs)

**Number of Designs Explored: 50488**

**Total Lifecycle Cost ($M2002)**
Space Tug
General purpose orbital service vehicle

DESIGN VARIABLES (3)

- Physical Spacecraft Parameters
  - Tugging Capability: low, med, high, extreme
  - Propulsion Type: storable-bi, cryogenic, electric, nuclear
  - Propellant Mass (kg): 0-50000

ATTRIBUTES (3)

- Capability (kg), DeltaV (m/s), Fast (y/n)

Number of Designs Explored: 137
Terrestrial Planet Finder (TPF)
A “Big Science” Project

Number of Designs Explored: 10611

DESIGN VARIABLES (8+2)
- Orbit Type \{L2, LO, DA\}
- Num Apertures 4, 6, 8, 10
- Wavelength 7, 10, 20 microns
- Interferometer Type \{sci, ssi, tsi\}
- Aperture type \{circular optics, strip optics\}
- Aspect Ratio \{multi, const\}
- Aperture Size Variable
- Interferometer Baseline Variable
- [Schedule] [0-1 for each obs type]
- [Design Lifetime] 5 or 10

ATTRIBUTES (4+2, 2+1)
- Science
  - Num of Surveys (num), Num Medium Spectroscopies (num), Num Deep Spectroscopies (num), Number of Images (um) [Num Long Baseline Images (num), Num Short Baseline Images (num)]
- Agency
  - Lifecycle Cost ($M), Operational Lifetime (years), [Annual Ops Cost $M]
Operationally Responsive Disaster Surveillance System
A Multi-Concept Responsive System

Design Variables (5+7)

- Aircraft DV
  - Configuration Flag 1-13 (3x jet, 2x small prop, 2x med UAV, small UAV, existing Cessna, Orion, Predator, ScanEagle, Global Hawk)
  - Gross Weight Flag low, medium, high
  - Number of Assets 1-6
  - Payload Type visible, infrared
  - Aperture Size 0.01, 0.02, 0.04, 0.07, 0.08 m

- Spacecraft DV
  - Deployment Strategy 1-4 (on-orbit, launch-ready, pre-fab parts, classic design)
  - Altitude 120-1100 km
  - Inclination 0, 23, 90, sun-synch
  - Number of assets 1-5
  - Payload Type visible, infrared
  - Excess Delta-V 600-1200 m/s
  - Ops Lifetime 5-10 yrs

Attributes (10): Firefighter/Owner

- Acquisition Cost ($M), Price/day ($K/day), Cost/day ($K/day), Responsiveness
- Time to IOC (days), Max % of AOI (%), Time to Max Coverage (min), Time between AOI (min), Imaging Capability (NIIRS level), Data Latency (min)

Number of Designs Explored: 2340+8640
Satellite Radar System
Satellite-based radar multi-mission system of system

DESIGN VARIABLES (10)

• Orbit DV
  – Orbit Altitude 800, 1200, 1500 km
  – Constellation design 8 Walker IDs

• Spacecraft DV
  – Antenna Size 40, 80, 100 m²
  – Peak power 1.5, 10, 20 kW
  – Radar bandwidth 0.5, 1, 2 GHz
  – Comm Arch relay, downlink
  – Tactical Downlink yes/no
  – Path enablers (Extra sats, fuel)

EPOCH VARIABLES (6)

– Technology avail, Comm infrastructure, Target list, AISR avail, Environment, Mission priorities

ATTRIBUTES (3 “missions”, 15 total)

– Tracking, Imaging, Programmatic

Number of Designs Explored: 23328; Number of Epochs Explored: 245