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

Lecture: Lecture 14: Summary of a New Method

Author: Adam Ross and Donna Rhodes

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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 SEArigenerated 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.
Value-Driven Tradespace Exploration for System Design

Summary of a New Method

Dr. Donna H. Rhodes
rhodes@mit.edu

Dr. Adam M. Ross
adamross@mit.edu

Massachusetts Institute of Technology
Outline

• Summary of key concepts
• Research directions
• Where to find more information
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?
A Method for the Front End

- MATE Method for Tradespace Exploration
  - Means for understanding complex solutions to complex problems
- ICE Integrated Concurrent Engineering
  - Rapid Conceptual/Preliminary Design Method
- Allows informed upfront decisions and planning

Phases of Product Development

Most relevant to processes in these phases

Concept Development > System-Level Design > Detail Design > Testing and Refinement > Production Ramp-Up

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
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
Bound and Scope: Space Tug

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

- Low = 300kg
- Medium = 1000kg
- High = 3000kg
- Extreme = 5000kg
Aggregating Utilities

Diminishing returns, with breakpoints at targets

Single attribute utilities

Weighting factors

Aggregating Function

- If possible, define an aggregating function
  - Weighted sum often used (iff $\sum k_i=1!$)
  - MAUT Keeney-Raiffa function best
  - Weights defined by decision maker
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 designer’s control) that have been fixed - record reason

Space Tug Example:

### Design Var. Associated Quantities

<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/sec²)
- 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>$M_b = M_p + m_{bf}M_c$</td>
<td>$M_d = M_b + M_c$</td>
<td>$M_w = M_d + M_f$</td>
</tr>
<tr>
<td>Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment Capability</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>18</td>
<td>10</td>
<td>11</td>
<td>9</td>
</tr>
</tbody>
</table>

- Attributes

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta-V</td>
<td>$\Delta v = g \ I_{sp} \ \ln(M_w/M_d)$</td>
</tr>
<tr>
<td>Capability</td>
<td>Table lookup</td>
</tr>
<tr>
<td>Speed</td>
<td>Table lookup</td>
</tr>
</tbody>
</table>

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

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

Architecture Tradespace Analysis: Avoiding Point Designs

Differing types of trades
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$_3$, ..., X$_j$\}

Tradespace exploration enables big picture understanding
Increased knowledge (including understanding of uncertainties) allows better decisions.
Tradespace Exploration
Research Directions at MIT SEArI
Dynamic World Motivates Research Directions

- Stakeholder needs change as perception of system and value delivered evolves
- Systems exist in dynamic cultural, political, financial, market environments
- Highly complex and interconnected systems with changing technology over long lifespans
<table>
<thead>
<tr>
<th>Aspect</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRUCTURAL</td>
<td>related to form of system components and their interrelationships</td>
</tr>
<tr>
<td>BEHAVIORAL</td>
<td>related to function/performance, operations, and reactions to stimuli</td>
</tr>
<tr>
<td>CONTEXTUAL</td>
<td>related to circumstances in which the system or enterprise exists</td>
</tr>
<tr>
<td>TEMPORAL</td>
<td>related to the dimensions and properties of systems over time</td>
</tr>
<tr>
<td>PERCEPTUAL</td>
<td>related to stakeholder preferences, perceptions and cognitive biases</td>
</tr>
</tbody>
</table>
Behavioral Aspect: Incorporating "ilities" in Tradespace Exploration

Multi-Epoch Tradespaces

Epoch “171”
Baseline Program Context:
Standalone capability needed, Imaging mission (primary)

Epoch “193”
New Program Context:
Cooperative capability needed, Tracking mission (primary)

Epoch variables are defined in regard to uncertainties (for example, resources, policy, technology availability, and others). Epochs are computationally generated using the possible permutations of the epoch variable set values. This approach has enabled deeper analysis for assessing performance of concept designs across multiple epochs.

Contextual Aspect: Multiple System Concepts in Multiple Contexts

Illustrates set of design concepts for an operationally responsive surveillance system shown for three epochs (where epoch variables vary based on the characteristics of a context shift (different disaster situation))

Temporal Aspect Example: Epoch-Era Analysis

**Compare Alternatives**
Static tradespaces compare alternatives for fixed context and needs (per Epoch)

**Epoch Characterization**
Epoch set represents potential fixed contexts and needs

**Multi-Epoch Analysis**
Analysis across large number of epochs reveals “good” designs

**Era Construction**
Eras represent ordered epoch series for analyzing system evolution strategies
Temporal Aspect Example: Tradespace Exploration using Epoch-Era Analysis

Value (utility) of designs for cost shown across system era with four epoch shifts (arrow indicates design of interest)


Perceptual Aspect Example: Shift in What Stakeholder Values

Perceptual aspect can relate to need to understand ‘goodness’ of design concepts as a stakeholder’s preferences shift over time. Exogenous factors such as economic changes, available technology, threats and other factors may influence relative importance of what a stakeholder values.

Impact of Change in Stakeholder Weighting of Desired System Attributes in Tradespace showing Utility vs Cost for a Multi-Concept System

Combining Aspects Example: Temporal and Perceptual

What visual construct can combine:
• **temporal aspect** (effective display of time-based impacts) and
• **perceptual aspect** (ability of decision maker to cognitively process complex tradespace information)?

Richards (2009): Perceptually understandable display of value for cost of satellite radar designs with time-based information on survivability of system as it experiences possible finite disturbances over its lifespan.

Amount of information and complexities within a set of information are challenges, in that human cognitive limits for processing the visual display must be considered, as well as mechanism to compute and display synthesis of temporal analysis (survivability over system life)
Multi-Aspect Synthesis Example: Responsive Systems Comparison (RSC)

Using Multi-Attribute Tradespace Exploration, Epoch-Era Analysis, and other approaches, a coherent set of processes were developed into the RSC method.

RSC consists of seven processes:
1. Value-Driving Context Definition
2. Value-Driven Design Formulation
3. Epoch Characterization
4. Design Tradespace Evaluation
5. Multi-Epoch Analysis
6. Era Construction
7. Lifecycle Path Analysis

Seeking ways to combine multiple aspects is a source for further methodological innovation.

Synthesis of multi-aspect methods can be used to develop robust methods for engineering complex systems.

<table>
<thead>
<tr>
<th>Resources for Learning</th>
<th>More about Our Research</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Access to Research SUMMIT</th>
<th>Access to Research WEBSITE</th>
</tr>
</thead>
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**October 19, 2010**

**Cambridge, MA**

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Please contact: seari@mit.edu