Using Dynamic Multi-Attribute Tradespace Exploration to Develop Value Robust Systems

Dr. Adam M. Ross, MIT
adamross@mit.edu
Sikorsky IEEE CT AES Lunch
May 24, 2007
Meeting Customer Needs

• Goal of design is to create value (profits, usefulness, voice of the customer, etc…)
• Requirements capture a mapping of needs to specifications to guide design
Deploying a “Valuable” System…

Contexts change…
Meeting Customer Needs (cont.)

- Goal of design is to create value (profits, usefulness, voice of the customer, etc…)
- People change their minds…
- To continue to deliver value, systems must change as well…
What is System Success?

System success, $\Psi$, across $N$ decision makers at time $t$

$$\Psi(t) = \sum_{i=1}^{N} \left[ X_{DMi}(t) + \varepsilon_{C}^{X_{DMi}}(t) \right] \geq \sum_{i=1}^{N} \left[ Y_{DMi}(t) + \varepsilon_{C}^{Y_{DMi}}(t) \right]$$

where:
- $X_{DMi}(t)$: Decision maker i unaffected system “experience” at time $t$
- $Y_{DMi}(t)$: Decision maker i unaffected system “expectation” at time $t$
- $\varepsilon_{C}^{X_{DMi}}(t)$: Context effect on decision maker i “experience” at time $t$
- $\varepsilon_{C}^{Y_{DMi}}(t)$: Context effect on decision maker i “expectation” at time $t$

System Success: Net “experience” must meet or exceed net “expectations”

Success is defined across multiple perspectives and multiple time periods.
Characterizing the System Design Opportunity

- Decider Maker
  - Value
- Experience
- Expectations Experience
- Resources Expectations
- Needs
- Exogenous Influences
- Design Opportunity
  - Designs
  - Constraints
- System
- Context
- Exogenous Influences
- Designer
  - Value
- Experience
- Expectations Experience
Types of Changes

- Δ Designs (including technology)
- Δ Context (including operating environment, competition)
  - Physical (e.g. nature)
  - Human-made (e.g. policy, schedule)
  - Resources (e.g. capital)
  - Scoping (e.g. self-imposed)
- Δ Constraints (including “laws”)
- Δ Needs (including attributes)
- Δ DMs (including individuals and groups)
- Δ Resources (including dollars and time)

How can System Designers cope with these types of changes during design?
Aspects of Dynamic MATE

How can System Designers cope with these types of changes during design?

- **System Success criteria**
  - Expanding scope of system “value”

- **Tradespace exploration**
  - Understanding success possibilities across a large number of designs

- **Change taxonomy**
  - Specifying and identifying change types

- **Tradespace networks**
  - Analyzing changeability of designs

- **System Epoch/Era analysis**
  - Quantifying effects of changing contexts on system success
Tradespace Exploration

Value-driven design...

Firm
Designer
Customer
User

Value
Attributes
Utility

Concept
Design
Variables
“Cost”

Tradespae: \{Design, Attributes\} ↔ \{Cost, Utility\}

X-TOS
Small low-altitude science mission

Example

DESIGN VARIABLES:
Design trade parameters

Orbital Parameters
- Apogee Altitude (km)
- Perigee Altitude (km)
- Orbit Inclination (deg)

Spacecraft Parameters
- Antenna Gain
- Communication Architecture
- Propulsion Type
- Power Type
- Total Delta V

ATTRIBUTES:
Design decision metrics

- Data Lifespan (yrs)
- Equatorial Time (hrs/day)
- Latency (hrs)
- Latitude Diversity (deg)
- Sample Altitude (km)

Assessment of cost and utility of large space of possible system designs
Example “Real Systems”

### Spacetug vs CX-OLEV

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Mass kg</td>
<td>1405</td>
<td>1400</td>
</tr>
<tr>
<td>Dry Mass kg</td>
<td>805</td>
<td>670*</td>
</tr>
<tr>
<td>Propellant kg</td>
<td>600</td>
<td>730*</td>
</tr>
<tr>
<td>Equipment kg</td>
<td>300</td>
<td>213*</td>
</tr>
<tr>
<td>DV m/s</td>
<td>12000 – 16500***</td>
<td>15900**</td>
</tr>
<tr>
<td>Utility</td>
<td>0.69</td>
<td>0.69</td>
</tr>
<tr>
<td>Cost</td>
<td>148</td>
<td>130*</td>
</tr>
</tbody>
</table>

### XTOS vs Streak

- **XTOS (2002 study)**
  - Wet Mass kg: 325 - 450
  - Lifetime (yrs): 2.3 - 0.5
  - Orbit: 300 - 185 km @ 20°
  - LV: Minotaur
  - Utility: 0.61 - 0.55
  - Modified Utility**: 0.56 - 0.50
  - Cost $M: 75 - 72
  - Instruments: Three (?)

- **Streak (Oct 2005 launch)**
  - Wet Mass kg: 420
  - Lifetime (yrs): 1
  - Orbit: 321a-296p -> 200 @ 96°
  - LV: Minotaur
  - Utility: 0.57 - 0.54*
  - Modified Utility**: 0.59
  - Cost $M: 75***
  - Instruments: Ion gauge and atomic oxygen sensor
Tradespace Analysis: Selecting “best” designs

If the “best” design changes over time, how does one select the “best” design?
Tradespace Networks

Tradespace designs = nodes
Applied transition rules = arcs

Transition rules are mechanisms to change one design into another.
The more outgoing arcs, the more potential change mechanisms.
Tradespace Networks

Example: X-TOS Transition Rules

<table>
<thead>
<tr>
<th>Rule</th>
<th>Description</th>
<th>Change agent origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Plane Change</td>
<td>Increase/decrease inclination, decrease $\Delta V$</td>
<td>Internal (Adaptable)</td>
</tr>
<tr>
<td>R2: Apogee Burn</td>
<td>Increase/decrease apogee, decrease $\Delta V$</td>
<td>Internal (Adaptable)</td>
</tr>
<tr>
<td>R3: Perigee Burn</td>
<td>Increase/decrease perigee, decrease $\Delta V$</td>
<td>Internal (Adaptable)</td>
</tr>
<tr>
<td>R4: Plane Tug</td>
<td>Increase/decrease inclination, requires “tugable”</td>
<td>External (Flexible)</td>
</tr>
<tr>
<td>R5: Apogee Tug</td>
<td>Increase/decrease apogee, requires “tugable”</td>
<td>External (Flexible)</td>
</tr>
<tr>
<td>R6: Perigee Tug</td>
<td>Increase/decrease perigee, requires “tugable”</td>
<td>External (Flexible)</td>
</tr>
<tr>
<td>R7: Space Refuel</td>
<td>Increase $\Delta V$, requires “refuelable”</td>
<td>External (Flexible)</td>
</tr>
<tr>
<td>R8: Add Sat</td>
<td>Change all orbit, $\Delta V$</td>
<td>External (Flexible)</td>
</tr>
</tbody>
</table>

Tradespace designs = nodes

Applied transition rules = arcs

Transition rules are mechanisms to change one design into another.
The more outgoing arcs, the more potential change mechanisms.
Tradespace Networks: Changing designs over time

Select changeable designs that can approximate “best” designs in new contexts
Changeability Metric: Filtered Outdegree

**Outdegree**
- # outgoing arcs from a given node

**Filtered Outdegree**
- # outgoing arcs from design at acceptable “cost”
  (measure of changeability)

Filtered outdegree is a measure of the apparent changeability of a design.
Ex: X-TOS Outdegree function

Pareto Set designs (903, 1687, 2535, 2471) are not the most changeable

Outdegree functions reveal differential nature of apparent changeability
Tradespace Networks in the System Era

Pareto Tracing across Epochs

Changeability Quantified as Filtered Outdegree

Temporal strategy can be developed across networked tradespace
Example System Timeline

Example system: Serviceable satellite

System timeline with “serviceability”-enabled paths allow value delivery
Research suggests two strategies for “Value Robustness”:

1. **Passive**
   - Choose “clever” designs that remain high value
   - Quantifiable: Pareto Trace number

2. **Active**
   - Choose changeable designs that can deliver high value when needed
   - Quantifiable: Filtered Outdegree

Value robust designs can deliver value in spite of inevitable context change.
Thank you for your attention!
Any questions?
adamross@mit.edu

For further details on topic please see: