SEArri Short Course Series

Course: PI.27s Value-driven Tradespace Exploration for System Design
Lecture: Lecture 5: Modeling and Exploring the Tradespace
Author: Adam Ross and Donna Rhodes
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A slightly earlier version of this course was taught at PI.27s as a part of the MIT Professional Education Short Programs in June 2009 in Cambridge, MA. The lectures are provided to satisfy demand for learning more about Multi-Attribute Tradespace Exploration, Epoch-Era Analysis, and related SEArri-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.
PI.27s VALUE-DRIVEN TRADESPACE EXPLORATION FOR SYSTEM DESIGN

Lecture 5
Modeling and Exploring the Tradespace

Dr. Donna Rhodes and Dr. Adam M. Ross
MIT
Simulating the 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
Outline

• Modeling Techniques
  – Defining analysis modules
  – Designing analysis system
  – Cost modeling
  – Verification of models

• Verification & Preliminary Exploration Techniques
  – Understanding sensitivities
  – Dealing with shifting User needs
  – Comparing to real systems

Additional Example System:
X-TOS Atmosphere Science Satellite
Evaluating Value: Models & Simulations

• Models and Simulations…
  – Take advantage of advances in computation (hardware)
  – Can utilize advances in numerical techniques with consideration for the appropriate level of fidelity (software)
  – Enable designers to “experiment” before implementing
  – Can incorporate humans into a real-time collaborative design environment

• Transform design variables into attributes
Example Project: X-TOS

**DESIGN VARIABLES**

- **Mission Scenarios**
  - Single satellite, single launch
  - Two satellites, sequential launch
  - Two satellites, parallel

- **Orbital Parameters**
  - Apogee altitude (km) 150-1100
  - Perigee altitude (km) 150-1100
  - Orbit inclination 0, 30, 60, 90

- **Physical Spacecraft Parameters**
  - Antenna gain
  - Communication architecture
  - Propulsion type
  - Power type
  - \( \Delta V \) km

**Problem:** Inadequate drag models cause low-orbit objects to become “lost”

**Need:** Better information on atmospheric drag

**Concept:** In-situ vehicle carrying known instrument suite

**Number of Designs Explored:** 50488
X-TOS Scope

Spacecraft

Atmosphere Ionosphere

Output Raw Data

Atmospheric Physics Model

Global Atmospheric Model Current State

Global Atmospheric Model Predict Future State

"Scientist" User Set

AFRL Model

Database

"Space Weather" User Set

Other Data Sources (Various assets)

"Knowledgeable" User Set

User-Specific System Integration

Ground Processing

output data

Density, Ionospheric characteristics

"Scientist" User Set

"Knowledgeable" User Set

"Space Weather" User Set
Spacecraft part of complex science, space weather, and end user system.

Scoping decision (only design spacecraft) made based on available resources and time, knowledge of team, and maturity of sub-systems.

Science user needs chosen; well defined, users available.
X-TOS Attributes
Defined by Science User

<table>
<thead>
<tr>
<th>1) Data Life Span</th>
<th>(1) DATA</th>
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<tr>
<td>2) Data Altitude</td>
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<td>3) Latitude Diversity</td>
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<td>4) Time Spent at Equator</td>
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<td>5) Data Latency</td>
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</table>

(2) km

(3) km

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Generating DV-Att Mappings

Design-Value Mapping

**DVM**

**X-TOS**

**DESIGN-ATTRIBUTE**

Attributes are elicited from Decision Makers

Design Variables are proposed to “perform” in the attributes. Concepts are aggregation of the DV

**VARIABLES**

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>Units</th>
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<th>Weighting</th>
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<tr>
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<td>0 0 0</td>
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</table>

Qualitative filtering of design drivers and attributes (low, mid, high effect → 1,3,9)

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Generating DV-Att Mappings

Design-Value Mapping

DVM X-TOS

DESIGN-ATTRIBUTE

Attributes are elicited from Decision Makers

Design Variables are proposed to “perform” in the attributes.

Concepts are aggregation of the DV

This process is equivalent to a qualitative modeling of the tradespace

Goals:
1. Ensure attributes are “driven”
2. Remove non-value adding design variables

Qualitative filtering of design drivers and attributes (low,mid,high effect → 1,3,9)
Determining the Design Vector

**Example DVM (midstream)**

**Example DVM (almost final)**

**Design-Value Matrices…**

- Map potential Design Variables to Attributes
- Reflect qualitative assessment of strength of relationship

**Goal: minimize number of DV elements and ensure adequate modeling**
Growth of the Design Space

Beware growth of tradespace size!

- Space Tug runs in seconds on a spreadsheet
- X-TOS took a day on a workstation
- System “A” (8 steps, 10 design vars) would take 27 years…
Tradespace Exploration

Compared 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)

Design tradespaces provide high-level insights into system-level trade-offs
Defining the Design Space

The potential design space is specified through enumeration, which lists the range and steps possible for each design variable. Sampling is the strategy for selecting a subset of designs to evaluate from the enumerated potential design space.

The models to be developed must be capable of assessing the potential design space. The actual tradespace will reflect the sampled subset of considered designs.

### X-TOS Example DV

<table>
<thead>
<tr>
<th>Constants</th>
<th>Enumerated</th>
<th>Sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Variables</td>
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<td></td>
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<tr>
<td>Model(s)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Orbital Parameters
- Apogee altitude (km): 150-1100
- Perigee altitude (km): 150-1100
- Orbit inclination: 0, 30, 60, 90

#### Physical Spacecraft Parameters
- Antenna gain: hi, low
- Communication architecture: TDRSS, direct
- Propulsion type: elec, chem
- Power type: solar, battery
- Delta_v (km/s): 6-12

Each point represents a feasible solution.
Issues in Selecting DV Levels

• Tradespace usually a discretization of span of design vector set
• Size of tradespace grows quickly, analyst must tradeoff breadth versus depth
  – More detailed modeling requires more time (depth)
  – More designs explored requires more time (breadth)
• Various techniques exist to “sample” the tradespace without requiring full factorial
  – e.g. Random Sampling, Design of Experiments
• Question: Why not use Optimization?

Must not lose sight of goal:
Understand Tradespace (not just pick optimum)
Sampling Strategies

- For smaller design spaces, use full factorial (size depends on computation considerations)
- For larger ones, need a sampling strategy
  - Ordered sampling: Latin Hypercube, Taguchi Design of Experiments
  - Random: Pick designs until patterns in tradespace emerge
- May need to use optimization techniques to find patterns, Pareto Front of very large tradespaces

Be wary of how selected sampling strategy may introduce “false” patterns in the tradespace
Considerations for Sampling

• Design spaces tend to be “bumpy”*
  – Non-linear and discontinuous dependencies
  – Numerous local minima
• Ordered searches presume linear or low-order dependencies, so may be valid only in local regions
• Recommended:
  – Flat-probability (every design vector element has an equal chance to be chosen) random sampling
  – Frequent expert interpretation of resulting tradespace
  – Adding detail
    • Globally
    • To “interesting” regions of tradespace

*Response Surface Models (RSM) are difficult to develop for such spaces…
Example from X-TOS

- Several thousand points necessary to reveal tradespace features
- Full enumeration necessary to find sharp knee in Pareto front
  - find by local sampling?
### X-TOS Design Vector

<table>
<thead>
<tr>
<th>Variable: Mission Scenarios:</th>
<th>First Order Effect:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single satellite, single launch</td>
<td>Cost</td>
</tr>
<tr>
<td>Two satellites, sequential launch</td>
<td>Life span, Cost</td>
</tr>
<tr>
<td>Two satellites, parallel launch</td>
<td>Latitude Diversity, Time at Equator, Cost</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Orbital Parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apogee altitude (200 to 2000 km)</td>
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<tr>
<td>Perigee altitude (150 to 350 km)</td>
</tr>
<tr>
<td>Orbit inclination (0 to 90 degrees)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical Spacecraft Parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna gain (low/high)</td>
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<tr>
<td>Comm Architecture (TDRSS/AFSCN)</td>
</tr>
<tr>
<td>Propulsion type (Hall/Chemical)</td>
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<tr>
<td>Power type (fuel/solar)</td>
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<tr>
<td>Total ΔV capability (200 to 1000 m/s)</td>
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</tbody>
</table>

**NOTE**

The contents of the Design Vector determine the concept. Each concept is a set of design variables.
The Constants Vector

- To keep modeling general and adaptable to later changes, *do not “hardwire” assumptions into code*
- Instead, keep a list (data structure) where “constants” are kept
- Five types (at least):
  - True constants (g, \( \pi \)) These might still change if your unit system does…
  - 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 why*
Recall four types of constants:
1. True constants (e.g., physical constants)
2. Assumed quantities (e.g., technology levels)
3. Associated variables (e.g., mass/power for a given design variable level)
4. Potential design variables (e.g., “weak” value drivers… for now!)

The models to be developed must be capable of assessing the potential design space. The constants reflect important assumptions in the modeling and should be explicitly “collected” and communicated when exploring the tradespace.

### X-TOS Example Constants

- **Universal**
  - Radius of Earth: 6378.137 km
- **Spacecraft module**
  - Payload data rate: 5000 bps
  - Coefficient of drag (CD): 1.7
  - S/C aspect ratio and shape: 2:1:1 cylinder
  - Van Allen belt altitude: 1000 km
  - Radiation hardening scale factor: 1.25
  - Discount rate: 1.9%
  - Inflation rate (2002): 3.4%
  - Learning curve slope: 95%
Modeling

- Start with DVM

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Data Lifespan</th>
<th>Sample Altitude</th>
<th>Diversity of Latitudes</th>
<th>Time at Equator</th>
<th>Latency</th>
<th>Total</th>
<th>Cost</th>
<th>Total w/Cost</th>
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</table>

Number of Sats, etc.

Easy orbital mechanics

Hard orbital mechanics (drag)

Comm Sys Design
Modeling a Tradespace

- Map design variables to attributes (DVM)
- Brainstorm “modules” that simulate design variables and determine attribute values
- Create an N-squared to determine information flow
- Partition effort to develop software code

<table>
<thead>
<tr>
<th>X-TOS Module list</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Orbits</td>
</tr>
<tr>
<td>2. Spacecraft</td>
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<tr>
<td>3. Launch</td>
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<tr>
<td>4. Mission Scenario</td>
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<td>5. Cost</td>
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<tr>
<td>6. Attributes</td>
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<tr>
<td>7. Utility</td>
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</tbody>
</table>
Design Structure Matrix (DSM) Principles

- Mapping model modules against each other to clarify interactions - sometimes called N-squared matrix
- ‘X’ indicates that the module in the column provides input to the module in the row

See DSMweb.org for more information on DSMs
Using the DSM

- Arrange rows and columns to group interactions, keep interactions “below the diagonal” or as close to the diagonal as possible.
- If all the interactions are one way (below the diagonal) iterations can be eliminated (or at least kept within the modules).

### DSM Example

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Spacecraft</th>
<th>Launch</th>
<th>Cost (TFU)</th>
<th>SATDB</th>
<th>Mission Scenarios</th>
<th>Cost (Lifecycle)</th>
<th>Calc Attributes</th>
<th>Utility</th>
<th>Outputs</th>
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Using the DSM

- Arrange rows and columns to group interactions, keep interactions “below the diagonal” or as close to the diagonal as possible.
- If all the interactions are one way (below the diagonal) iterations can be eliminated (or at least kept within the modules).

```
Using the DSM

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Satellite Database</th>
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<th>SATDB</th>
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<th>Cost (Lifecycle)</th>
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“close to diagonal” interactions require iteration only between two modules (consolidate?)

“above diagonal” interactions would require iteration of entire model (not good)
(Parametric) Modeling with Simulation

An approach enabling broad tradespace numerical assessment

- Parametric modeling linked with simulation provide both static and dynamic insights into tradespace
- Modular software design enables integration with various software tools and fidelity adjustments
Breadth versus Depth: Model Fidelity

Key considerations when choosing fidelity

- “Smoothness” of objective space (enumeration)
- “Consistency” of fidelities across models (consistency)
- Parametric v. human-in-loop “models” (appropriateness)
- “Hooks” for later feedback (verification)

Low fidelity
Square cylinder

Mid fidelity
Simple CAD model

Fidelity feedback
e.g. inability to fit on launch vehicle

Appropriate fidelity choice critical in early design
Cost Modeling:
Criteria for selecting an Estimating Approach

• Have a balance of
  – Statistical significance (i.e., good fit to the data)
  – Practical significance (i.e., intuitively appealing cost drivers)
• Explainable to management
  – Defensible to skeptics
  – Reliable enough to justify $M or $B commitments
• General approaches are categorized as
  – Analogy
  – Parametric
  – Bottoms up/Engineering buildup
  – Extrapolation
  – Expert opinion (including usage of Delphi method)
  – Cost factors
## Selecting a Cost Methodology

<table>
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<tr>
<th></th>
<th>Formulation Phase</th>
<th>Implementation Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-Phase A &amp; Phase A</strong></td>
<td><img src="https://via.placeholder.com/15" alt="Primary" /></td>
<td><img src="https://via.placeholder.com/15" alt="Secondary" /></td>
</tr>
<tr>
<td><strong>Phase B</strong></td>
<td><img src="https://via.placeholder.com/15" alt="Applicable" /></td>
<td><img src="https://via.placeholder.com/15" alt="Occasionally Used" /></td>
</tr>
<tr>
<td><strong>Phase C</strong></td>
<td><img src="https://via.placeholder.com/15" alt="Not Applicable" /></td>
<td></td>
</tr>
<tr>
<td><strong>Phase D</strong></td>
<td><img src="https://via.placeholder.com/15" alt="Not Applicable" /></td>
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<tr>
<td><strong>Parametric</strong></td>
<td><img src="https://via.placeholder.com/15" alt="Primary" /></td>
<td><img src="https://via.placeholder.com/15" alt="Secondary" /></td>
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<td><strong>Engineering Buildup</strong></td>
<td><img src="https://via.placeholder.com/15" alt="Applicable" /></td>
<td><img src="https://via.placeholder.com/15" alt="Occasionally Used" /></td>
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<tr>
<td><strong>Analogy</strong></td>
<td><img src="https://via.placeholder.com/15" alt="Not Applicable" /></td>
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</tr>
</tbody>
</table>

**Exhibit 4-5:** Selecting a Cost Estimating Methodology is Influenced by Program Phase

Variation/Uncertainty in Cost Models

- Cost estimation uncertainty may stem from
  - inaccuracies in cost-schedule estimation models
  - misuse (or misinterpretation) of cost-schedule data
  - misapplied cost-schedule estimation methods
  - economic uncertainties that influence the cost of technology
  - labor force
  - geo-political policies

The Cone of Uncertainty

Unrealistic Cost Estimates of U.S. Space Systems

• U.S. Government Accountability Office found chronic cost growth
  – Not caused by poor cost estimating
  – Rather, pressures to secure funding that lead to unrealistic expectations
• Analysis of six space programs found unrealistic expectations

---

Table 1: Areas Where Program Officials Were Too Optimistic in Their Assumptions

<table>
<thead>
<tr>
<th>Optimistic assumptions</th>
<th>Space programs affected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AEHF</td>
</tr>
<tr>
<td>Industrial base would remain constant and available</td>
<td></td>
</tr>
<tr>
<td>Technology would be mature enough when needed</td>
<td></td>
</tr>
<tr>
<td>TSPR would reduce costs and schedule</td>
<td></td>
</tr>
<tr>
<td>Savings would occur from experience on heritage systems</td>
<td>X</td>
</tr>
<tr>
<td>No weight growth would occur</td>
<td>X</td>
</tr>
<tr>
<td>Funding stream would be stable</td>
<td>X</td>
</tr>
<tr>
<td>An aggressive schedule</td>
<td>X</td>
</tr>
<tr>
<td>No growth in requirements</td>
<td>X</td>
</tr>
</tbody>
</table>

• There are larger pressures to produce low estimates that are more likely to win support for funding

Domain-specific Cost Models

**Software Engineering**
- COCOMO II [Boehm et al., 2005]
- CostXpert [Cost Xpert Group, 2003]
- CoStar [SOFTSTAR, 2006]
- Price-S [PRICE, 2006]
- SEER-SEM [Golorath, 2001]
- SLIM [QSM, 2006]

**Hardware Engineering**
- Price-H [PRICE, 2006]
- SEER-H [Golorath, 2001]

**Systems Engineering**
- COSYSMO [Valerdi, 2005]

**COTS Integration**
- COCOTS [Abts, 2004]
- SEER-SEM [Golorath, 2001]
Model Verification

- Good software practices - make sure code works
- Check sensitivities to both design vector and constants vector elements
  - Verify both model and assumptions (e.g. if results are very sensitive to constants vector elements, reconsider assumptions)
  - Discussed in tradespace exploration
- Verify against more detailed analysis if available
  - Conventional studies
  - Real products
  - ICE studies
Coupled with Tradespace Exploration

More techniques, coupled to issues of modeling:

- Examining the effects of uncertainty in “constants”
- Uncertainty in user needs and interaction with users
- Basic confidence check - Does MATE yield realistic results?

The goal here is to get a feeling for models to verify they produce “reasonable” results before proceeding to deeper tradespace exploration.

Remember ultimate goal: turn data generated by model into knowledge for decisions makers. In addition, generate confidence in model and understandings of its limits.
Examining X-TOS Sensitivities

- Multi-satellite mission designs were found to have large extra costs and very small benefits, so were excluded.
- Single satellite designs shown.
- Pareto designs collect low altitude data (most valuable) at the expense of lifetime.

**Warning**: “good” is not always in the upper left (read the axes!).

"Good" Direction
Examining X-TOS Sensitivities

- Multi-satellite mission designs were found to have large extra costs and very small benefits, so were excluded.
- Single satellite designs shown.
- Pareto designs collect low altitude data (most valuable) at the expense of lifetime.

Warning: “good” is not always in the upper left (read the axes!)
Parametric Uncertainty Sources in X-TOS

Use a tree diagram to identify key sources of uncertainty

Chosen for sensitivity analysis
Sensitivity Analysis

Select relevant set of designs

Vary key uncertain parameters and observe effect on selected designs’ performances

Green – Low altitude, short lifetime

Purple – Mid altitude, mid lifetime

Red – Higher altitude, higher lifetime

All Pareto Front designs
Sensitivity to Satellite Density

- Three designs chosen (colored lines)
- Density varied about a nominal value, effect on Utility and Cost plotted
- Not very sensitive except at lowest densities

Effects small, but implies there is +/- 5% (?) uncertainty in results
Uncertainty does NOT affect all designs equally
Sensitivity to Area Ratio (AR) and Coeff. of Drag (CD)

- Same trend as $\rho_{s/c}$

- Lifetime decreases as CD increase
  - Note the non-linear relationship
  - Arises from non-linear utility function for lifetime
Sensitivity to Atmospheric Density

- Density varied about nominal value; mean value varied based on solar cycle; solar cycle state assumed constant throughout life.
- Effect is most notable at solar max, and is quite large then.
- Effect does not affect all designs equally.

Variation caused by the solar cycle

MIN  MEAN  MAX

Utility vs. density multiplier
Sensitivity to Atmospheric Density

- Density is a key driver of utility
- Its value is uncertain
  - Uncertainty of launch date leads to uncertainty of location in solar cycle
  - Current atmospheric model have large errors
  - The purpose of this mission is to study atmospheric density!

Design spacecraft to have enough fuel and thrust to dynamically change its orbit in response to current atmospheric conditions as mission progresses.

We will discuss such adaptable approaches later.
Sensitivity to User Preferences

Design tradespace reevaluated in less than one hour

User changed preference weighting for lifespan

X-TOS Case
X-TOS Comparison with Real System

Blue points represent X-TOS initial tradespace exploration
Red points represent possible STEP 1 equivalent architectures

Clearly dominated solutions

Provides info for negotiation

“Best” set of designs

STEP 1 mission is X-TOS precursor flown in early 1990s (into ocean)
Flown on multi-payload launch, resulting in sub-optimal system
Streak - Successful System

X-TOS vs. Streak

Inclination different
A user preference for data at the terminator unexpressed at time of X-TOS

Streak values from information in published sources (Aviation Week)
*Calculated with X-TOS preferences
**Modified to account for changed preferences
***Estimate using X-TOS model

• Streak launched 2005
• Very similar to Pareto X-TOS design

<table>
<thead>
<tr>
<th></th>
<th>XTOS (2002 study)</th>
<th>Streak (Oct 2005 launch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Mass kg</td>
<td>325 - 450</td>
<td>420</td>
</tr>
<tr>
<td>Lifetime (yrs)</td>
<td>2.3 - 0.5</td>
<td>1</td>
</tr>
<tr>
<td>Orbit</td>
<td>300 - 185 km @ 20°</td>
<td>321a-296p -&gt; 200 @ 96°</td>
</tr>
<tr>
<td>Launch Vehicle</td>
<td>Minotaur</td>
<td>Minotaur</td>
</tr>
<tr>
<td>Utility</td>
<td>0.61 - 0.55</td>
<td>0.57 - 0.54*</td>
</tr>
<tr>
<td>Modified Utility</td>
<td>0.56 - 0.50</td>
<td>0.59</td>
</tr>
<tr>
<td>Cost $M</td>
<td>75 - 72</td>
<td>75***</td>
</tr>
<tr>
<td>Instruments</td>
<td>Three (?)</td>
<td>“Ion gauge and atomic oxygen sensor”</td>
</tr>
</tbody>
</table>
Examining Space Tug Sensitivities

**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

**Cost, Attributes**
- Delta-V
- Capability
- Response time

**Simple performance model**
- Delta-V calculated from rocket equation
- Capability solely dependent on manipulator mass
- Response time binary (electric propulsion=slow)
- Cost calculated from vehicle wet and dry mass

Utility functions were assumed, not assessed
How sensitive are the results?
Space Tug Parametric Study: Impact of Shifts in User Needs

Unlimited DV demand favors high ISP propulsion
Changing Weightings - Capability Stressed

Utility-Cost Discriminated by Tugging Capability, varied weightings

- Low Capability
- Medium Capability
- High Capability
- Extreme Capability

Spreads front at high-performance end

SPACETUG
- General purpose orbit transfer vehicles
Changing Weightings - Response Time Stressed

Utility-Cost Discriminated by Prop Subsys, varied weightings

- Biprop
- Cryo
- Electric
- Nuclear

Eliminates electric propulsion

SPACETUG
- General purpose orbit transfer vehicles
General Insights

By varying the utility functions, we can find designs that may interest various customers.
Full Scale Development of an Electric Cruiser: Orbital Recovery Corp.

“Orbital tugboat” to supply propulsion, navigation and guidance to maintain a satellite in its orbital slot for 10+ years

CX-OLEV values from information in published sources (ORC website)
*Back-calculated using models
**,**,** Accounts for changed assumption on ISP

<table>
<thead>
<tr>
<th></th>
<th>Electric Cruiser (2002 study)</th>
<th>CX-SLES (2009 launch)</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>

Project cancelled??
Orbital Express: An Experimental Tender

Orbital Express (OE)

On-orbit validation of autonomous docking, refueling, component swapping; focus on non-proprietary interfaces

Flown 2007

Utility

Cost ($M)

- Trade Space
- Freebird
- Biprop GEO tender
- Biprop LEO 2 tender
- LEO 4A Tender
- Biprop GEO tug
- Orbital Express

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Summary

• Modeling Techniques
  – Defining analysis modules
  – Designing analysis system
  – Cost modeling
  – Verification of models

• Related Tradespace Exploration Techniques
  – Understanding sensitivities in model and constants
  – Understanding sensitivities to DM needs
  – Comparing to real systems
References for Cost Models

- PRICE, Program Affordability Management, [http://www.pricesystems.com](http://www.pricesystems.com)
- SOFTSTAR, [http://softstarsystems.com](http://softstarsystems.com)