Concept Design and Tradespace Exploration

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The following slides are an excerpt from this lecture
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 and design choices?
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?

After Fabrycky and Blanchard 1991

Key Phase Activities

Needs Captured

Resources Scoped

Concept(s) Selected

In Situ

Top-side sounder

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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.
Define the Mission

- Understand the “mission”
- Create a list of attributes
- Interview the decision maker(s)
- Create utility curves
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.
MATE Method for Tradespace Exploration
Example: Space Tug

General purpose vehicle to intercept, interact with, and accelerate other vehicles:
General question - what would be a useful design for such a vehicle?

Recently flown Astro/NextSat mission:
Robotic, autonomous on-orbit refueling and reconfiguration test program-
Proof of concept!
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 benefit (e.g. utility) and cost of a large space of possible system designs
Rich data sets can be explored to reveal complex relationships between design-space and value-space for generating intuition into problem—a multi-dimensional analogy to graphing $y=f(x)$.

“Explore” tradespace data to develop intuition into complex design-value relationships.
Steps for Multi-Attribute Tradespace Exploration (MATE)

- 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
Key Concepts in MATE

Stakeholder preferences defines multi-attribute set

defines design variable set

{fitness, safety, unit cost}

{size, shape, material}

Evaluation

eval’d attributes (utility)
benefits
eval’d costs
costs

evaluated alternatives

tradespace

Selection

insights
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
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
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

Exotic Propulsion: Directed Energy, Sails

Conventional

Advanced Propulsion: Electric, Nuclear-Thermal

Exotic Architectures: Swarms, Wireless bus-free architectures

Resources ISS, Depot

Launch

Interaction Equipment

Target Spacecraft

Control Center

Owner Stakeholder

Customer Stakeholders

Owner Stakeholder

Resource Owner Stakeholders

Control Center

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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

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Aggregating Utilities

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

\[
KU(X) + 1 = \prod_{i=1}^{N} (Kk_iU(X_i) + 1)
\]
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, π), 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:**

**Design Var. Associated Quantities**

<table>
<thead>
<tr>
<th>Propulsion System</th>
<th>$I_{sp}$ (sec)</th>
<th>Base Mass $m_p$ (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)
  - $m_{pd}$ Propulsion system base mass (kg)
  - $m_{pf}$ 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

Design Vector

Constants Vector

Model(s)

Costs

Attributes/Utilities

Intermediate Variables
Motivating the Model: Space Tug

- Very simple, explicit, physics-based model
- Intermediate Variables (masses):
  - Propulsion System Mass: $M_p = m_{p0} + m_{pf}M_f$
  - Bus Mass: $M_b = M_p + m_{bf}M_c$
  - Dry Mass: $M_d = M_b + M_c$
  - Wet Mass: $M_w = M_d + M_f$

- Attributes
  - Delta-V: $\Delta v = g I_{sp} \ln\left(\frac{M_w}{M_d}\right)$
  - Capability: Table lookup
  - Speed: Table lookup

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

Design-Value Mapping (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
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    – Electric (NSTAR)
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  > Fuel Load - 8 levels

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

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
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)

Physical phenomena create patterns; must look at full data set to find root causes
Tradespace Reveals Promising Designs

Sets of “good” designs share features/architectures

Often insight is emergent - the tradespace can reveal good design concepts

- Small, light, cheap vehicles with low-mid ΔV capability (tenders)
- Small, slow, high-ΔV electric propulsion vehicles (cruisers)
- Big, fast vehicles require nuclear power (expensive)
Structuring Exploration: Question-Guided Approach

- Decade of tradespace research encapsulated in papers and theses, but “art” of exploration resided in experts
- Need for codifying exploration in order to mature the method and aid in deployment
- Proposed series of case study explorations guided by inquiry (i.e., “questions”) in order to codify expertise (through hypothetical “user” sessions)
  - Activity uses VisLab* software and pre-populated database
  - During a TSE session, users will seek to answer the following questions:

1. Can we find “good value” designs?
2. What are strengths and weakness of selected designs?
3. Are lower cost designs feasible?
4. What about time and change?
5. What about uncertainty
6. How can detailed design development be initiated to have increased chance of program success?

*VisLab software is MATLAB®-based, in-house analysis and visualization program for interactive TSE, but any suite of applications that can perform the necessary functions can be used

Finding “Compromises” Across Missions and Decision Makers

Method provides quantitative approach for discovering “best” mission-specific designs, as well as “efficient” (benefit at cost) compromises across missions and decision makers.

Discover “best” alternatives for individual missions, as well as “efficient” compromises.
Role-Playing Session

Motivation: Wanted to test proposed methods using decision makers, not analysts

- Decision makers filled out preferences in advance using a provided worksheet that constrained preferences to derive from existing model data set
- 2 hour role-playing session using VisLab 1.0 with the following tasks:
  - Find “best” designs per mission
  - Seek “compromise” solutions across missions
  - Vary mission priorities (weights) and repeat
  - Vary mission acceptance ranges (time permitting)
  - Vary mission contexts (time, capability permitting)

Hypothesis: real-time database interaction with multiple simultaneous decision makers will allow for feedback between preference updating and “favorite” solutions, allowing for better compromises

Typical Benefits: Assessing Changing Requirements

Space Tug example: added requirement for rapid response drastically lowers utility of electric propulsion designs
Example MATE Benefits

The following strengths of MATE 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.
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

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

Utility

Cost

Tradespace exploration enables big picture understanding
Value-Driven Conceptual Design Through Tradespace Exploration

Value is a measure of net benefit specified by a stakeholder

Value-centric perspective enables unified evaluation of technically diverse system concepts

Operationalized through the application of decision theory to engineering design -- quantifies benefits, costs, and risks

Tradespace exploration uses computer-based models to compare many alternatives on a common basis

- Avoids limits imposed by myopic local point solutions
- Maps decision maker preference structure to potential designs
- Reveals conflicts and confluence in delivering value to stakeholders

A MATE study can be conducted at different levels of effort and should be scaled appropriately
MATE includes an ordered set of steps for creating an information-rich tradespace:

1. Scoping and bounding the mission
2. Choosing attributes
3. Choosing design variables
4. Modeling and evaluating concepts
5. Creating the tradespace
6. Conducting tradespace exploration

The goals of concept design and tradespace exploration are the extraction of knowledge and the identification of potentially valuable solutions.
Decade of Foundational Research in Tradespace Exploration (TSE)

A method for understanding complex solutions to complex problems
Better informs “upfront” decisions and planning
Evolved through 14 multi-faceted case studies using method

- 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 basis to explore technical and policy *uncertainties*
- Provides a way to assess the value of *potential* capabilities

Importance lies in power to generate knowledge and to engage senior decision makers in effective dialogue and negotiations
Increased knowledge (including understanding of uncertainties) and value-focused thinking allows for better up front decisions.
## MATE Applications

<table>
<thead>
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<th>Name</th>
<th>Num DV</th>
<th>Num Att</th>
<th>Size Tradespace</th>
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<tr>
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<td>5</td>
<td>1</td>
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<td>6, 6, 4</td>
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</table>

There have been 14 case studies as of June 2012
A-TOS
Swarm making in-situ ionosphere measurements

In Situ Ionospheric 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)


Number of Designs Explored: 1380
Hills swarm making ionosphere soundings

B-TOS

Number of Designs Explored: 4033

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 (%),
**C-TOS**

ICE design of B-TOS like vehicles*

*Design similar to “D” from B-TOS

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<table>
<thead>
<tr>
<th>System Engineer</th>
<th>Subsystem Engineer</th>
<th>Subsystem Engineer</th>
<th>Subsystem Engineer</th>
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<tr>
<td><strong>Performance Evaluation</strong></td>
<td><strong>Performance Specifications</strong></td>
<td><strong>Interface Parameters (I.P.s)</strong></td>
<td><strong>Interface Parameters (I.P.s)</strong></td>
<td><strong>Interface Parameters (I.P.s)</strong></td>
</tr>
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</table>

**Number of Designs Explored:** 1

---

*All dimensions in meters*
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**

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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

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Terrestrial Planet Finder (TPF)
A “Big Science” Project

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

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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