2011 SEAri Annual Research Summit

Research Report from the Field

"MATE Applied in Industry: A Satellite Constellation Trade Study"

Dr. Andrew Rader,
COM DEV Mission Development Group

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Cambridge, MA

Massachusetts Institute of Technology

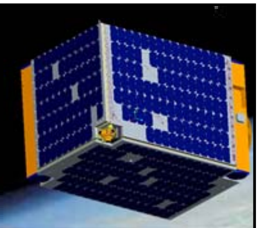
Outline

- Introduction
  - MATE in an industry satellite application
- Method:
  - Populating the tradespace by iteration using expert tools
- Exploring the Tradespace by Attribute
- Multi Attribute Tradespace Exploration (MATE)
- Conclusions

The Mission

- Earth observation constellation with global coverage and requirements for:
  - high observation times
  - frequent revisits
  - fast downlinks
  - with high reliability for multiple points on Earth
- How these attributes should be traded off versus each other or versus costs?

The Team



- How do we engage knowledge from groups of domain experts:
  - Orbital analysts
  - Mission analysts
  - Spacecraft bus engineers
  - Payload specialists
  - Launch analysts & contractors
  - Ground station engineers
  - Operations engineers

Introduction

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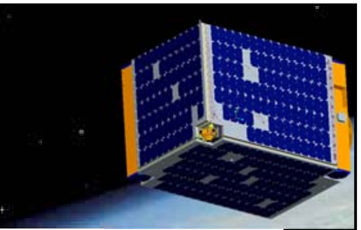
Application of MATE



- Space missions have competing design alternatives that span tradeoffs across multiple subsystems
  - It is not straightforward to select from design alternatives
- Customer requested tradeoff studies
  - However, previous tradeoff studies had been individual performance tradeoffs within a single subsystem – no comprehensive system level trades
- No system level performance model available
- How do we consider interactions across multiple subsystems while mobilizing domain expert knowledge?

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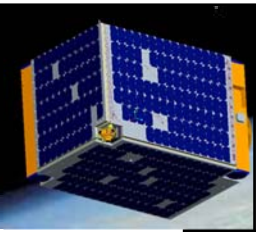
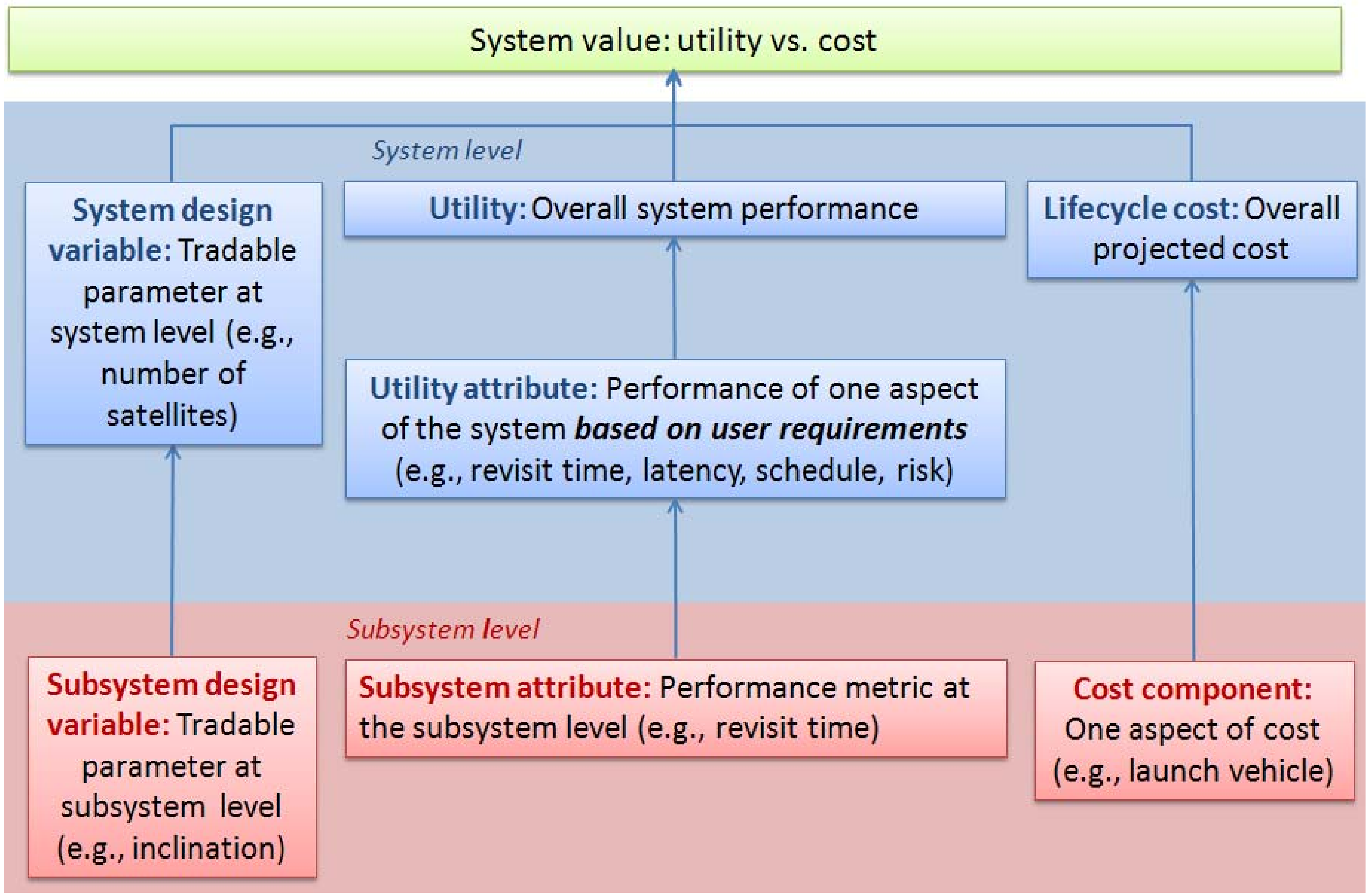
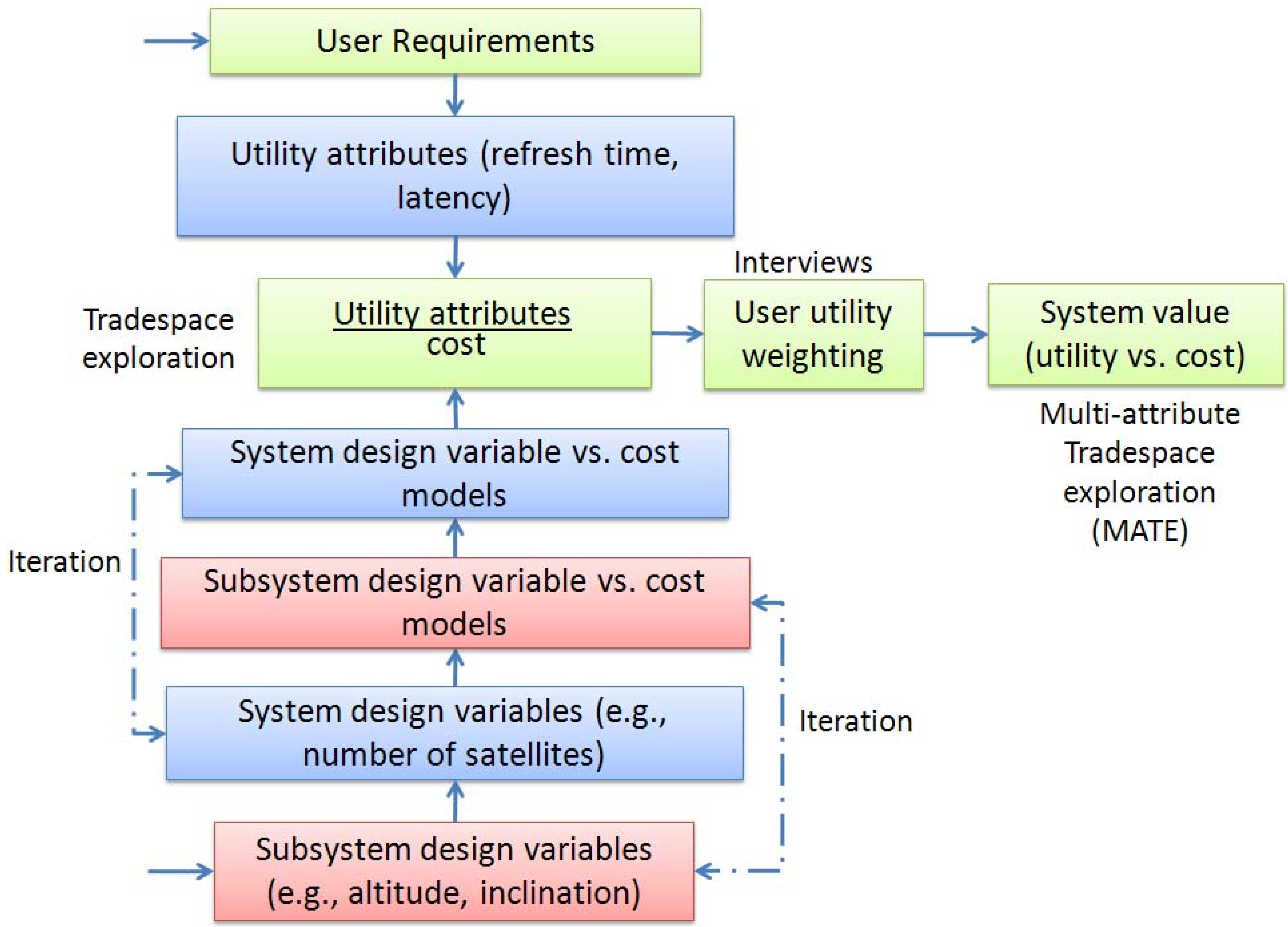
Terminology & Hierarchy



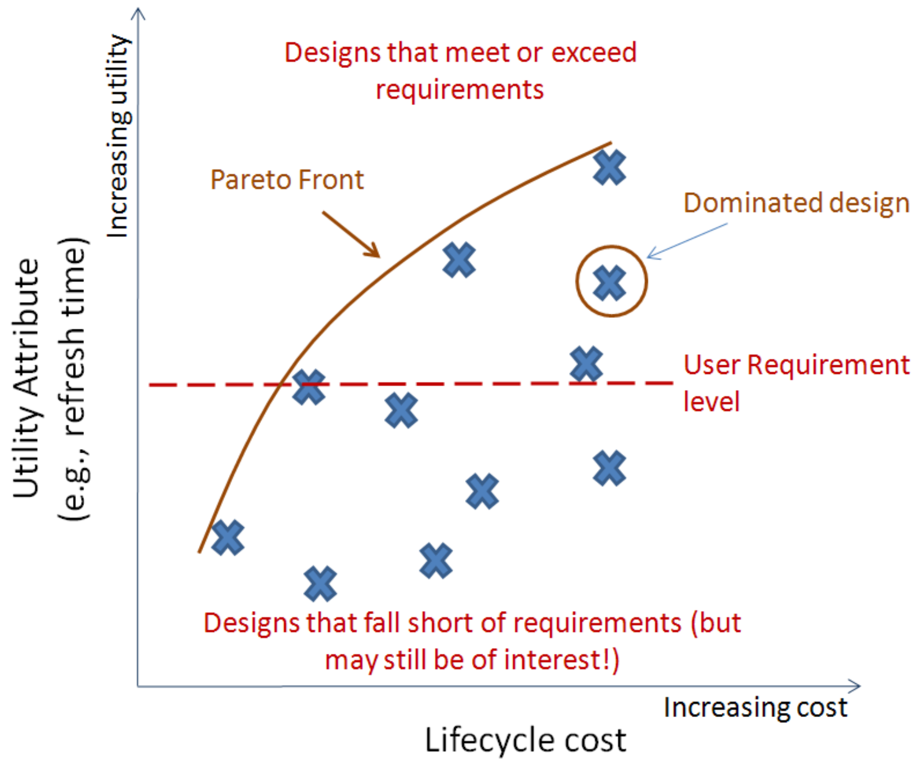


Tradespace Exploration Flow



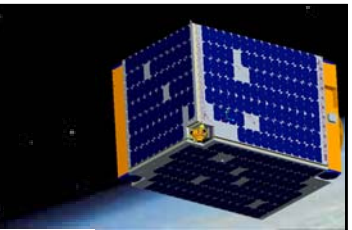
Example Tradespace

- Increasing *value* is composed of:
  - increased utility (increasing along the y-axis, and
  - lower cost (decreasing along the x-axis).
- Pareto Front represents designs that have:
  - the highest utility for a given cost, or
  - the lowest cost for a given utility.
- Designs falling closer to the Pareto Front are higher in value.
- Designs falling father below the Pareto Front are dominated by higher value designs.



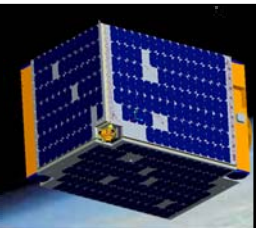
Introduction

Method

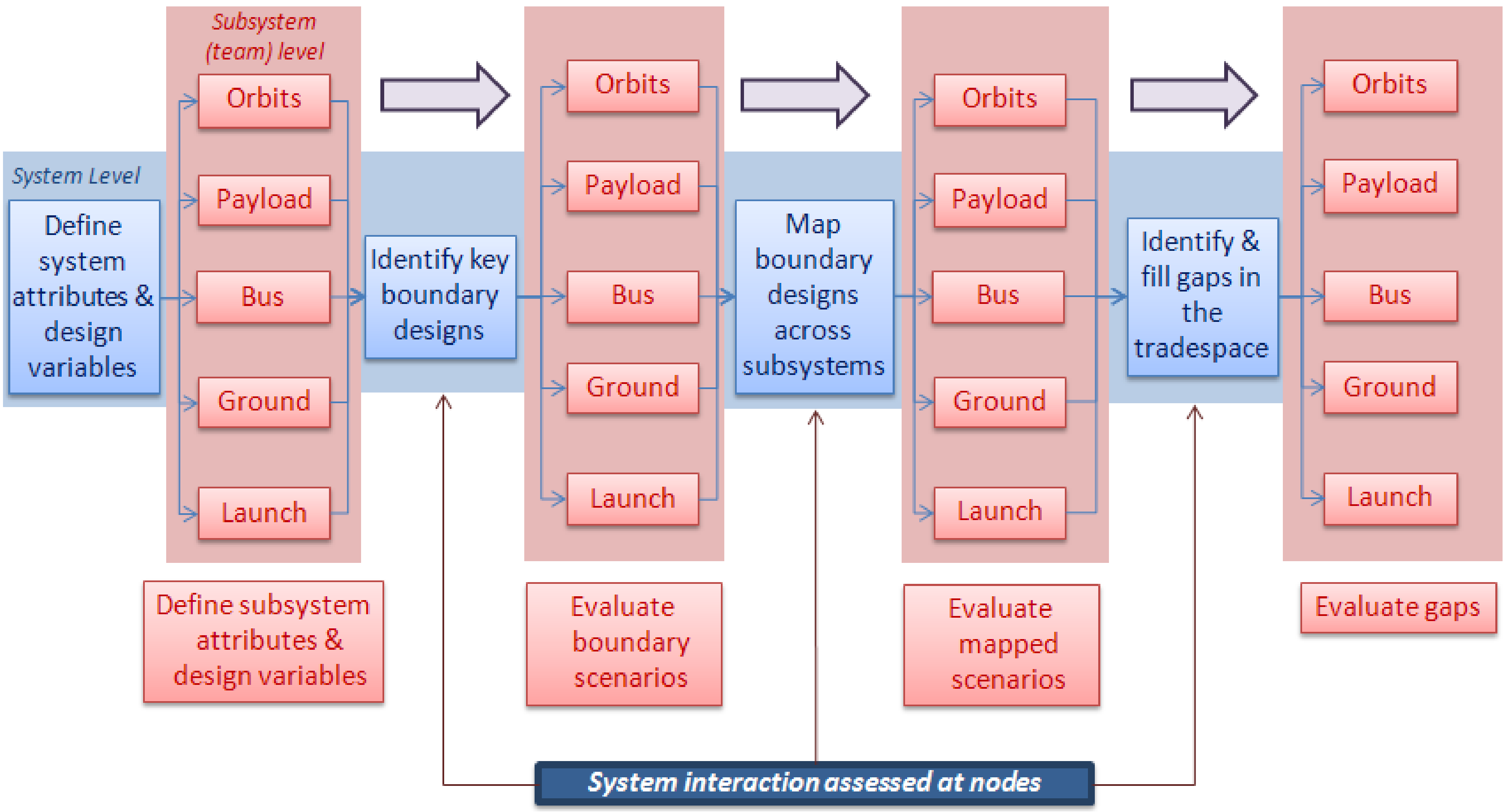


- Subsystem level optimizations performed in parallel by domain experts using their own tools.
- Allows independent partitioning of the design space by expertise (e.g., orbit, ground, launch, payload, etc.).
- Interactions between subsystems assessed and propagated at system level using key nodal checkpoints.
- Assembled system level tradespace automatically captures individual subsystem level trades (i.e., it is pre-filtered).

Populating the Tradespace by Iteration



Methods



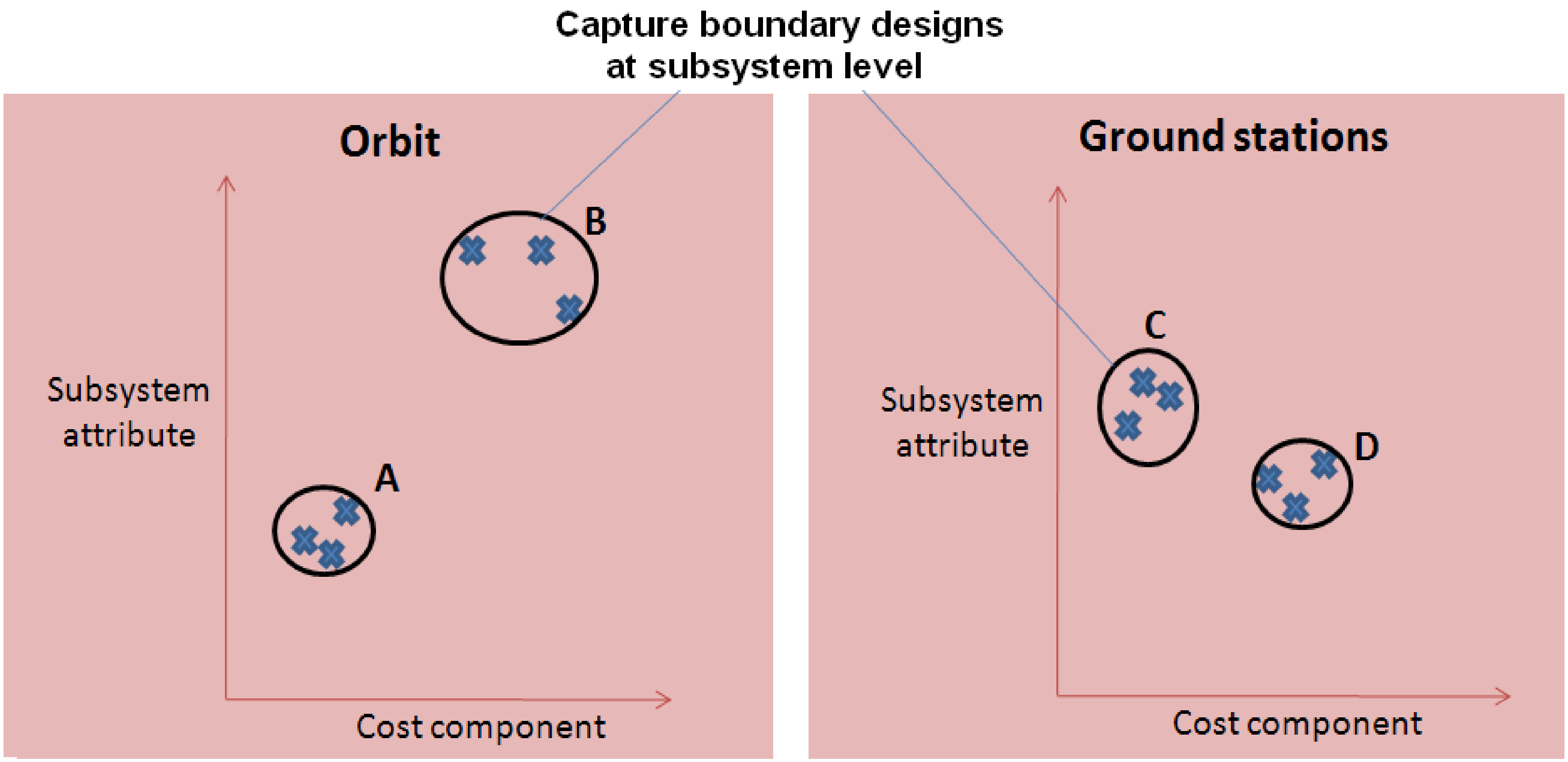
System Level Interactions

1. Evaluate interactions at system level: i.e., how do subsystem design variables influence system level utilities and costs?
2. Map subsystem-generated design variables across subsystems (possible full factorial expansion, e.g., 5 orbit x 3 ground station x 2 launch = 5 x 3 x 2 = 30, but overlaps are likely).
3. Potential for pruning the initial Tradespace.
4. Add missing "gap" designs based on exploration of initial Tradespace – especially when two or more subsystems share design variable elements (e.g., launch analysis suggests cost savings from implementing an orbital configuration).

Expert Group Communication

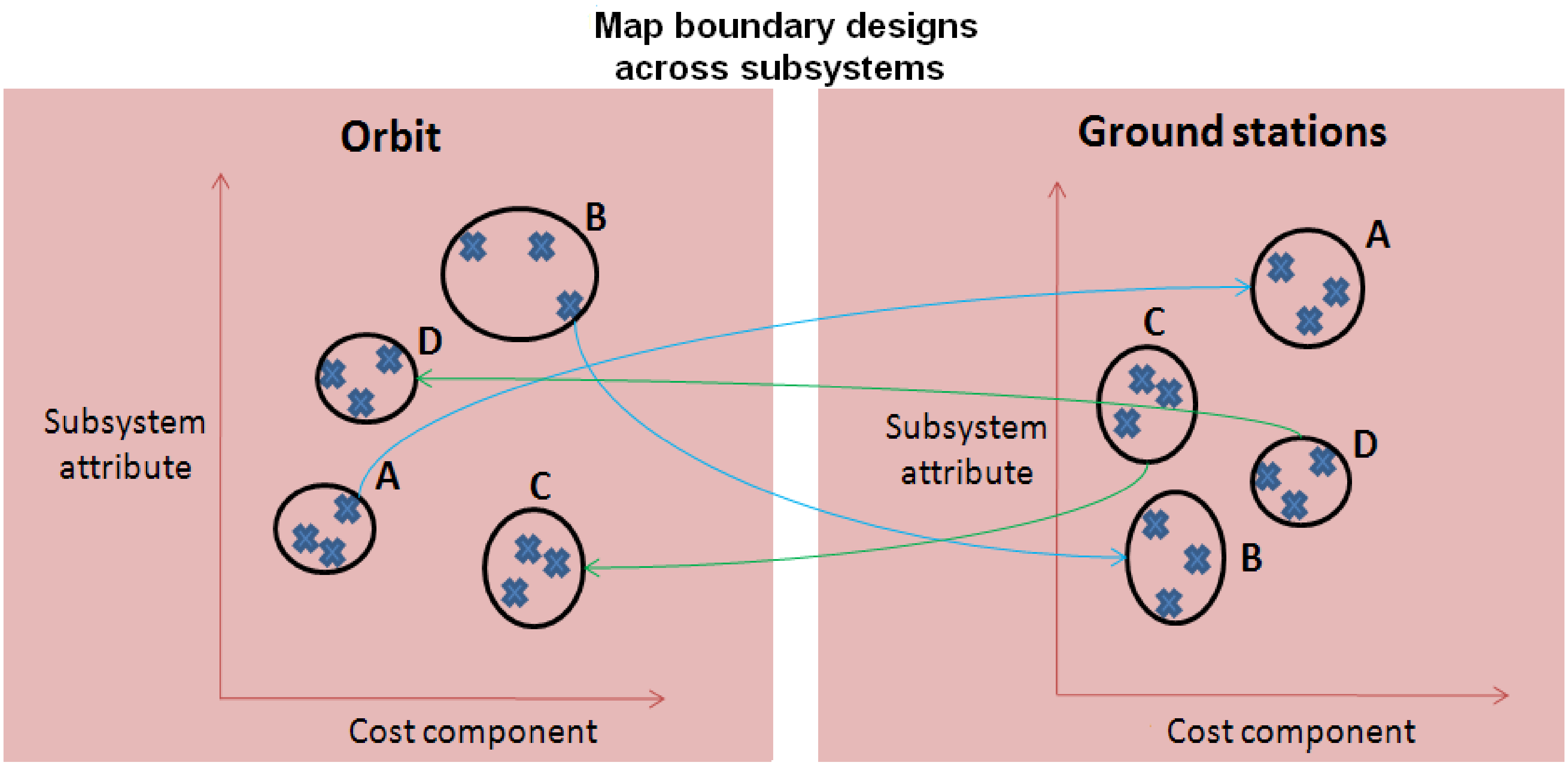
- Minimal communication between expert groups is required to ensure that designs are feasible (though not necessarily efficient) across subsystems.
- No need to account for interactions at the subsystem level.
- Note that two subsystems may not produce the same result even with the same goal.

Capture Boundary Designs



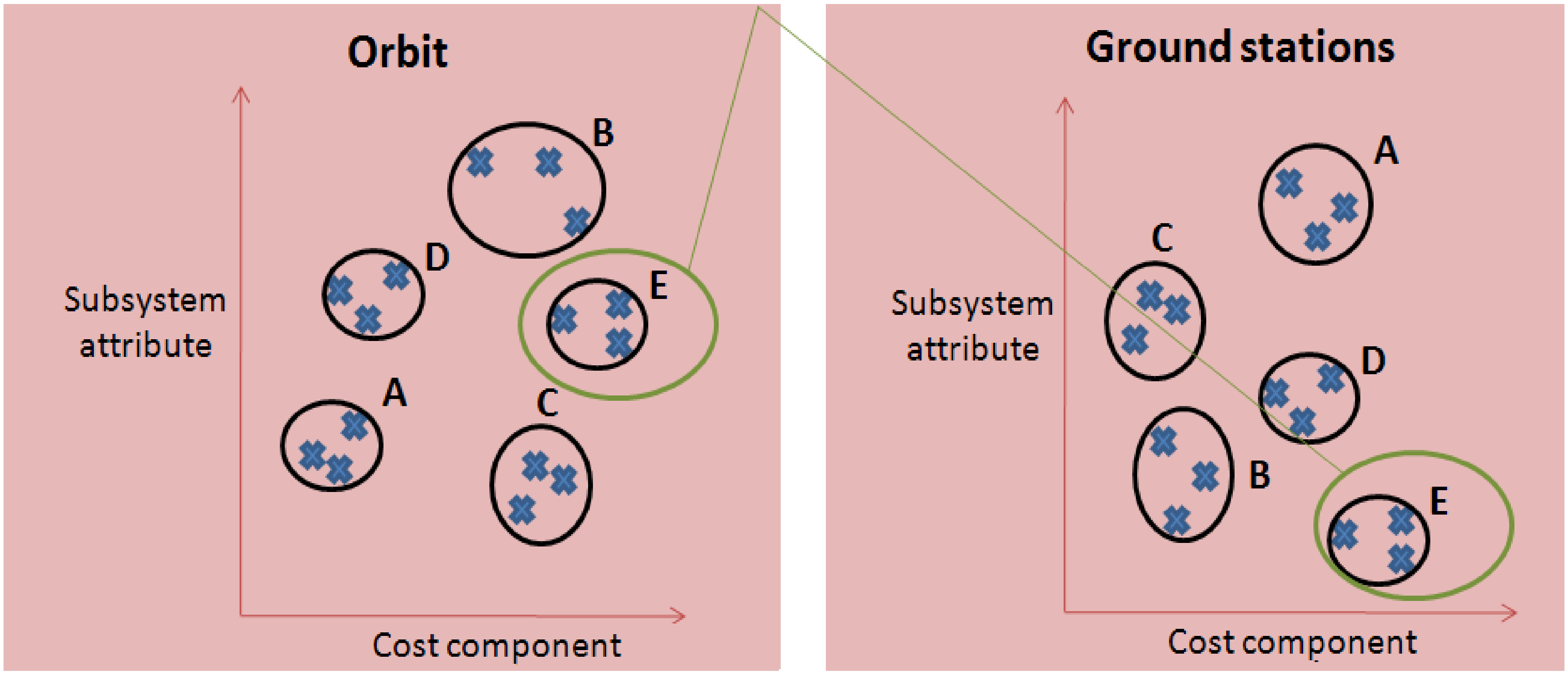
Methods

Map Across Subsystems



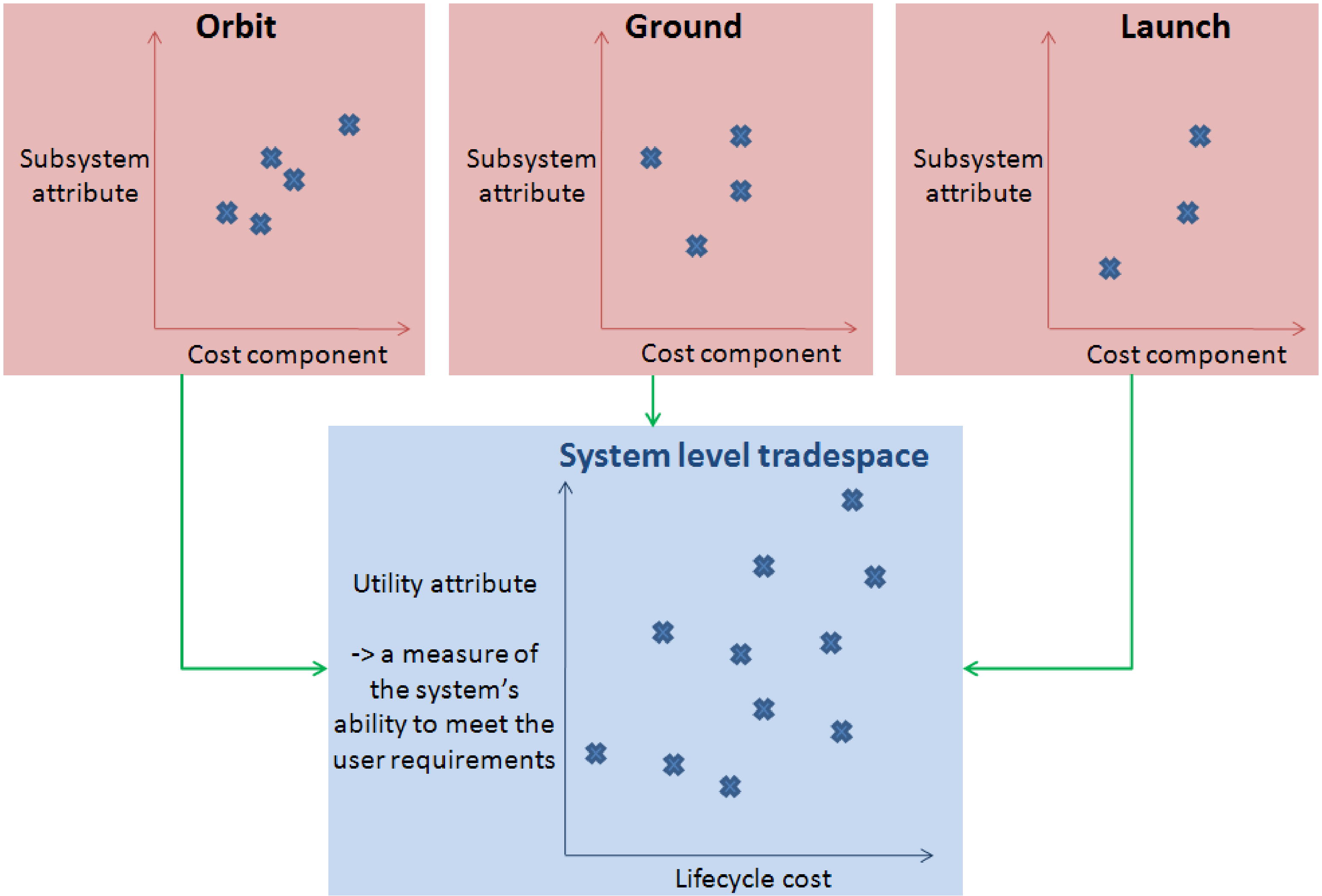
Fill Gaps in Tradespace

Fill gaps in tradespace: Design E not captured as a boundary design



Methods

Build System Level Tradespace

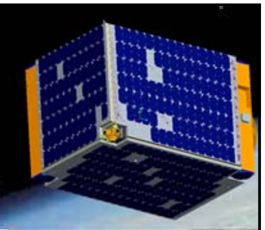


Methods

Satellite Constellation Attributes

Utility attribute	Contributing subsystems
Refresh time globally	• Orbit • Launch (only as an orbit driver) • Ground
Refresh time over particular area of interest	• Orbit • Launch (only as an orbit driver) • Ground
Time on target	• Orbit • Launch (only as an orbit driver) • Payload (footprint, duty cycle)
Latency	• Orbit • Launch (only as an orbit driver) • Payload (data volume and format, downlink rate) • Ground (time to downlink, distribute, & process data)
Redundancy	• Bus (reliability/availability) • Orbit (refresh time with loss of spacecraft) • Ground (refresh time with loss of ground station)

Satellite Constellation Design Variables



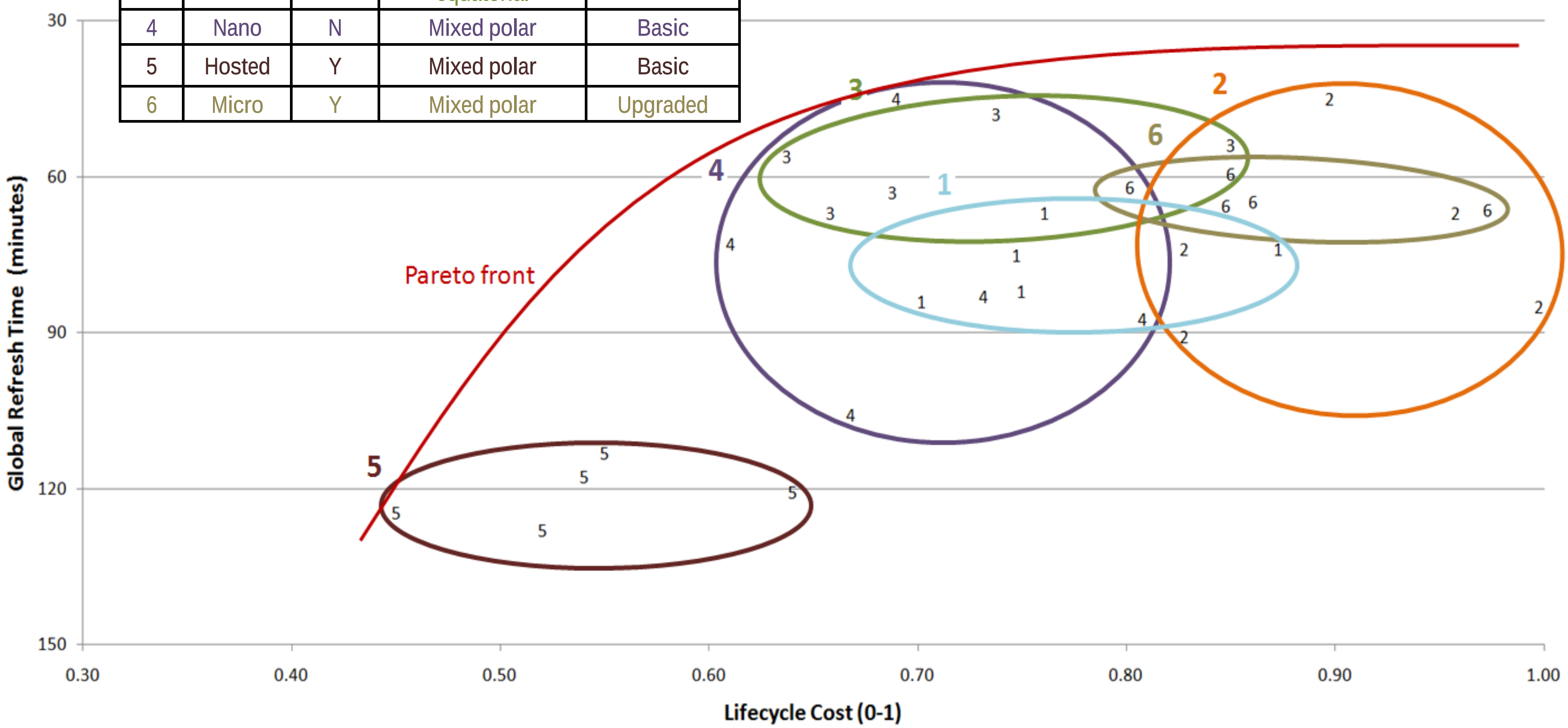
System design variables	Subsystem design variables	Associated cost drivers
Spacecraft/bus	• Number of spacecraft • Nanosat/microsat/smallsat/hosted payload • Controlled/uncontrolled	• Design & build • Launch • Operations
Orbital characteristics	• Orbit planes • Eccentricities • Separation • Special cases (e.g., sun-synchronous)	• Launch • Propulsion & delta-v
Launch vehicle	• Number of satellites per launch • Primary vs. secondary payload • Replacement availability	• Launch vehicles • Launch operations
Payload	• Selection of payload for mission	• Equipment design & build cost • Operations
Downlink	• Frequency • Bandwidth • Geographic availability	• Equipment design & build cost • Regulatory issues
Redundancy, reliability, & replacement strategy	• On-orbit (hot or cold) spares vs. replacement • Spacecraft reliability (expected lifespan)	• Initial cost vs. replacement cost
Ground station	• Number and placement of stations • Build vs. buy • Stationary vs. mobile	• Equipment design & build cost • Start-up vs. operational costs
Data processing & handling	• Storage • Security	• Start-up costs • Operational costs

Example Designs

Design number	Bus	Propulsion?	Orbit type	Ground station configuration
1	Microsatellites	Y	Mixed polar	Basic
2	Microsatellites	N	Mixed polar	Basic
3	Microsatellites	N	Mixed including equatorial	Upgraded
4	Nanosatellites	N	Mixed polar	Basic
5	Hosted payload	Y	Mixed polar in historical locations	Basic
6	Microsatellites	Y	Mixed polar	Upgraded

Tradespace Exploration by Attribute: Global Refresh

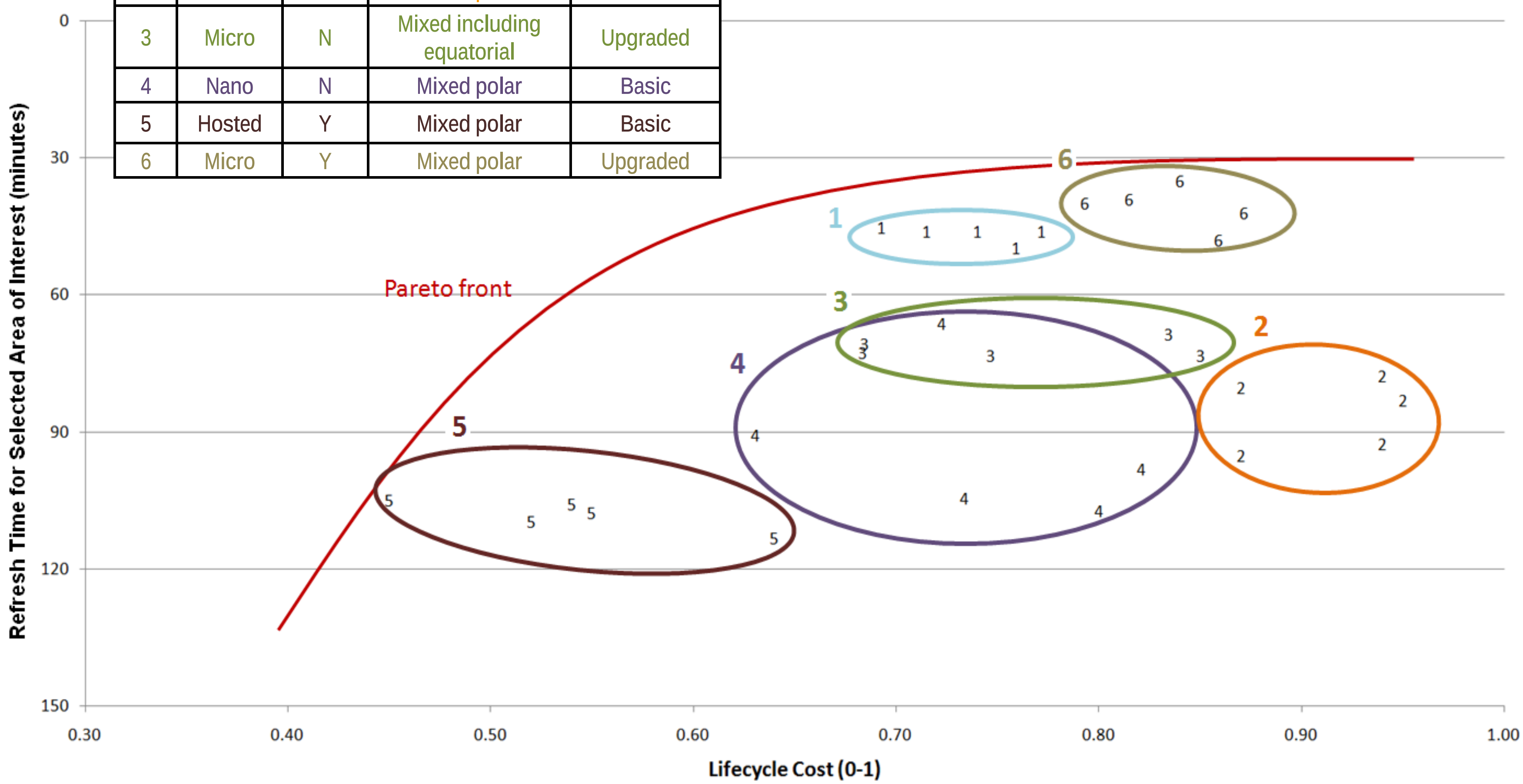
	Bus	Prop?	Orbit	Ground station
1	Micro	Y	Mixed polar	Basic
2	Micro	N	Mixed polar	Basic
3	Micro	N	Mixed including equatorial	Upgraded
4	Nano	N	Mixed polar	Basic
5	Hosted	Y	Mixed polar	Basic
6	Micro	Y	Mixed polar	Upgraded



Tradespace Exploration

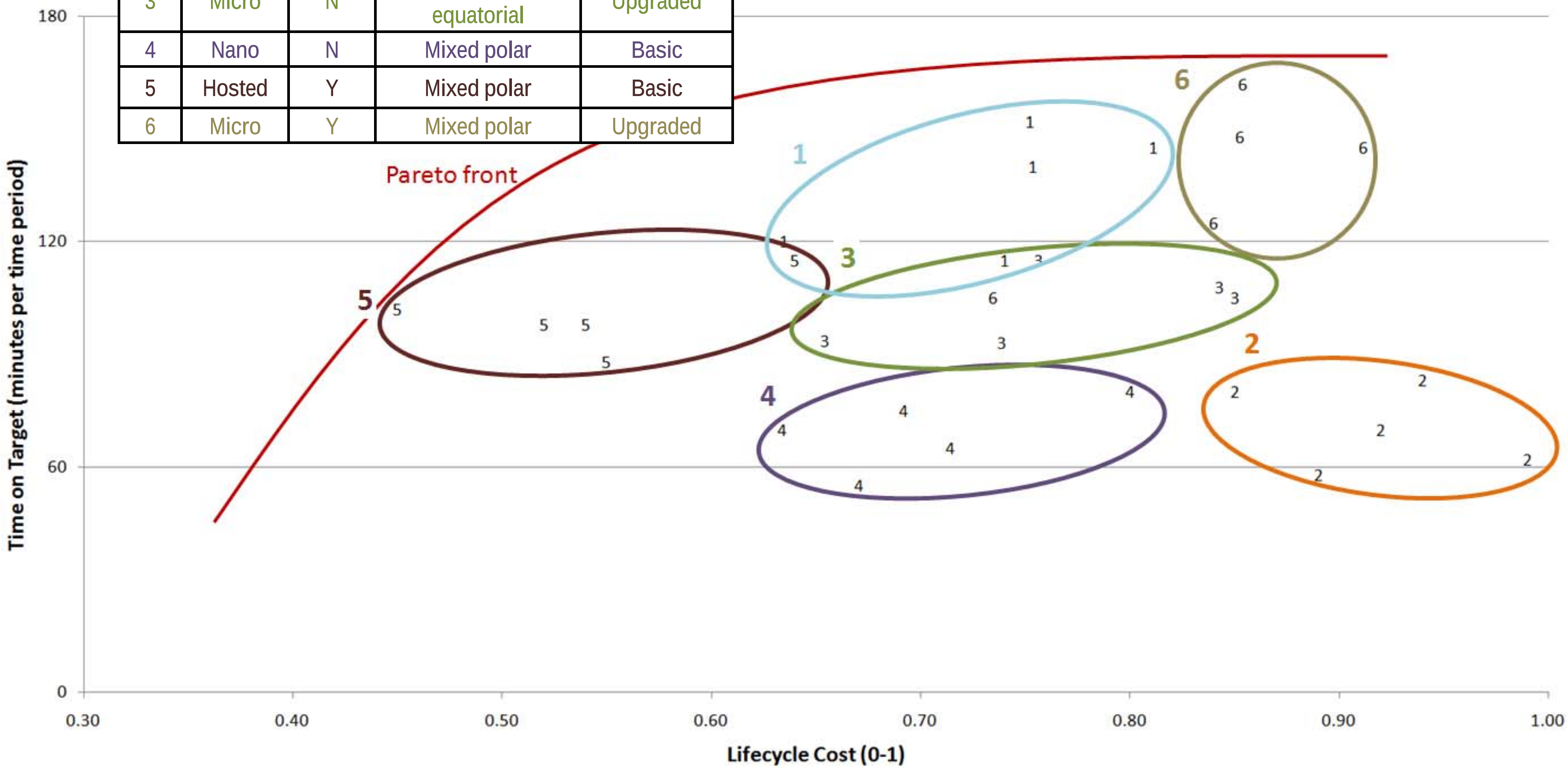
Tradespace Exploration by Attribute: Local Refresh

	Bus	Prop?	Orbit	Ground station
1	Micro	Y	Mixed polar	Basic
2	Micro	N	Mixed polar	Basic
3	Micro	N	Mixed including equatorial	Upgraded
4	Nano	N	Mixed polar	Basic
5	Hosted	Y	Mixed polar	Basic
6	Micro	Y	Mixed polar	Upgraded



Tradespace Exploration by Attribute: Observation Time

	Bus	Prop?	Orbit	Ground station
1	Micro	Y	Mixed polar	Basic
2	Micro	N	Mixed polar	Basic
3	Micro	N	Mixed including equatorial	Upgraded
4	Nano	N	Mixed polar	Basic
5	Hosted	Y	Mixed polar	Basic
6	Micro	Y	Mixed polar	Upgraded



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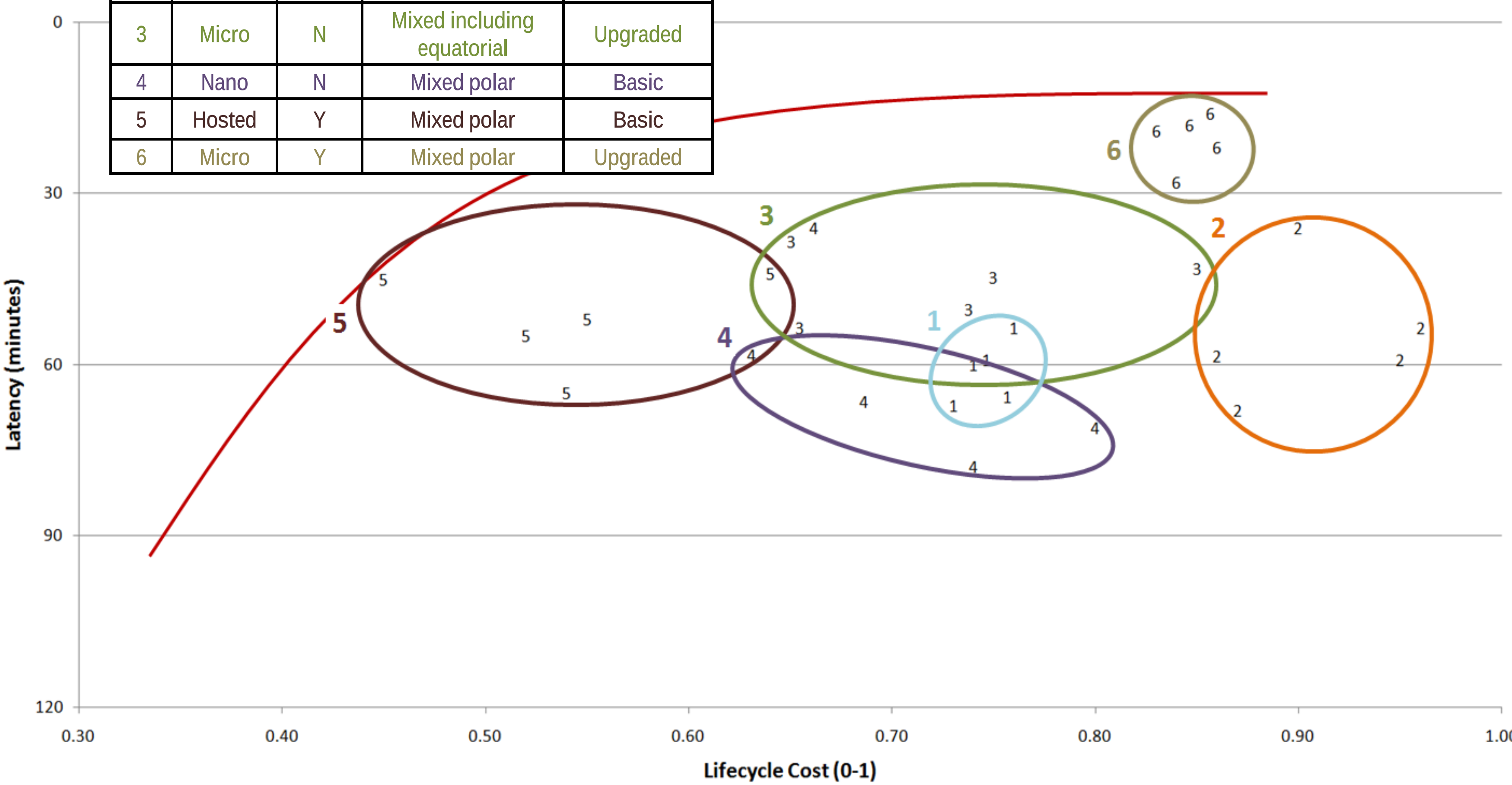
Tradespace Exploration by Attribute: Latency

	Bus	Prop?	Orbit	Ground station
1	Micro	Y	Mixed polar	Basic
2	Micro	N	Mixed polar	Basic
3	Micro	N	Mixed including equatorial	Upgraded
4	Nano	N	Mixed polar	Basic
5	Hosted	Y	Mixed polar	Basic
6	Micro	Y	Mixed polar	Upgraded



Tradespace Exploration

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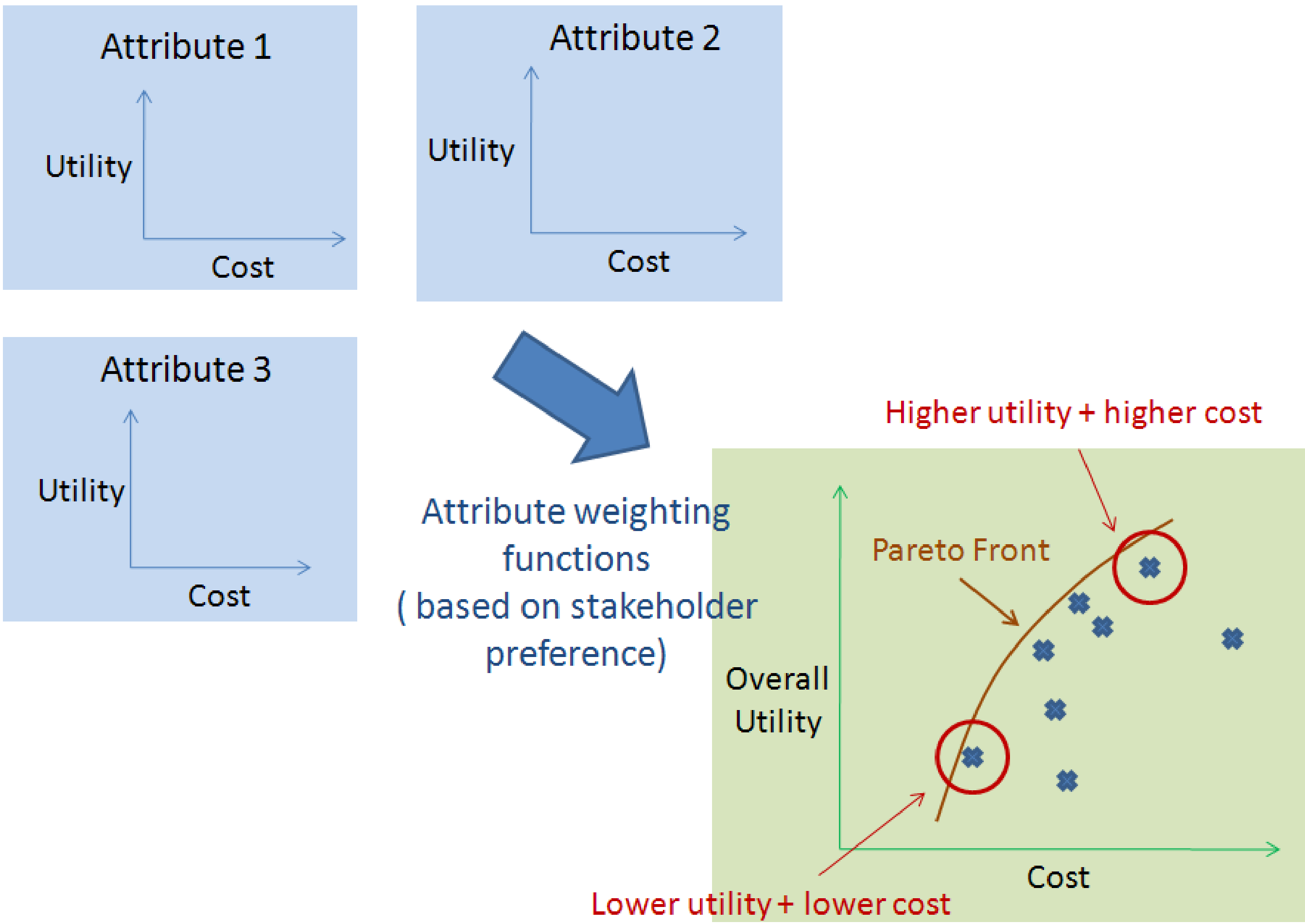
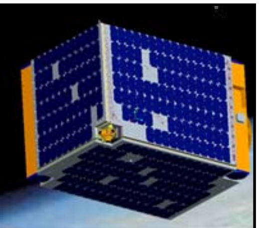
MATE: Assembling the Multi-Attribute Tradespace

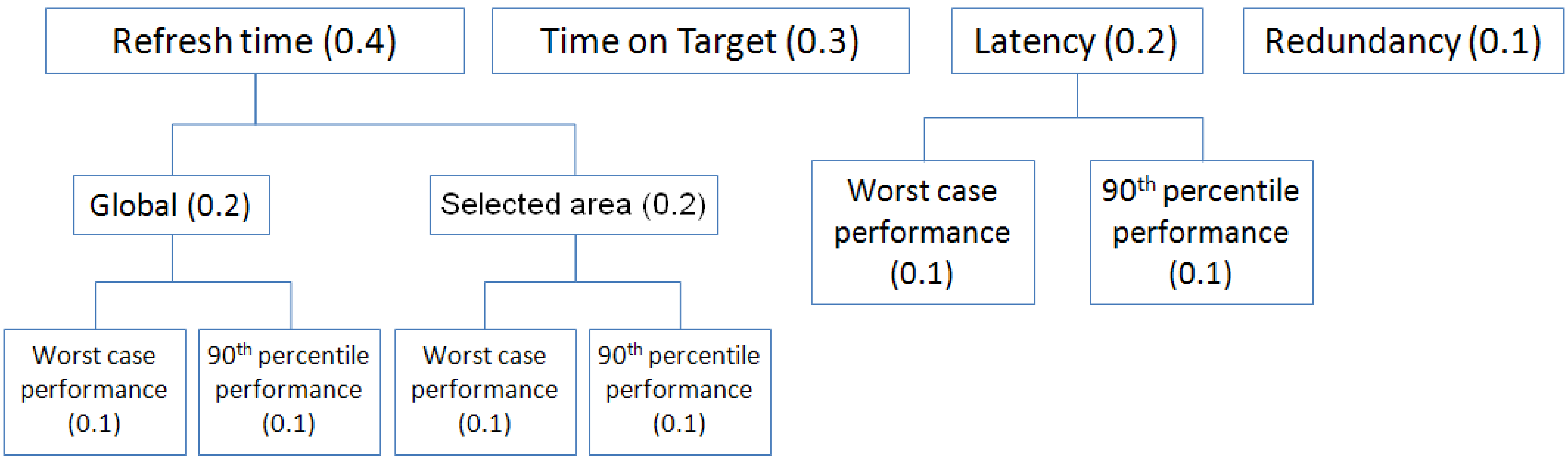


Tradespace Exploration

MATE: Utility Weightings



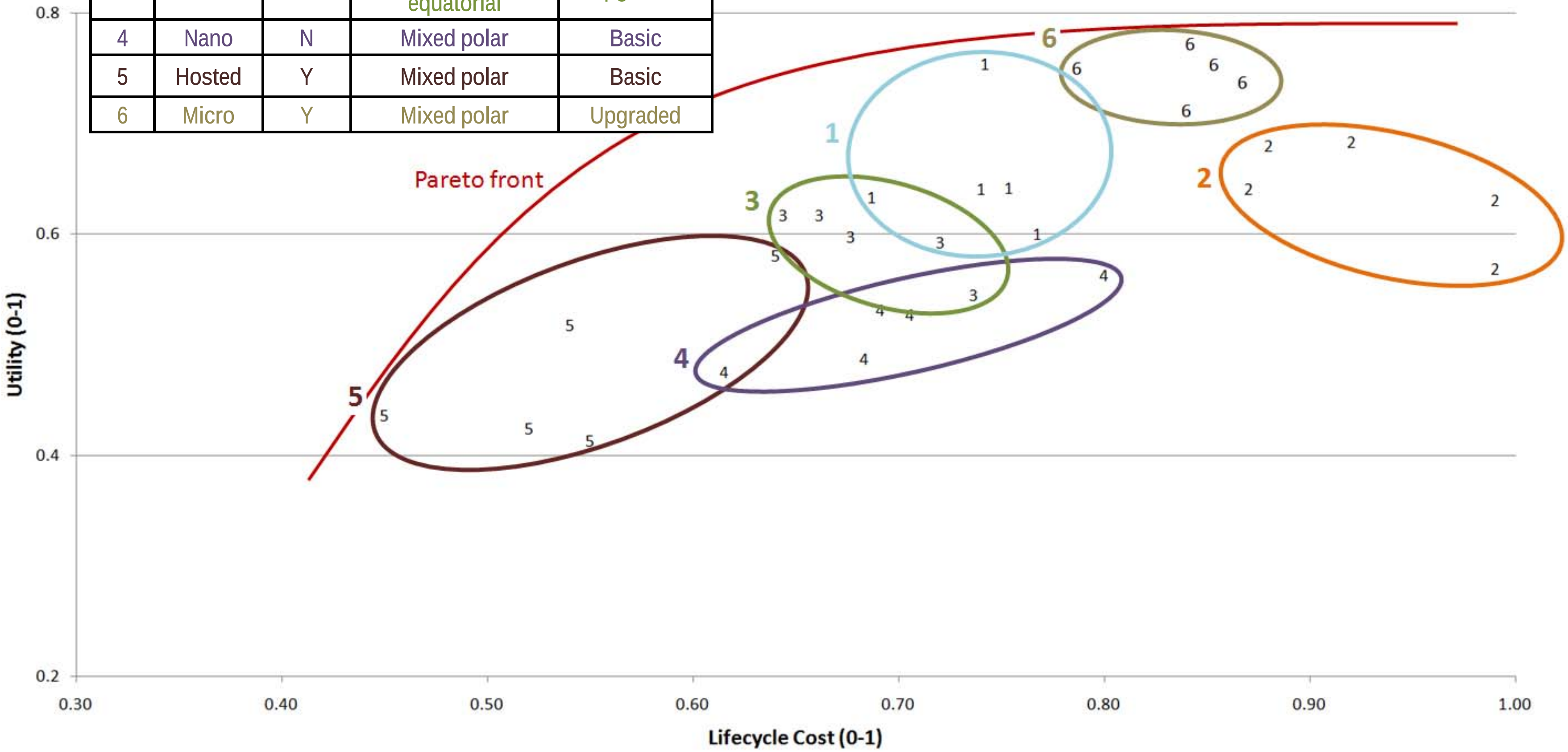
- Conjoint Analysis used to elicit utility weightings:
  - User selects preference from 2 “equal” alternatives of varying attributes multiple times.
  - Difference between nominal attribute rank and true attribute rank allows inference of attribute weightings.



Tradespace Exploration

Multi-Attribute Tradespace

	Bus	Prop?	Orbit	Ground station
1	Micro	Y	Mixed polar	Basic
2	Micro	N	Mixed polar	Basic
3	Micro	N	Mixed including equatorial	Upgraded
4	Nano	N	Mixed polar	Basic
5	Hosted	Y	Mixed polar	Basic
6	Micro	Y	Mixed polar	Upgraded



Tradespace Exploration

Conclusions: Methodology

- Engaging subsystem domain experts early:
  - Capitalizes on expert knowledge
  - Takes advantage of existing tools
  - Saves time
  - Reduces risk
- Result is a filtered subset containing only high value solutions
  - Performance optimizations at the subsystem level have already been performed in the assembled system level tradespace
- Potential drawback: possible missed solutions in filtered tradespace

Conclusions: Industry Application of MATE

- Allowing domain experts to user their own tools meant that no restructuring was required
- Subsystem groups were not required to be familiar with MATE
- Tasks were discretized and structured hierarchically (with information flow in both directions)
- Customer and company recognized power of methodology (and were more ready to accept it)

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Andrew A. Rader
COM DEV Mission Development Group

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