Using Pareto Trace to Determine System Passive Value Robustness

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Managing System Cost, Schedule, and Performance in a Dynamic Reality

- Shift in contexts often occur more frequently than typical system development timelines (e.g., budgets, administrations, near-term warfighter needs)
- Fluctuations feed back on programs, creating cost, schedule and performance risks (e.g., reduced budgets, shifting priorities, change in adversary capabilities)
- By modeling tradespaces of system designs and the impact of context changes across the system’s lifecycle, one can:
  - Gain insight into how context changes affect alternative system value delivery
  - Identify and develop system strategies that promote value robustness
  - Gain insight into possible future operational scenarios, informing affordability trades

Fact: Expectations and contexts for a given system will change over time

Goal: Develop *value robust* solutions
If the “best” design changes over time, how does one select the “best” design?
Tradespace Analysis: Identifying “Good” Designs

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

“Good”, or “satisficing”, designs can be identified across changing objectives

Cost
Utility

The diagram illustrates the concept of identifying “good” designs. Designs that maintain value delivery in spite of changes in needs or contexts are called value robust. *If no system changes are required, then it is “passively value robust”.*
Epoch-Era Analysis for Generating Future Scenarios

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

Define Epochs
Epoch set represents potential fixed contexts and needs

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

Parameterizing future epochs allows for quantification of epoch effects on designs
Tradespace Exploration

Compares 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
Calculating Pareto Trace to Uncover Value Robust Designs

Find non-dominated solutions within a given epoch (Pareto Set)
Calculating Pareto Trace to Uncover Value Robust Designs

Find non-dominated solutions within a given epoch (Pareto Set)

Across many epochs, track number of times solution appears in Pareto Set
Calculating Pareto Trace to Uncover Value Robust Designs

Find non-dominated solutions within a given epoch (Pareto Set)

Across many epochs, track number of times solution appears in Pareto Set

Identify designs with high Pareto Trace for further investigation

e.g. “design 3435” is in 67% of Pareto Sets

Higher Pareto Trace designs are more passively value robust
Case 1: Quantifying Robustness to Expectations Change

1. Apply needs (expectations) changes to tradespace
2. Assess Pareto Trace statistics across tradespaces
3. Find designs that remain preferred across epochs

DESIGN VARIABLES (9)
- Mission scenario, Apogee altitude (km), Perigee altitude (km), Orbit inclination (deg), Antenna gain, Communication architecture, Propulsion type, Power type, Delta V (m/s)

ATTRIBUTES (5)
- Data lifespan (mos), Sample altitude (km), Latitude diversity (deg), Equatorial time (hr/day), Latency (hrs)

Project X-TOS
Single-Satellite in-situ density measurements
Pareto Set Tracing for Single DM
(Δ attribute set)

What if you don’t elicit all of the “right” attributes?

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What if you don’t elicit all of the “right” attributes?
Pareto Set Tracing for Single DM
($\Delta$ attribute set)

Design 2471 is in all 7 Pareto Sets
Designs 903, 1687, 2535 are in 5 Pareto Sets each
These points are “robust” in ranking to tested attribute set change

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Pareto Set Tracing for Single DM (linearized preferences)

What if you don’t elicit the “right” utility curve shape?
Pareto Set Tracing for Single DM (linearized preferences)

15 design options are in all 16 Pareto Sets and are "robust" to Exp1c preference variations (linearization of SAU)

Includes designs 2471, 903, 1687, 2535
Pareto Set Tracing for Single DM
(Δ Eval Fcn)

What if you don’t use the “right” utility aggregating function?

1. $U = \left( \prod_{i=1}^{N} [KkU_i + 1] \right)^{-1}$
2. $U = \prod_{i=1}^{N} k_i U_i$
3. $U = \prod_{i=1}^{N} [k_i U_i + 1]$
4. $U = \sum_{i=1}^{N} k_i U_i$
5. $U = \prod_{i=1}^{N} [KkU_i + 1]$

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Pareto Set Tracing for Single DM
(△ Eval Fcn)

26 design options are in all 5 Pareto Sets and are “robust” to Exp1d preference variations (MAU functional forms)
Includes designs 2471, 903, 1687
Pareto Set Tracing for Dual DM (additional of second DM)

What if a second decision maker enters the mix?
Multiple tradespaces are differentiated by Decision Maker instead of time.

Joint Pareto Set contains 122 common designs, including design 2471!
Discovering “Compromises”

**Designs in Joint Pareto Set**

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“Optimal” solutions per DM are (a) or (b)

“Optimal” solutions for both DM are (c)

Compromise set (d) difficult to determine through traditional means

Approach can be used to discover “efficient” compromises as basis for negotiation
1 design option, 2471, is in all 60 Pareto Sets and is “robust” to all preference variations (+/- \(X\), \(k_{ij}\) linear SAU, MAU forms).

4 more designs are in 57 or more Pareto Sets, including designs 903, 967, 1687, and 2535.

Pareto Tracing can be used to identify obvious or non-obvious passively value robust designs.
Performing Pareto Tracing

Perform anticipatory exploration of possible preference permutations
– Answering “what if” questions on needs…

• What if you don’t elicit the “right” attribute priorities?
• What if you don’t elicit all of the “right” attributes?
• What if you don’t elicit the “right” utility curve shape?
• What if you don’t use the “right” utility aggregating function?
• What if a second decision maker enters the mix?
• …

– Find designs common in Pareto Sets across varying “needs” and “contexts” epochs

Pareto Trace is a metric of passive value robustness across epoch variations

But what does absolute Pareto Trace mean, and what about designs that are “close” to the Pareto Front? Aren’t these “good” also?
Case 2: Quantifying Robustness to Epoch Changes

1. Apply epoch changes (needs and contexts) to tradespace
2. Assess Pareto Trace statistics across tradespaces
3. Find designs that remain preferred across epochs

DESIGN VARIABLES (10)
- Orbit Altitude (km), Constellation design, Antenna size (m^2), Peak power (kW), Radar bandwidth (GHz), Comm arch, Tactical downlink, Tugability, Maneuver package, Constellation option

EPOCH VARIABLES (6)
- Technology avail, Comm infrastructure, Target list, AISR avail, Environment, Mission priorities

ATTRIBUTES (3 “missions”, 15 total)
- Tracking (GMTI), Imaging (SAR), Programmatic

Project SRS
Satellite radar multi-mission system of system
Addressing Epoch-Sampling Bias

Since there are infinite permutations of possible needs and contexts… normalize Pareto Trace to determine robustness as fraction of considered “futures”

Normalized Pareto Trace (NPT) = \[ \frac{\text{Pareto Trace}}{\text{Total Number of Epochs Considered}} \]

Total enumerated epochs = 648

Sampling strategy

Randomized sampling of epochs seeks to balance computation with stability of NPT

NPT will be dependent on epochs considered. Correlation between high NPT designs and epochs gives insights into epoch-specific classes of “best” designs
Extending Pareto Tracing

Fuzzy Pareto Optimality*

Assuming goal is to minimize \( J^1 \) and \( J^2 \), \( J^1 \) dominates \( J^2 \) if:

\[
J^1 + K(J_{\text{max}} - J_{\text{min}}) \leq J^2, \text{ and } J^1 \neq J^2
\]

(1)

\[
J^1_i + K(J^\text{max}_i - J^\text{min}_i) \leq J^2_i \quad \forall \quad i \quad \text{and}
\]

(2)

\[
J^1_i + K(J^\text{max}_i - J^\text{min}_i) < J^2_i \quad \text{for at least one } i,
\]

(3)

Fuzzy Pareto Trace, Varying K

K=0%
Max NPT=0.7
1 Design

K=5%
Max NPT=1.0
2 Designs

K=10%
Max NPT=1.0
19 Designs

K=15%
Max NPT=1.0
62 Designs

Tuning K allows for discovery of “good” designs
Discovery of “Good” Designs

New designs that were “almost” best are discovered at K=5%

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Discussion

• Changes in static analysis assumptions should not be a post-analysis consideration (e.g., “sensitivity analysis”)
• Using Pareto Trace with Multi-Epoch Analysis makes such considerations a central part of trade studies
• (F)NPT can be used to gain insight into:
  – Differential impact on systems of non-subtle, discrete changes in
    • Expectations or needs
    • Contexts
  – Epoch-specific valuable families of solutions
  – Inclusion of “satisficing” designs (i.e., slightly “suboptimal”)

Metric is most useful as an indicator for further investigation (e.g., What is “so special” about these designs? In what epochs do they perform well and why?)
Summary

For Multi-Epoch Tradespace Exploration…

Three metrics for passive value robustness

- Pareto Trace (PT)
  - # Pareto Sets across epochs in which design is considered “best”
- Normalized Pareto Trace (NPT)
  - Fraction of epochs in which design is considered “best”
- Fuzzy Normalized Pareto Trace (FNPT)
  - Fraction of epochs in which design is considered “good”

Passive value robustness is only part of the story…
Complementary research addresses active value robustness and developing system evolution strategies…

Questions?

For more information, please visit http://seari.mit.edu
or contact: adamross@mit.edu, rhodes@mit.edu
Back-up Slides
Tradespaces with Highest NPT Designs

- Black = 3435 (NPT = 0.7@K = 0%)
- Red = 5067 (FNPT = 1.0@K = 5%)
- Blue = 7659 (FNPT = 1.0@K = 5%)
High NPT Designs in U-U-C Tradespace
High NPT Designs in U-U-C Tradespace
Tradespace Networks: Changing Designs over Time

Generate tradespace networks
- Tradespace designs = nodes
- Applied transition rules = arcs

“Best” designs in new contexts may differ; Changeability may provide opportunity
Filtered Outdegree

# outgoing arcs from design at acceptable “cost”
(measure of changeability)

Defined 8 System Transition Paths (Rules)
1. Redesign (Design Phase)
2. Redesign (Build Phase)
3. Redesign (Test Phase)
4. Add satellites to constellation (Ops Phase)
5. Alter altitude with on-orbit fuel (Ops Phase)
6. Alter altitude through tug (Ops Phase)
7. Alter inclination with on-orbit fuel (Ops Phase)
8. Alter inclination through tug (Ops Phase)

One can identify “changeable” designs and design choices (real options) by determining the filtered outdegree at a given acceptable transition “cost” threshold.
Calculating Filtered Outdegree to Uncover Changeable Designs

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

Quantification and specification of “ilities” can be made explicit (e.g., flexibility, adaptability, scalability, survivability, etc.)

One can identify “changeable” designs and design choices (real options) by determining the filtered outdegree at a given acceptable transition “cost” threshold

Variation in design “changeability” in response to context change

In some cases… “changeability” goes to zero

Design 3435, All Epochs, All Rules

Design 3435, All Epochs, All Rules