“Multi-Epoch Analysis of a Satellite Constellation to Identify Value Robust Deployment across Uncertain Futures”

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AIAA Space 2014

SSEE-04: Early Mission Design Decisions

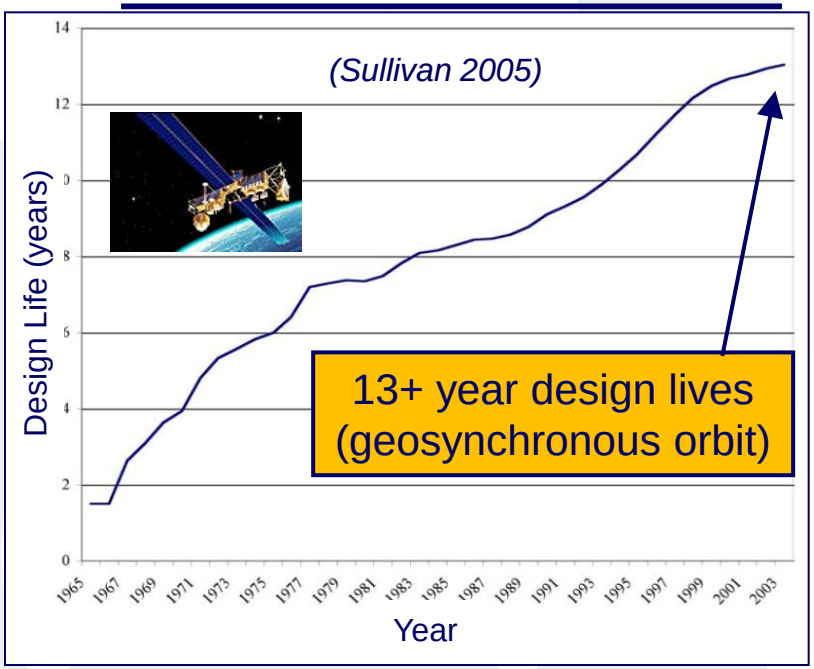
5 August 2014, San Diego, CA

Perverse Emergent Dynamic: Mismatch of Design with Context

1960's Paradigm

- CORONA: 30-45 day missions
- 144 spacecraft launched between 1959-1972 *(Wheelon 1997)*

Evolution to Current State



- Inability to adapt to uncertain future environments, including disturbances, leads to "gold-plated" designs

"Our spacecraft, which take 5 to 10 years to build, and then last up to 20 in a static hardware condition, will be configured to solve tomorrow's problems using yesterday's technologies." *(Dr. Owen Brown, DARPA Program Manager, 2007)*

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Example Embodied Ilities

Robust

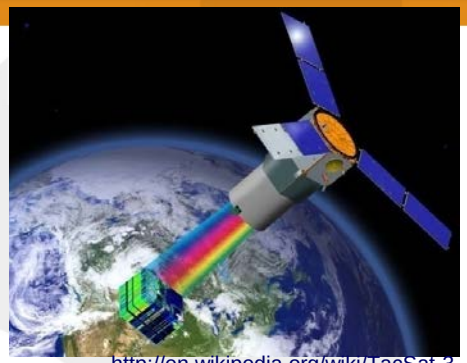
Milstar

*"Milstar is the most **robust** and reliable SATCOM system currently employed by the Department of Defense."*

Source: http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=5328, posted 12/7/12

Versatile

TacSat-3



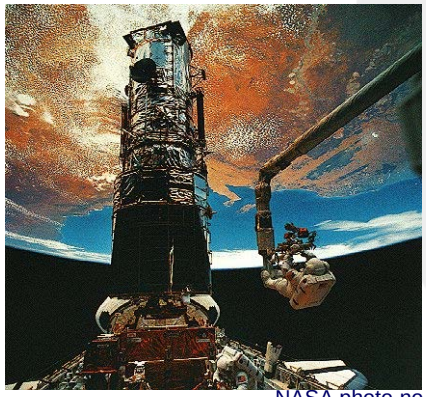
http://en.wikipedia.org/wiki/TacSat-3

*"The results remain nothing short of stunning as TacSat-3 demonstrated the **versatility** of its hyper spectral imaging payload..."*

Source: http://www.afspc.af.mil/news1/story_print.asp?id=123300881 posted 5/4/12

Flexible

Hubble Space Telescope



NASA photo no. 94-H-16

*"Designed to be **serviceable** in orbit, the Hubble Space Telescope was the most mechanic-friendly spacecraft ever flown."*

Source: http://history.nasa.gov/SP-4219/Chapter16.html, accessed 4/28/13

Adaptable

Earth Observing-1

http://en.wikipedia.org/wiki/Earth_Observing-1

*"The [Autonomous Sciencecraft Experiment]… aboard EO-1… spot[s] science targets **autonomously**, to change a science satellite's priorities without the involvement – or even knowledge – of ground controllers so it can observe unexpected phenomena in its path…"*

Source: http://eo1.gsfc.nasa.gov/new/extended/sensorweb/ase.html , accessed 4/28/13

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The Dynamic Value Problem

Challenge: need to balance short run vs. long run in the face of various types of uncertainties (e.g. known unknowns and unknown unknowns)

- Architects, designers, and operators often face changes in…
  - User needs
  - Available technologies
  - Political and technical contexts
- Solutions must be able to deliver value in spite of these changes in context and needs

  Example strategies:
  - Develop “Changeable” solutions (*i.e.,* use “ilities” in architecture)
  - Develop “Versatile” solutions (*i.e.,* build in “extra” value)
  - Develop “Robust” solutions (*i.e.*, be insensitive to perturbations)

Success over time requires matching system with changing needs in changing contexts (e.g. ilities)

Q: How can ilities become an active consideration during the design and operations of systems?

A: Potentially through the use of dynamic tradespace exploration

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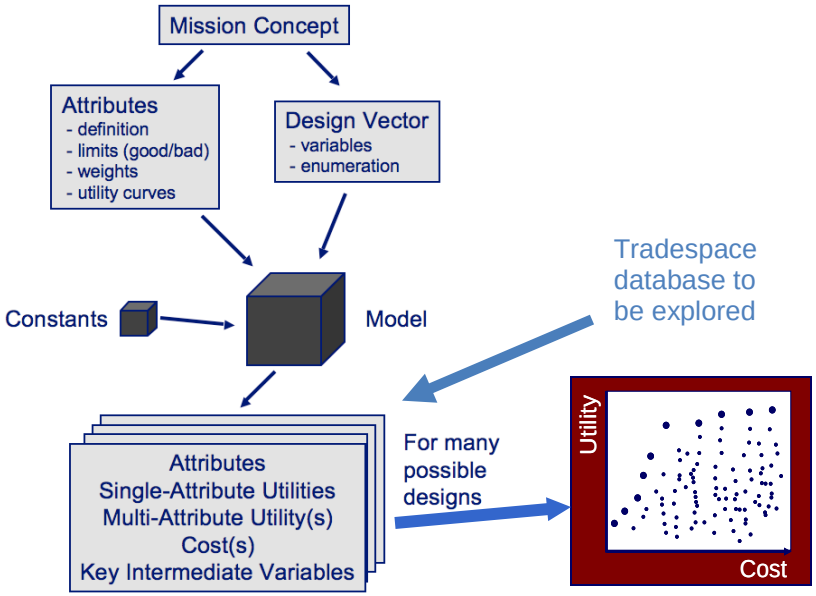
Tradespace Exploration

- Early design process is high leverage, with consequences for achievable benefits and cost goals
- Early design is rife with uncertainty and possibilities as well, making "good" decisions more difficult
  - Many possible designs
  - Many possible (changing?) needs and stakeholders
  - New (changing?) technology
  - New contexts (and missions)
- 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)



Value-based assessments allow for comparison of many different alternatives

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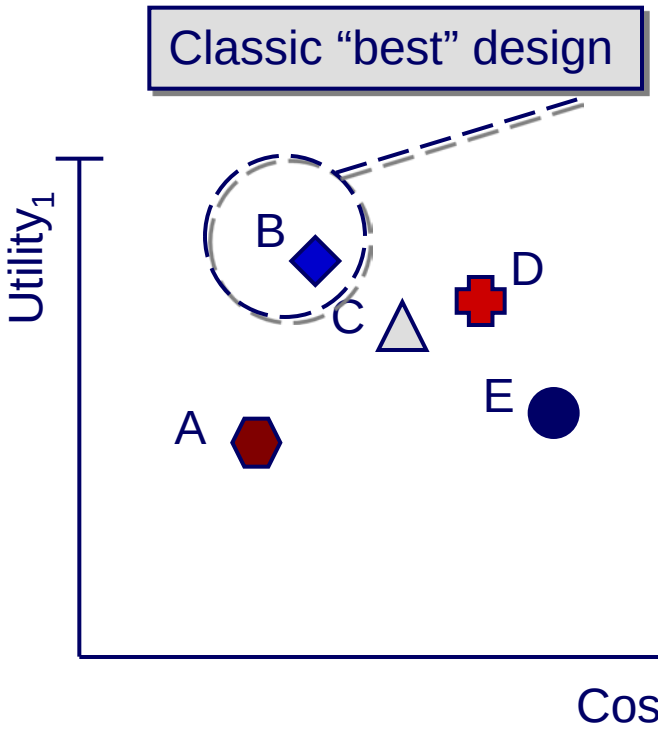
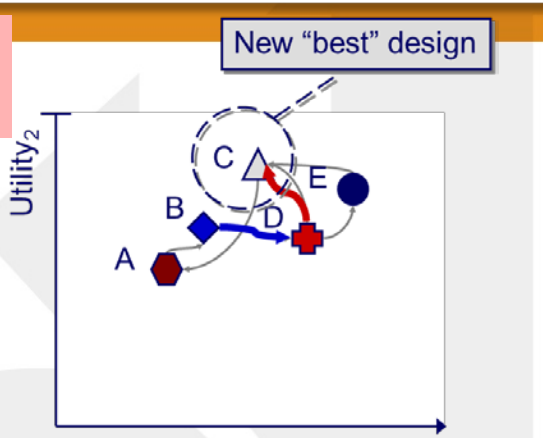
Selecting "Best" Designs

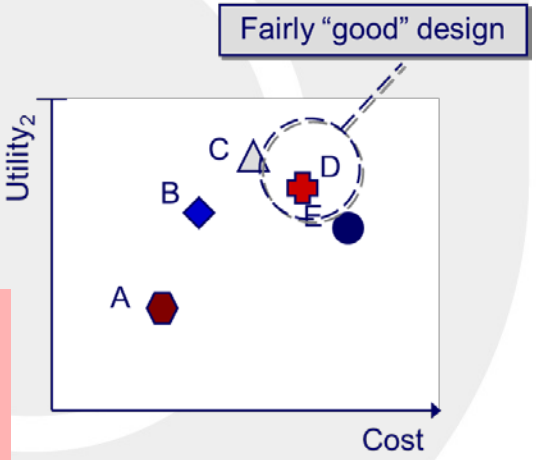


If the "best" design changes over time, how does one select the "best" design?

Strategy 1
Changeability



Time



Strategy 2
Robustness or Versatility

Changeable designs are *actively value robust*

Robust and Versatile designs are *passively value robust*

Changeability: Acceptable switch costs to new "designs"
Robustness: Insensitive to perturbations
Versatility: Inherent multiple "solutions" to perturbations

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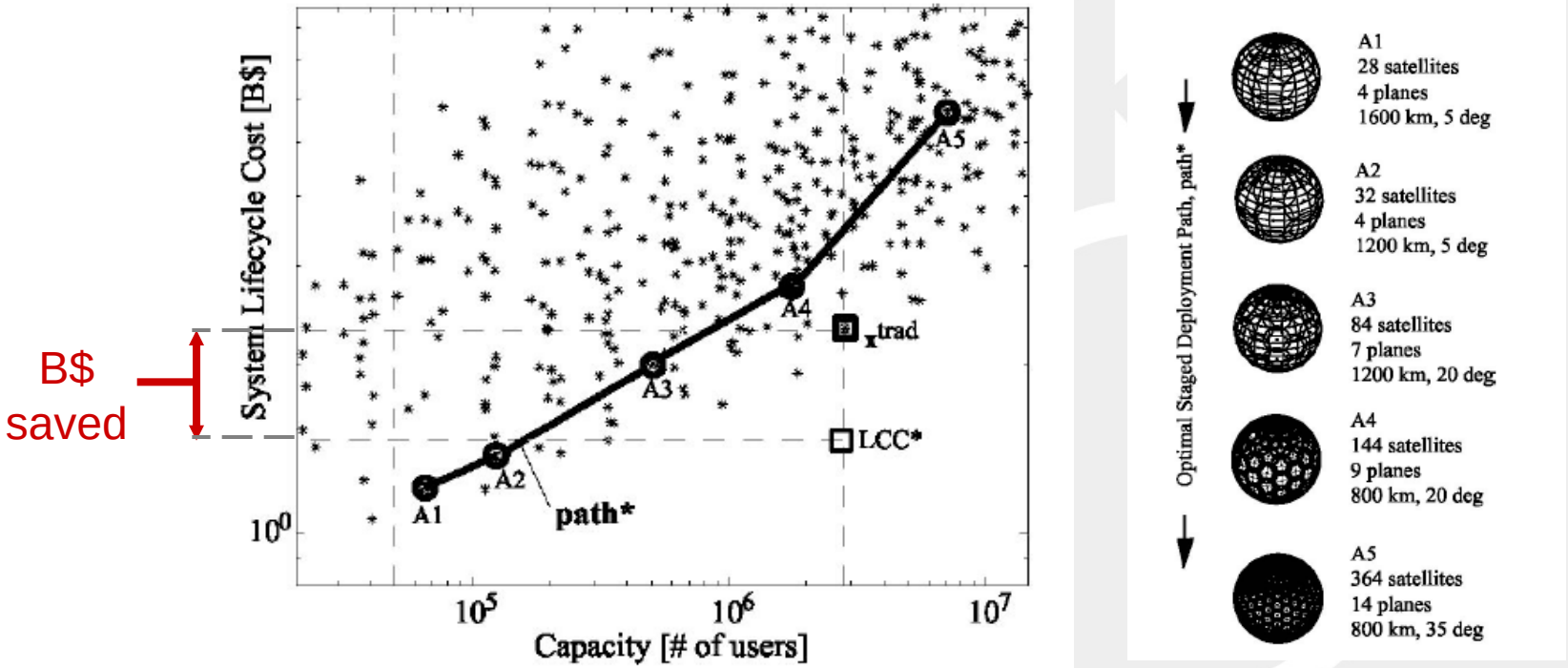
Example: Staged Deployment of Satellite Constellation



Embedding the *real option* to deploy system in stages allows for mitigation of demand uncertainty

Source: de Weck, O.L., de Neufville R. and Chaize M., "Staged Deployment of Communications Satellite Constellations in Low Earth Orbit", *Journal of Aerospace Computing, Information, and Communication*, **1** (3), 119-136, March 2004.

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Case Study Overview

- Mission: Data relay, communications RF
- Concept: LEO constellation
  - 1-9 microsatellites
  - Globally distributed ground stations for operational telecommanding and data downlink
- Three predefined geographic regions
  - Region 1: low latitude (15-35 deg)
  - Region 2: high latitude (35-60 deg)
  - Region 3: globally distributed targets

Design question: what should be the deployment strategy (orbit, deployment schedule) and ground station architecture?

- Key uncertainties: usage application, geographic location, and demand levels
- Restriction: use existing hardware (only minor changes can be implemented after deployment, so passive robustness preferred)

Ilities question: how to achieve passive value robustness across these uncertainties?

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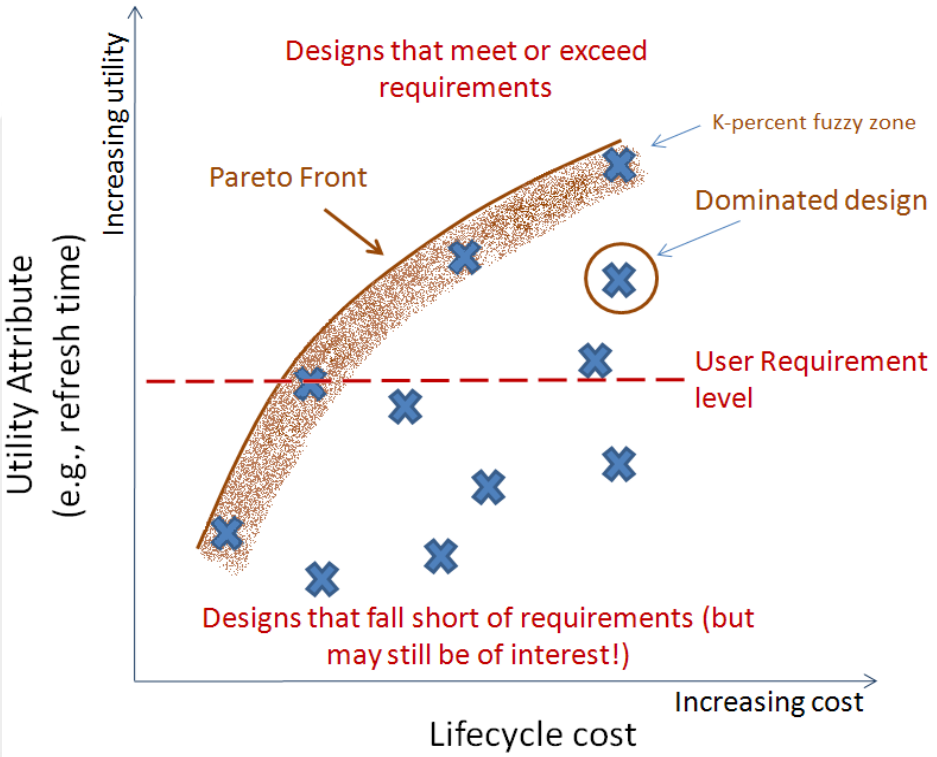
Orienting in the Tradespace

- Benefit vs. cost as top level decision criteria
- Each point as different potential solution
- Pareto front as region of interest
- Reqt level as above minimally acceptable
- Fuzziness allows for "good enough" solutions



Tradespaces provide a simple summary of potentially complex trade-offs across vastly different (or similar) system alternatives

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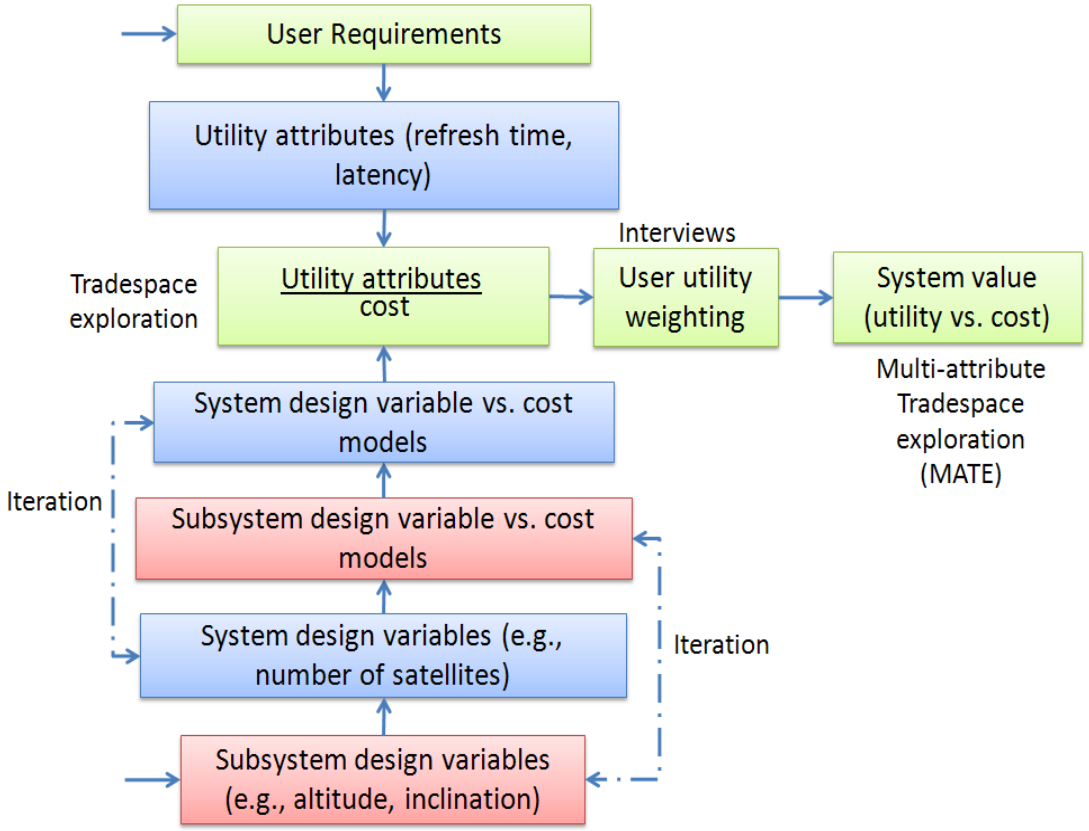
Approach for Generating Data

Iterative process for generating potential system designs to meet captured needs

This approach requires:

- interaction with “users”
- development of performance models
- development of value models
- development of cost models
- iteration in defining the potential solution space



This approach is described in more depth in Rader, Newland, and Ross, “An Iterative Subsystem-Generated Approach to Populating a Satellite Constellation Tradespace,” AIAA Space 2011

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Utility Attributes

In order to compare alternatives on a common value-centric basis, we use utility attributes as decision criteria

Utility attribute	Contributing subsystems
Revisit time	• Orbit (time to revisit anywhere on the globe) • Launch (only as an orbit driver) • Distribution of targets on Earth
Data latency	• Orbit (time to revisit the selected area) • Launch (only as an orbit driver) • Ground infrastructure (time to revisit a ground station after collecting data) • Downlink rate • Ground-based data distribution networks
Observation time	• Orbit • Launch (only as an orbit driver) • Payload (footprint, duty cycle)
Data downlink time	• Orbit (ground station contact time) • Launch (only as an orbit driver) • Ground infrastructure (location, elevation angle)

These are the criteria that reflect perceived benefit to the stakeholders

These are the subsystems that contribute to the benefits

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Design Variables and Cost Drivers

System design variables	Subsystem design variables	Associated cost drivers
Spacecraft bus	• Bus selection • Controlled/uncontrolled	• Design & build
Orbital characteristics	• Orbit planes • Eccentricities • Separation • Special cases (e.g., sun-synchronous)	• Launch • Propulsion & delta-v
Deployment	• Number of satellites deployed • Fixed deployment schedule vs. flexible deployment path	• Design & build • Launch • Operations
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

These are the factors under designer control

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Orbit, Ground Station, and Deployment Design Variables

Orbit index	Descriptor	Altitude	Inclination
O1	Near equatorial (+ polar satellites for deployed constellation)	600km	5°
O2	Low inclination (+ polar satellites for deployed constellation)	600km	63°
O3	All polar satellites	600km	97.8°
O4	Mixed – flexible deployment	mixed	Mixed

Ground station index	Descriptor	Ground Station Locations
G1	Minimized ground stations	• Equatorial case: 1 equatorial ground station • Mid-latitude case: 3 mid-latitude ground stations • Polar case: 2 polar ground stations
G2	Maximized downlink	• 7 globally distributed ground stations

Deployment index	Descriptor	No. sat	No. planes	Launches required
D1	Single Satellite	1	1	1
D2	Partial constellation – optimized constellation	5	3	3
D2’	Partial constellation deployment – flexible deployment	5	5	5 (secondary as available)
D3	Full constellation – optimized constellation	9	5	5
D3’	Full constellation deployment – flexible deployment	9	9	9 (secondary as available)

These result in 22 design alternatives

For illustration purposes, the paper focuses on these design variables

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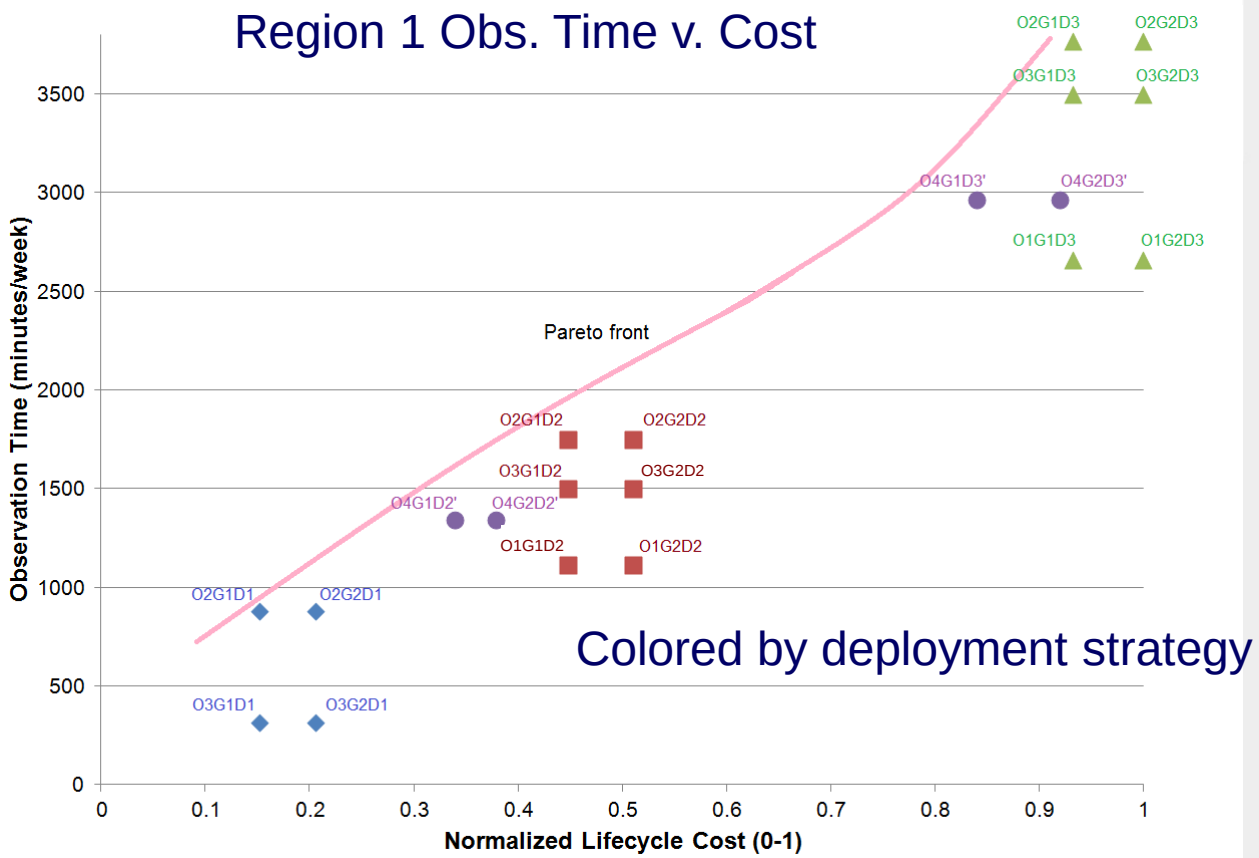
Example Single Attribute Tradespace

Utility attribute

- Revisit time
- Data latency
- **Observation time**
- Data downlink time



Insights

O2 > O3 > O1

G1→G2 : extra cost, no benefit

Flexible deployment : lower cost, lower benefit

Deployment index	Descriptor	No. sat	No. planes	Launches required
D1	Single Satellite	1	1	1
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Multi-Attribute Utility

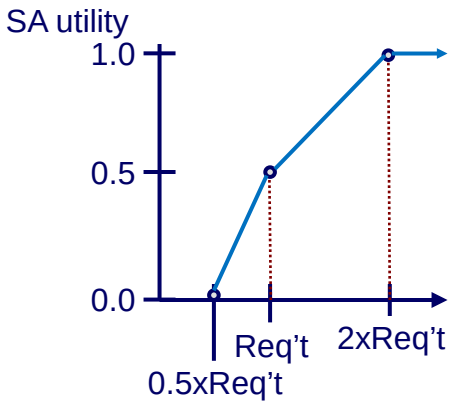
Users care about more than one criterion, so need to aggregate to manage complexity

Aggregation assumptions for this study:

- All attributes are continuous.
- Meeting a requirement achieves a single-attribute utility of 0.5.
- Doubling or exceeding double a requirement is assigned a utility of 1.
- Falling short of a requirement by half or more is assigned a utility of 0.
- Utilities between 0 and 1 are interpolated on a linear scale, giving a utility value of between 0 and 1.

Attribute	Revisit time	Data latency	Observation time	Data downlink time
Weighting	0.5	0.2	0.15	0.15
Breakdown	90th (0.25); WC (0.25)	90th (0.1); WC (0.1)	90th (0.075); WC (0.075)	90th (0.075); WC (0.075)

Single attribute utility weightings to construct multi-attribute utility (90th = 90th percentile worst case; WC = worst case)



$$MAU = \sum_{i=1}^{N} w_i \times SAU_i(X_i)$$

Assumption: each attribute contributes utility independently

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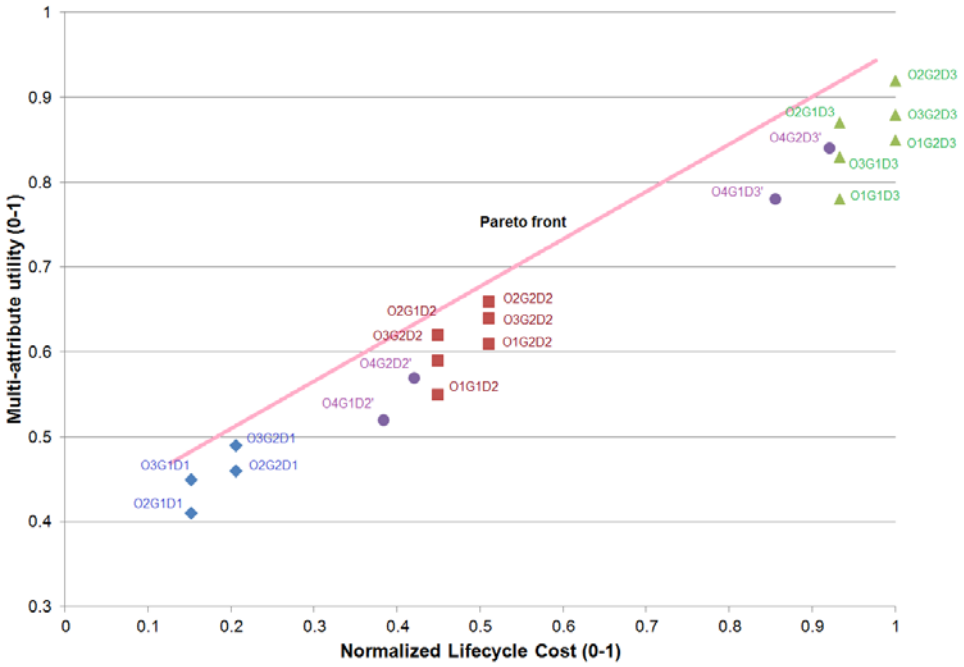
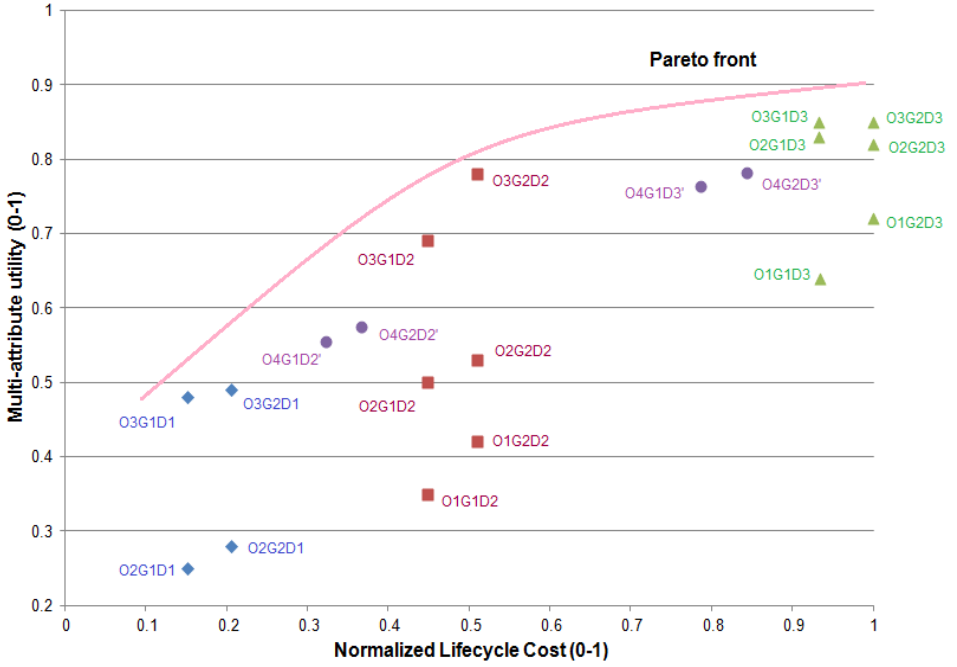
Example Multi-Attribute Tradespaces by Region

Region 1 (15-35 deg)



Region 2 (35-60 deg)



Insights

O2 < > O3 > O1 (reg 1: O2>O3, reg 2: O3>O2)
G1→G2 : extra cost, extra benefit (more region 1)
Reg 2 has diminishing MAU for cost

Deployment index	Descriptor	No. sat	No. planes	Launches required
D1	Single Satellite	1	1	1
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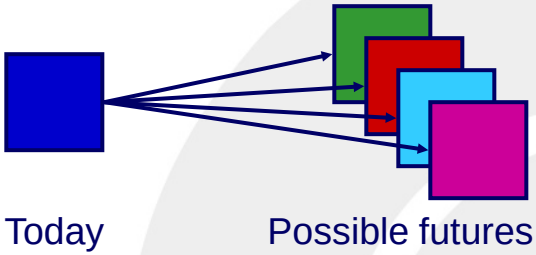
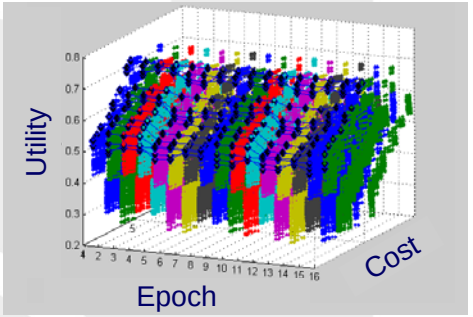
Generating Epochs

Many possible contexts and needs may unfold in the future, impacting actual and perceived system utility and cost

"Epoch-based thinking" can be used to structure anticipatory scenario analysis





Example triggers for epoch shifts impacting a system

- Change in political environment
- Entrance of new competitor in market
- Emergence of significant new or changed stakeholder need(s)
- Policy mandate impacting product line, services or operations
- ***Change in user service type and geographic region***

Categories of epoch variables can aid in thinking about key changing factors

E.g., Resources, Policy, Infrastructure, Technology, End Uses ("Markets"), Competition, etc.

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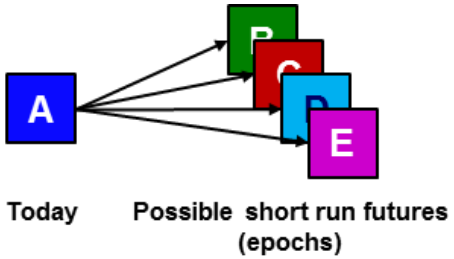
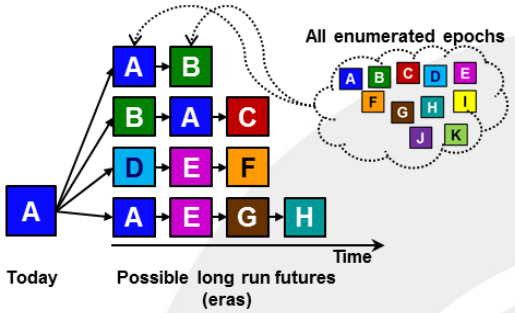
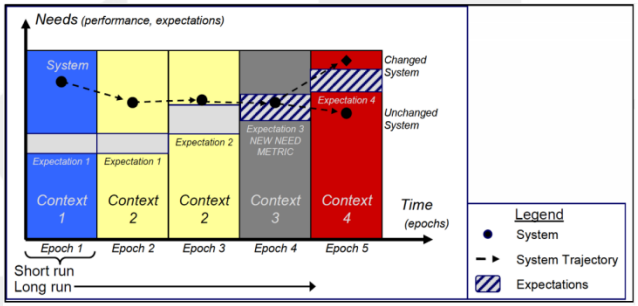
Multi-Epoch Analysis (and EEA)

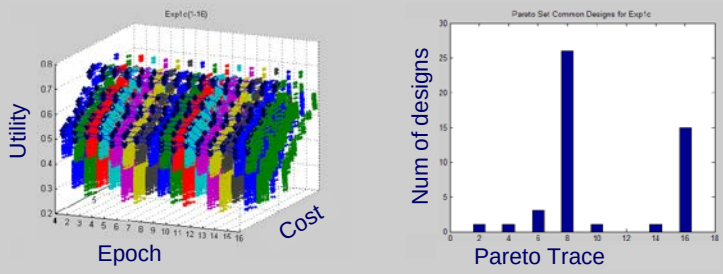






Pareto Trace

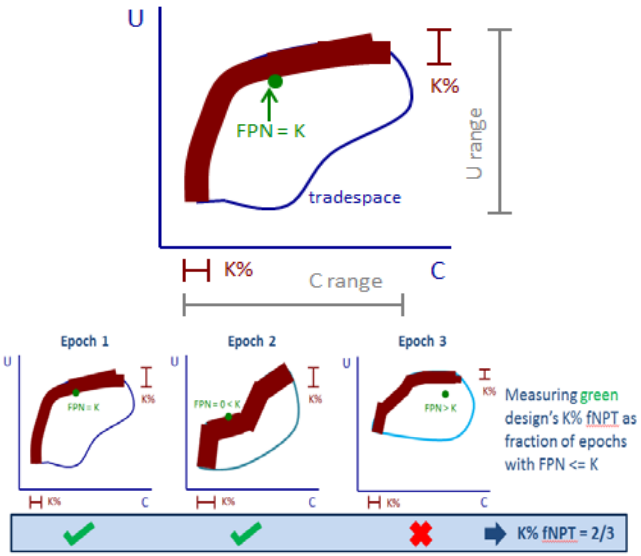
of Pareto Sets containing design
(measure of passive robustness)



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

Fuzzy Pareto Number

$$FPN(d) = \min\{ K \mid d \subset P_K \}$$



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Epoch Enumeration

The key uncertainties in this case are user subscription type and geographic region

Usage case	Usage index
No use of service	0
ST1 trial, no use of ST2	1
Full trial	2
ST1 full use, no use of ST2	3
ST1 full use, ST2 trial	4
Full use of service	5

Application index	Primary Service Type	Area of Interest	Epoch (with usage index from above)									
			I	II	III	IV	V	VI	VII	VIII	IX	X
A	ST1	Global	3	3	3	3	3	4	4	4	5	5
B	ST1	Global	1	3	3	3	3	4	4	4	5	5
C	ST1	Region 1	0	0	1	1	2	2	4	4	5	5
D	ST1	Region 1	0	0	1	1	2	2	4	4	5	5
E	ST1	Region 1	0	0	1	1	2	2	4	4	5	5
F	ST2	Global	0	0	1	1	2	2	4	4	5	5
G	ST2	Region 1	0	0	1	1	2	2	4	4	5	5
H	ST2	Region 1	0	0	1	1	2	2	4	4	5	5
I	ST2	Region 1	0	0	1	1	2	2	4	4	5	5
J	ST1	Global	0	0	0	1	0	2	2	4	2	5
K	ST2	Region 2	0	0	0	1	0	2	2	4	2	5
L	ST1	Region 2	0	0	0	1	0	2	2	4	2	5
M	ST2	Region 2	0	0	0	1	0	2	2	4	2	5

10 epochs with 13 applications within each, having different primary service types and areas of interest

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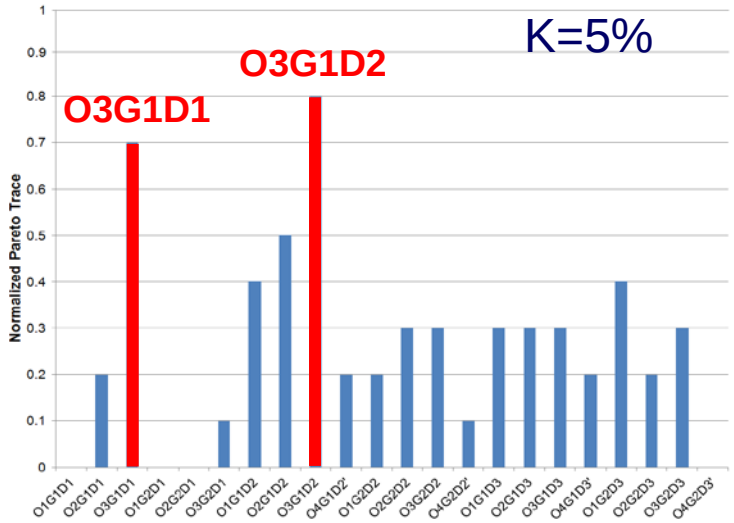
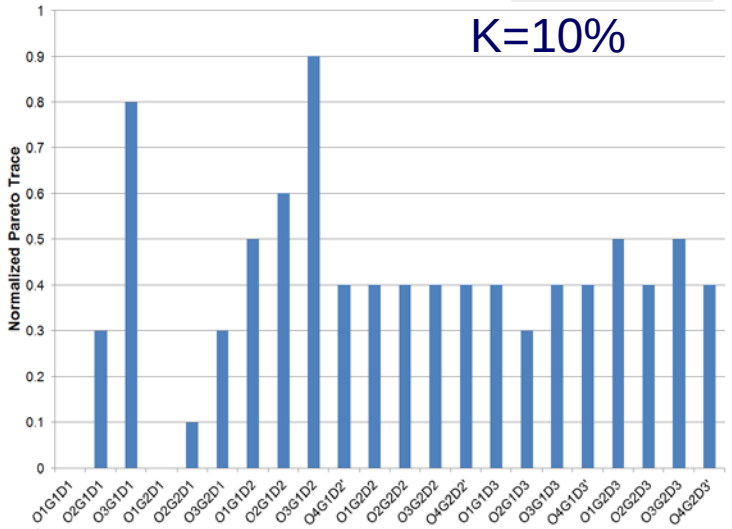
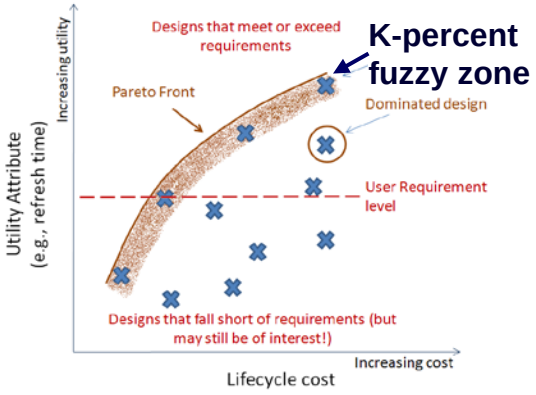
Comparing Designs across Epochs

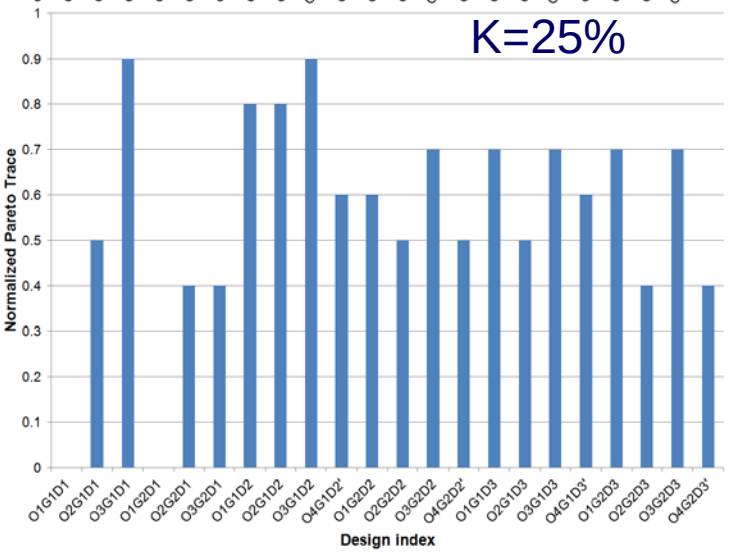




If we don't know what epoch will occur, the higher the fNPT, the more likely the design is utility-cost efficient



As K increases, more designs become "good enough", but none reach fNPT=1



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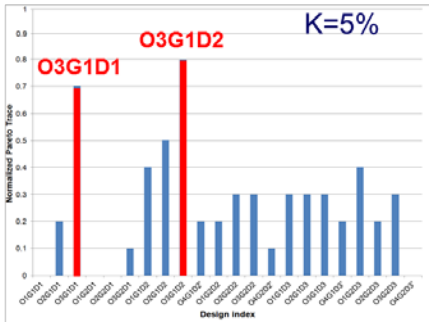
Discussion of Results



Polar constellation deployment with minimal ground stations

O3G1D1 → **O3G1D2** → **O3G1D3**

O1G2D3

Polar augmented with equatorial sat and maximal ground stations

- Based on the fNPT, start with designs **O3G1D1** and **O3G1D2**
  - O3 are constellations with polar sats, and are versatile to geographic locations
- As deployment progresses from D1→D2→D3, things change
  - Full deployment of constellation reduces advantage of O3 since O1 and O2 will have some polar sats
  - G2 offers improvement when constellation is full (under utilized otherwise)
- Once a partial polar constellation has been deployed, near-equatorial satellites offer the largest increase in passive robustness (i.e., **O1XXD3**)
- Conclusion:
  - instead of planned polar constellation deployment path of **O3G1D1 → O3G1D2 → O3G1D3**
  - consider deployment path such as **O3G1D1 → O3G1D2 → O1G2D3**
- Since additional ground stations could be added at any time, and satellites could be deployed in any order, this path is feasible and results in higher passive value robustness
- These results are a bit simplistic for illustration purposes and do not take into account path dependence (e.g. across eras)

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