Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System

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September 16, 2009

Track 43 MIL-4: Systems of Systems Analysis for NSS:
Answer the Why question
AIAA Space 2009

Outline

- Motivation
- Review of Responsive Systems Comparison Method (RSC)
- Design Tradespace Evaluation
- Multi-Epoch Analysis
- Discussion

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Motivation

- System designers and architects often face changes in…
  - User needs
  - Available technologies
  - Political and technical contexts
- Classical "scenario analysis" can be too opportunistic, qualitative, or sparse
- Lack of value-centric approaches results in point designs with questionable value delivery to stakeholders
- Structured method needed to characterize, analyze, and represent a wide variety of possible futures to identify "value robust" designs

Note: This paper is a "part 2" of last year's AIAA Space paper*

This paper presents the application of Responsive Systems Comparison (RSC) Method through "Multi-Epoch Analysis"

*Ross, *A.M., McManus, H.L., Long, A., Richards, M.G., Rhodes, D.H., and Hastings, D.E., "Responsive Systems Comparison Method: Case Study in Assessing Future Designs in the Presence of Change," AIAA Space 2008, San Diego, CA, September 2008.*

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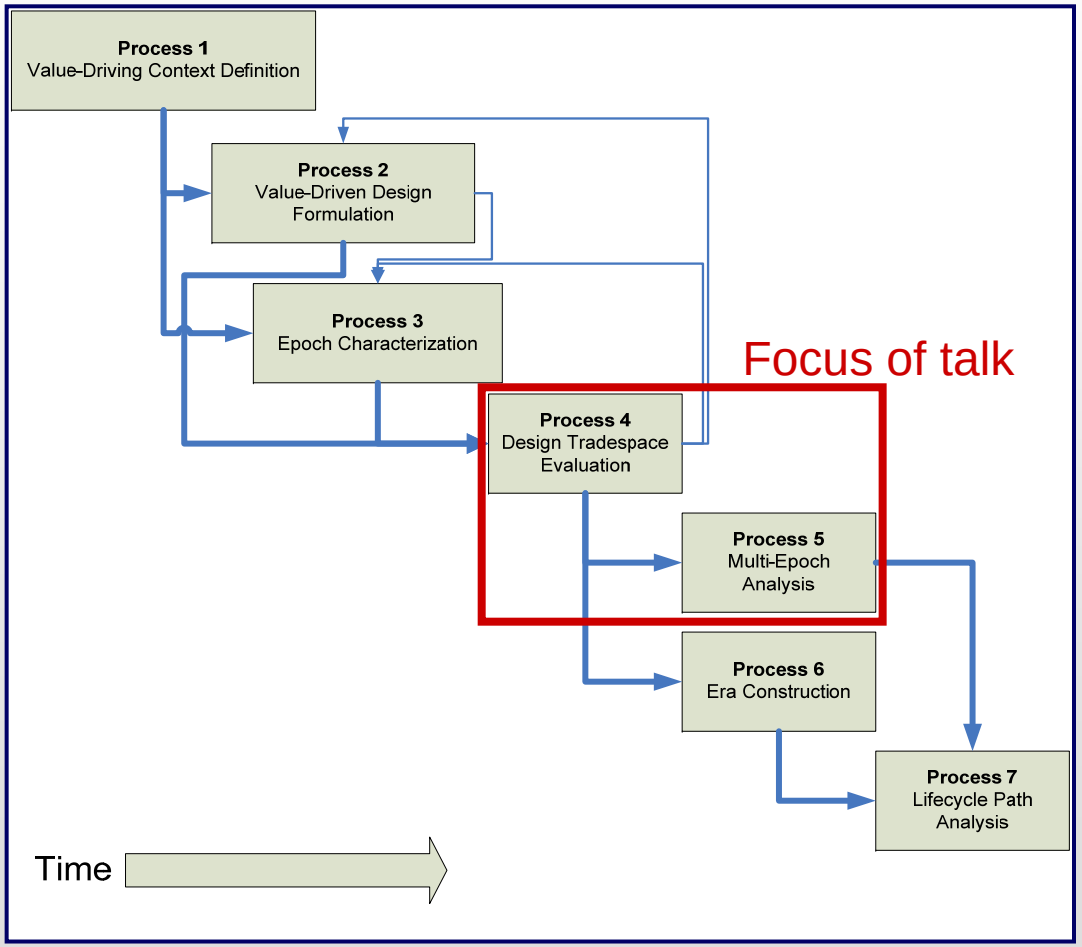
The RSC Method

Using Multi-Attribute Tradespace Exploration, Epoch-Era Analysis, and other approaches, a coherent set of processes were developed into the RSC method

- Processes consist of discrete set of activities
- Some feedback between processes is possible
- Some processes can occur in parallel to save time

RSC consists of seven processes:

1. Value-Driving Context Definition
2. Value-Driven Design Formulation
3. Epoch Characterization
4. Design Tradespace Evaluation
5. Multi-Epoch Analysis
6. Era Construction
7. Lifecycle Path Analysis



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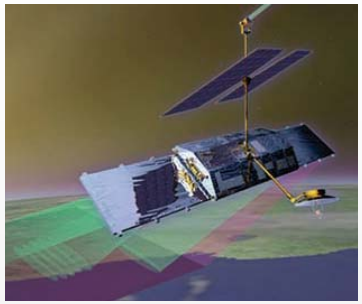
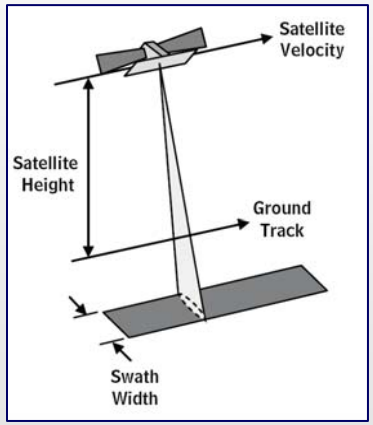
Case Application: Satellite Radar System (SRS)

In order to develop RSC, a test case was selected with requisite complexity…

Critical issue in national security space
- Unique all-weather surveillance capability
- Opportunity for impact given ongoing studies
- Rich multi-dimensional tradespace

Unit-of-analysis: SR architecture
- Radar payload
- Constellation of satellites
- Communications network





(CBO 2007)

Satellite Radar System (SRS) Value Proposition:

24 hour, all weather on-demand "Visibility and Tracking" over things that can be observed

Case Application Goal:

*To assess potential **satellite radar** system architectures for providing the United States Military a global, all-weather, on-demand capability to **image static, and track moving, ground targets**; supporting tactical military operations; and maximizing cost-effectiveness across many possible futures*

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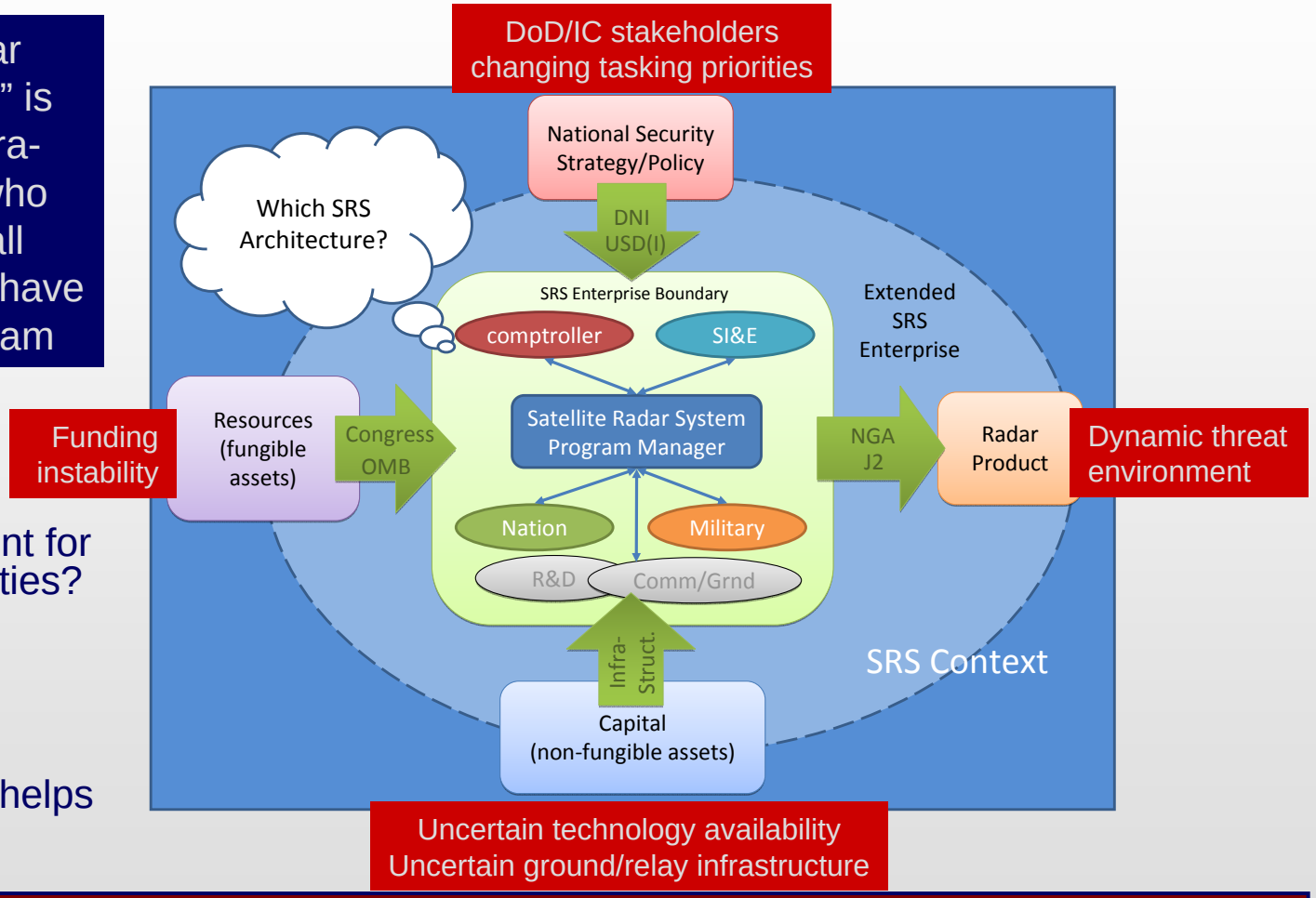
Process 1: Value-Driving Context Definition

A "Satellite Radar Program Manager" is chosen as a "supra-decision maker" who must represent all interests in order to have a successful program



How does one account for exogenous uncertainties?

- Policy
- Funding
- Infrastructure
- Environment

Enterprise boundary helps to define "context"

Evaluation Perspective: Given distributions of future uncertainties, how does Satellite Radar Program Manager select the "best" architecture?

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Process 2: Value-Driven Design Formulation

Systems Engineering Advancement Research Initiative

Design-space:

Designer-controlled parameters that define a system concept

DESIGN VARIABLES

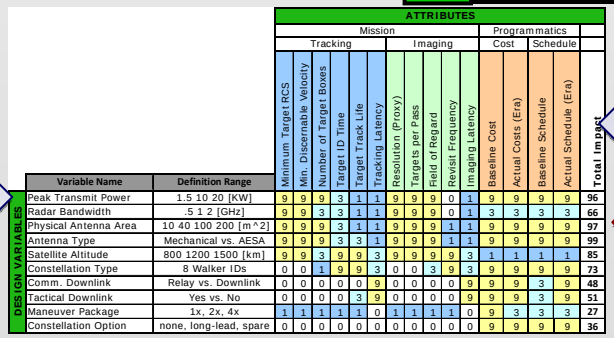
Variable Name	Definition Range
Peak Transmit Power	1.5, 10, 20 [kW]
Radar Bandwidth	0.5, 1, 2 [GHz]
Physical Antenna Area	10, 40, 100, 200 [m^2]
Antenna Type	Mechanical, AESA
Altitude	800, 1200, 1500 [km]
Constellation Configuration	8 Walker IDs
Communication Downlink	Relay, Direct downlink
Tactical Communication Able	Yes, No
Maneuver Capability	1x, 2x, 4x base fuel
Tugable	Yes, No
Constellation Option	None, long-lead, spares

Value-space:

Concept-neutral evaluation criteria specified by decision makers

ATTRIBUTES

	Attribute Name	units	range (U=0 to U=1)
Tracking	Minimum Target RCS	m^2	1000 --> 0
	Min. Discernable Velocity	m/s	50 --> 5
	Number of Target Boxes	#	1 --> 10
	Target Acquisition Time	min	120 --> 10
	Target Track Life	min	0 --> 60
	Tracking Latency	min	240 --> 0
Imaging	Resolution	m	5 --> 0.01
	Targets per Pass	#	1 --> 10^5
	Field of Regard	km^2	1000 --> 10^6
	Revisit interval	min	300 --> 10
	Imaging Latency	min	720 --> 60
	Geo-Location Accuracy	m	500 --> 50
Program	Baseline Cost	$B	
	Deviation from Cost	%	
	Baseline Schedule	years	
	Deviation from Schedule	years	



Design-Value Mapping (DVM):
Ensures alignment between Value-space and Design-space

Design-Value Mapping (DVM) ensures design decisions drive value delivery

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Process 2: Value-Driven Design Formulation

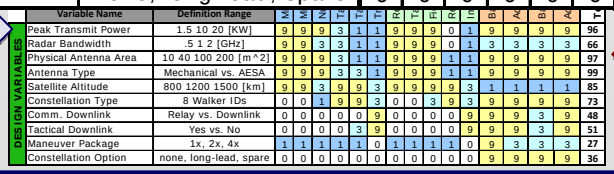
Design-space:
Designer-controlled parameters that define a system concept

Value-space:
Concept-neutral evaluation criteria specified by decision makers

1-3-9 scoring is intended to capture first order strength of interaction in order to quickly focus on important trades for analysis

			ATTRIBUTES															
			Mission										Programmatics					
			Tracking						Imaging				Cost		Schedule			
DESIGN VARIABLES	Variable Name	Definition Range	Minimum Target RCS	Min. Discernable Velocity	Number of Target Boxes	Target ID Time	Target Track Life	Tracking Latency	Resolution (Proxy)	Targets per Pass	Field of Regard	Revisit Frequency	Imaging Latency	Baseline Cost	Actual Costs (Era)	Baseline Schedule	Actual Schedule (Era)	Total Impact
DESIGN VARIABLES	Peak Transmit Power	1.5 10 20 [KW]	9	9	9	3	1	1	9	9	9	0	1	9	9	9	9	96
	Radar Bandwidth	.5 1 2 [GHz]	9	9	3	3	1	1	9	9	9	0	1	3	3	3	3	66
	Physical Antenna Area	10 40 100 200 [m^2]	9	9	9	3	1	1	9	9	9	1	1	9	9	9	9	97
	Antenna Type	Mechanical vs. AESA	9	9	9	3	3	1	9	9	9	1	1	9	9	9	9	99
	Satellite Altitude	800 1200 1500 [km]	9	9	3	9	9	3	9	9	9	9	3	1	1	1	1	85
	Constellation Type	8 Walker IDs	0	0	1	9	9	3	0	0	3	9	3	9	9	9	9	73
	Comm. Downlink	Relay vs. Downlink	0	0	0	0	0	9	0	0	0	0	9	9	9	3	9	48
	Tactical Downlink	Yes vs. No	0	0	0	0	3	9	0	0	0	0	9	9	9	3	9	51
	Maneuver Package	1x, 2x, 4x	1	1	1	1	1	0	1	1	1	1	0	9	3	3	3	27
	Constellation Option	none, long-lead, spare	0	0	0	0	0	0	0	0	0	0	0	9	9	9	9	36

e (U=0 to U=1)
1000 --> 0
50 --> 5
1 --> 10
120 --> 10
0 --> 60
240 --> 0
5 --> 0.01
1 --> 10^5
00 --> 10^6
300 --> 10
720 --> 60
500 --> 50



Design-Value Mapping (DVM):
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Design-Value Mapping (DVM) ensures design decisions drive value delivery

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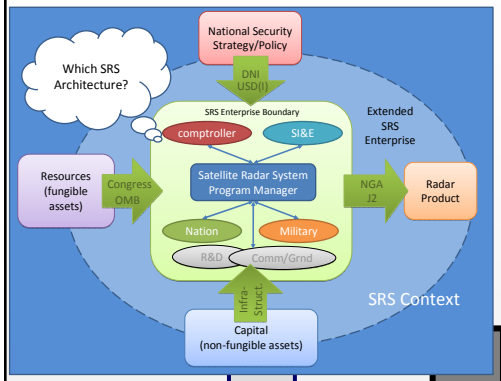
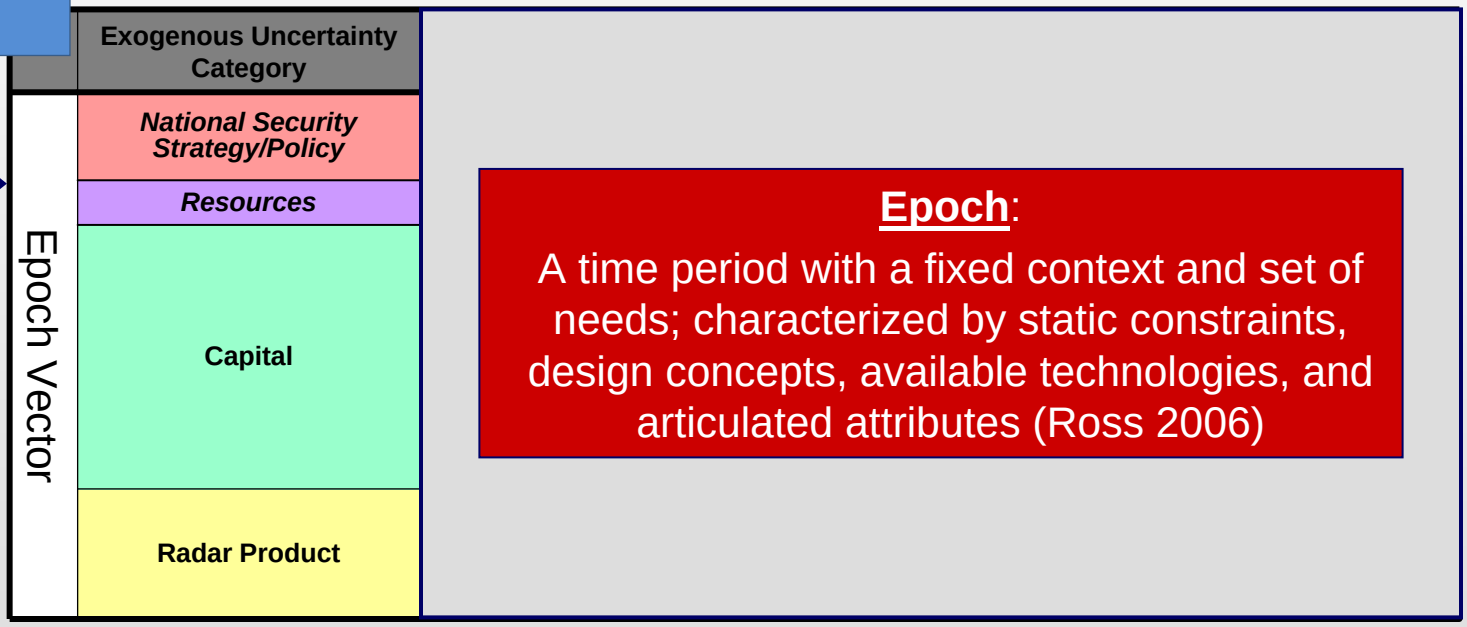
Process 3: Epoch Characterization



Epochs defined by specifying needs and context through Epoch Variables

- Enumerate hundreds of contexts
- Analogous to design variables



Epoch:
A time period with a fixed context and set of needs; characterized by static constraints, design concepts, available technologies, and articulated attributes (Ross 2006)

648 Future Contexts

Epoch variables allow for parameterization of some "context" drivers for system value

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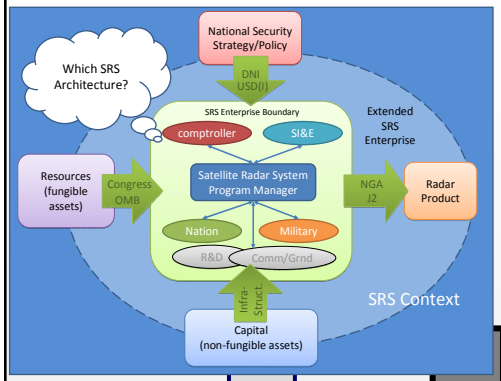
Process 3: Epoch Characterization



Epochs defined by specifying needs and context through Epoch Variables

- Enumerate hundreds of contexts
- Analogous to design variables

	Exogenous Uncertainty Category	Epoch Variable	Number of Steps	Units/Notes
Epoch Vector	*National Security Strategy/Policy*	**Imaging vs. Tracking Mission Priorities**	3	**Level 1** – SAR < GMTI **Level 2** – SAR = GMTI **Level 3** – SAR > GMTI
	Resources	***Budget Constraints***	na	Use tradespace to vary "costs"
	Capital	**Radar Technology Level**	3	**Level 1 (Mature),** TRL = 9 **Level 2 (Medium),** TRL = 6 **Level 3 (Advanced),** TRL = 4
		Communication Infrastructure	2	**Level 1** – No Backbone + AFSCN Ground Sites **Level 2** – WGS + AFSCN Ground Sites
		Collaborative AISR Assets	2	**Level 1** – Available **Level 2** – Not available
	Radar Product	**Operations Plans**	9	Lookup table of geographic region & target op. plans
		Environment	2	**Level 1** – No jamming **Level 2** – Hostile jamming

648 Future Contexts

Epoch: A time period with a fixed context and set of needs

Epoch variables allow for parameterization of some "context" drivers for system value

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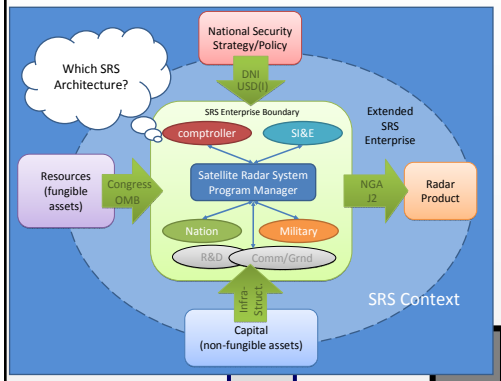
Process 3: Epoch Characterization



Enterprise scoping exercise informed the types of "epoch variables" encountered by program

- Enumerate hundreds of contexts
- Analogous to design variables

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648 Future Contexts

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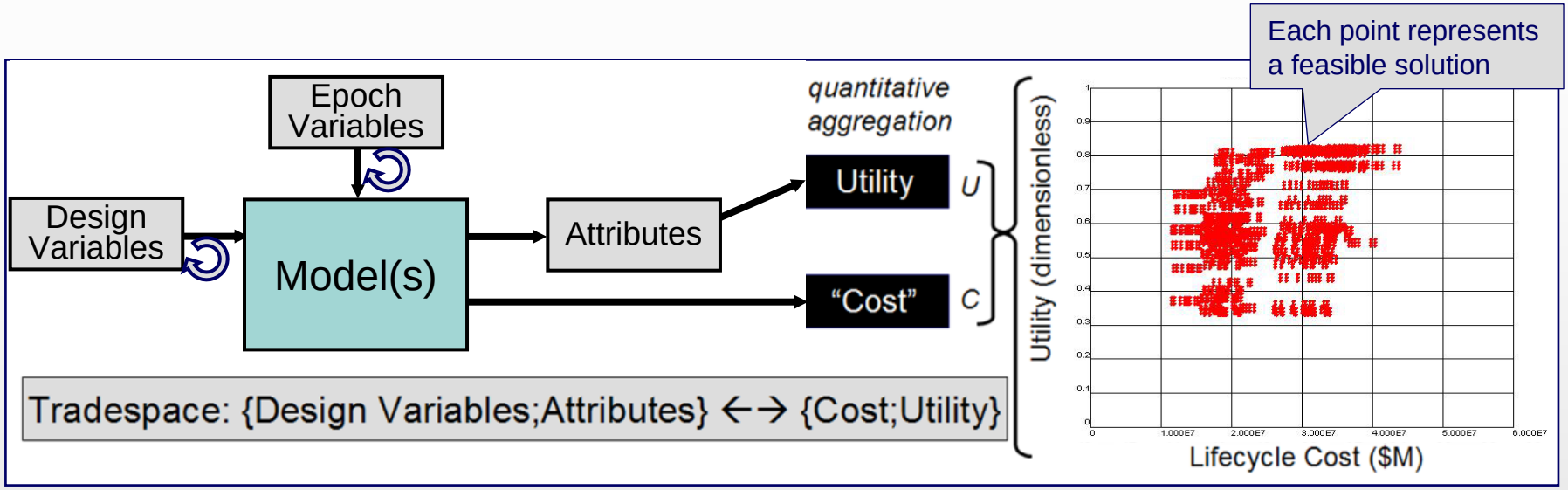
Process 4: Design Tradespace Evaluation



Compares system designs on a common, quantitative basis

- Uses computer-based models to compare thousands of designs
- Avoids limits of local point solutions
- Maps structure of stakeholder value onto design space
- Simulation can be used to account for design uncertainties (i.e., cost, schedule, performance uncertainty bubbles)

Design tradespaces provide high-level insights into system-level trade-offs.
Detailed system-level design would follow-on preferred system concept decisions

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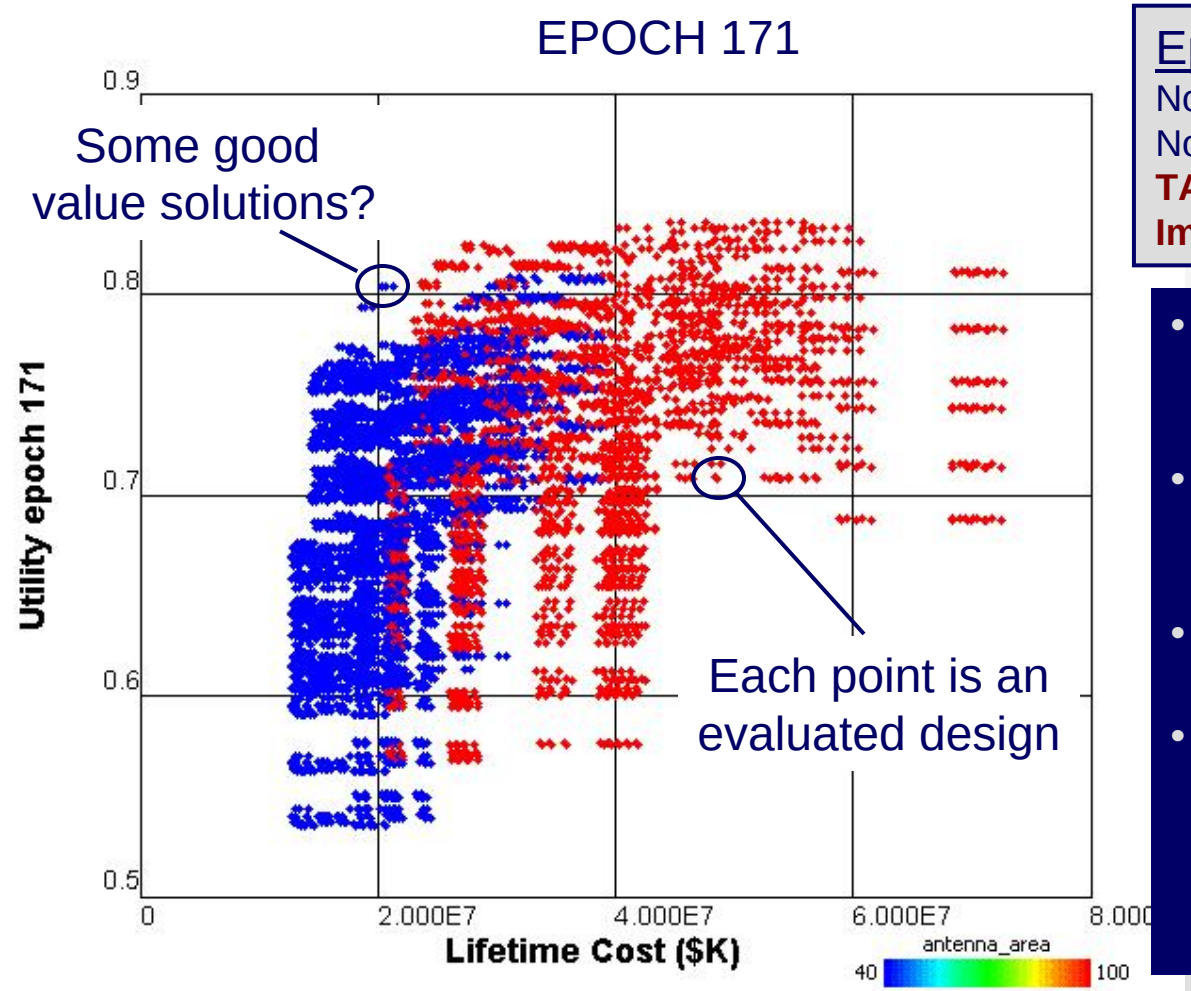
Typical Tradespace: Utility vs. Cost



Epoch 171

No AISR avail, WGS avail
No jamming, TRL 9 tech
TARGETS: Mid East, Asia
Imaging mission (primary)

- Color shows additional information; in this case, antenna area
- Larger area (100 m^2) gives better utility at higher cost
- Medium size (40 m^2) works, cheaper
- Smallest area in DV (10 m^2) does not appear - small antennas do not satisfy minimum user needs in this case

Visualizations used to get quick insights into key trades, which may be context dependent

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Process 5: Multi-Epoch Analysis

- Cross-epoch analysis
- Within-epoch analysis
- Identifying Passive Value Robust designs
- Identifying changeable designs

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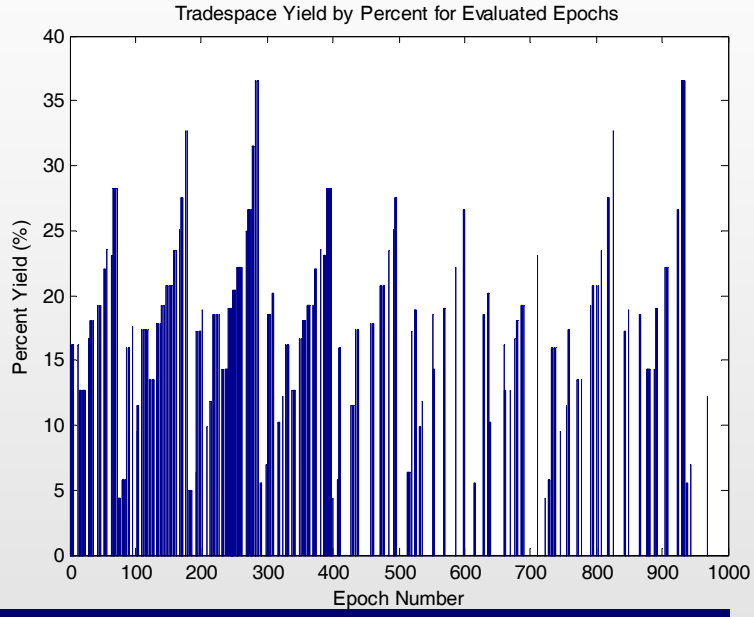
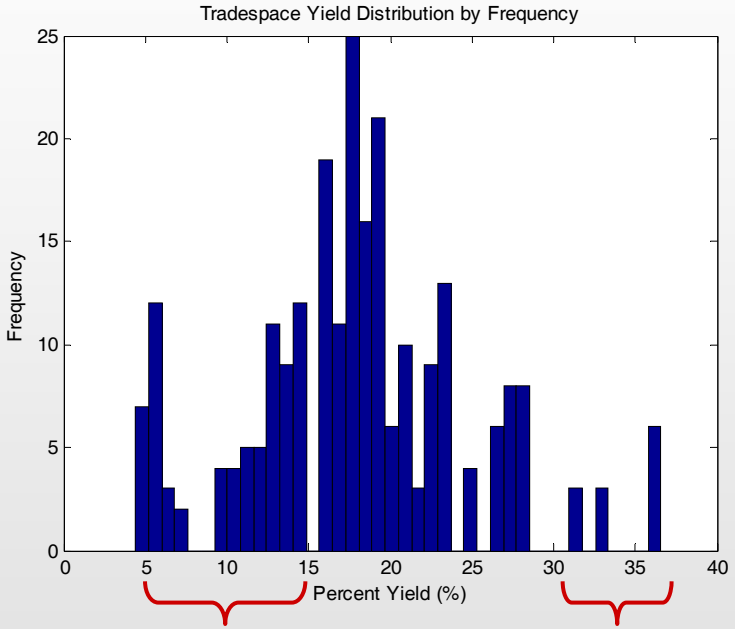
Cross-Epoch Analysis: Tradespace Yield

Yield = feasible designs / total designs per tradespace* (in %)





Epochs with demanding target sets

Epochs with collaborative AISR assets

Observations

- No epoch with more than 36% yield
- Most epochs with 18-20% yield

*For the SRS case study, total designs per tradespace = 23,328

Possible low yield causes: poor design enumeration, demanding constraints, difficult attribute range expectations

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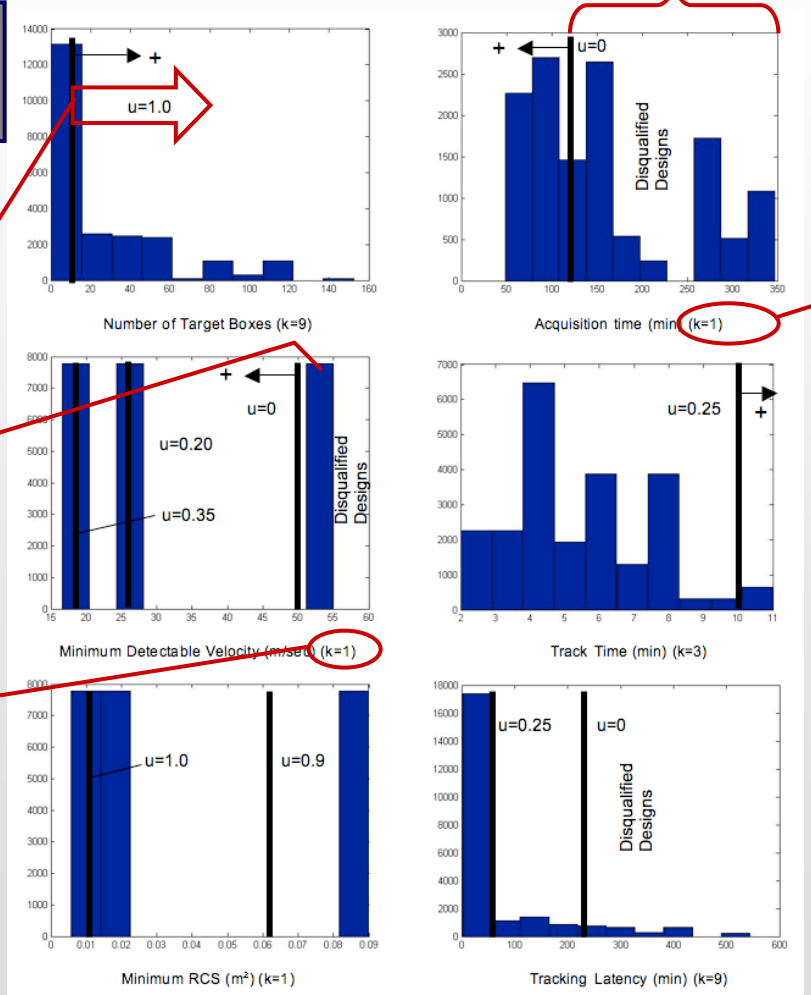
Within-Epoch Analysis: Tradespace Yield

Tracking mission attributes

"Easy" attribute

One third of tradespace disqualified!

Also low attribute importance



Many designs disqualified!

Low attribute importance

Relaxing attribute range constraints may make many otherwise attractive designs feasible

Especially for low attribute importance

Distribution of designs across attribute ranges shows the impact of "easy" and "hard" expectations

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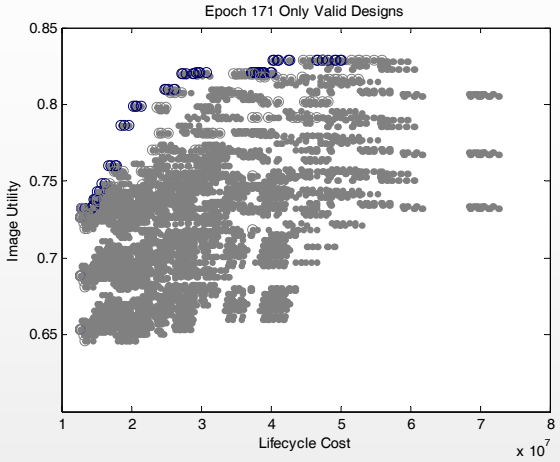
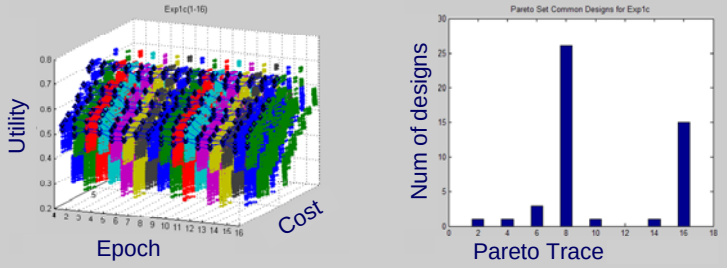
Calculating Pareto Trace to Identify Passive Value Robust Designs



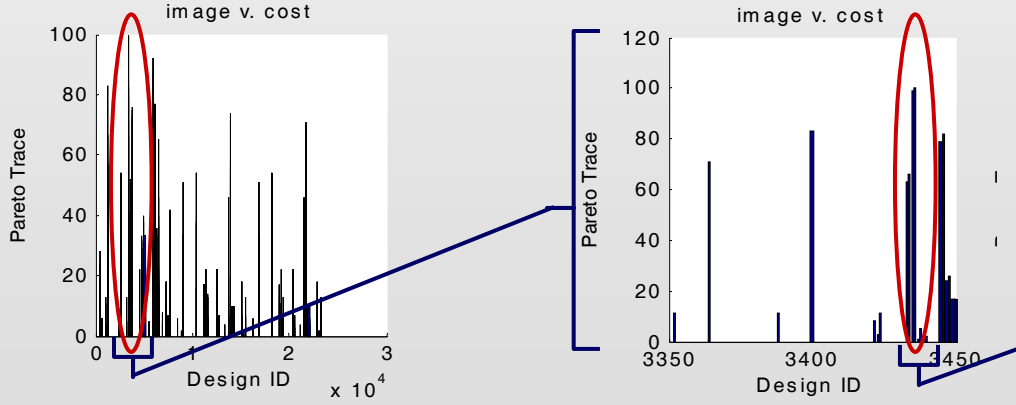
Pareto Trace

Pareto Sets containing design
(measure of passive robustness)



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

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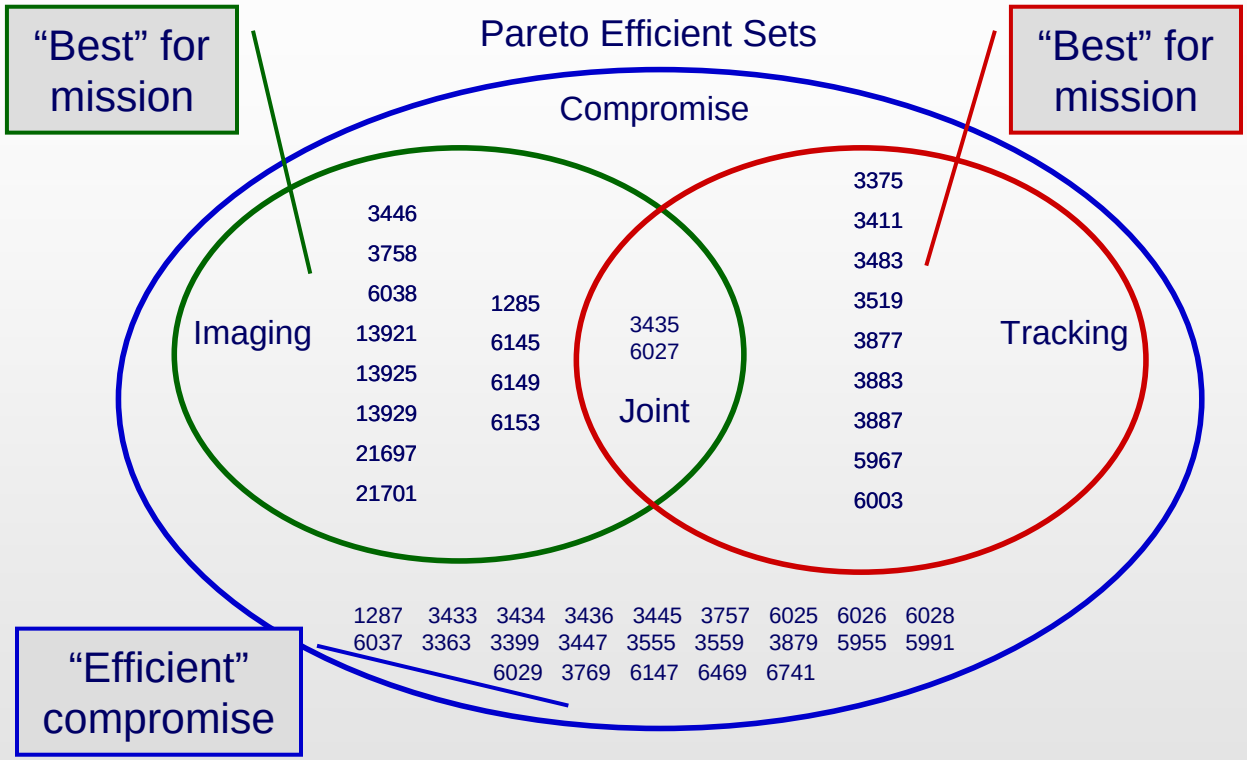
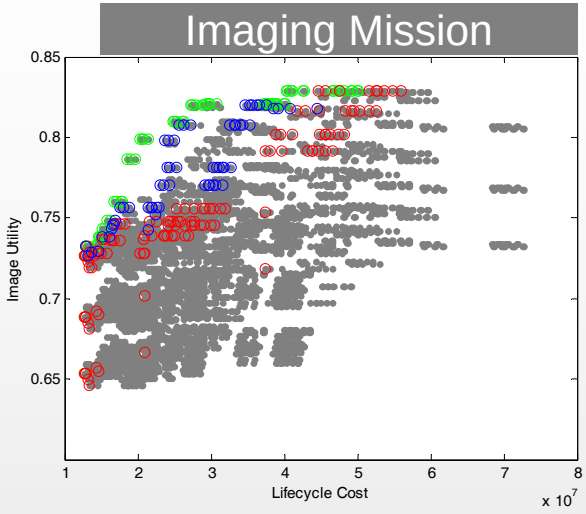
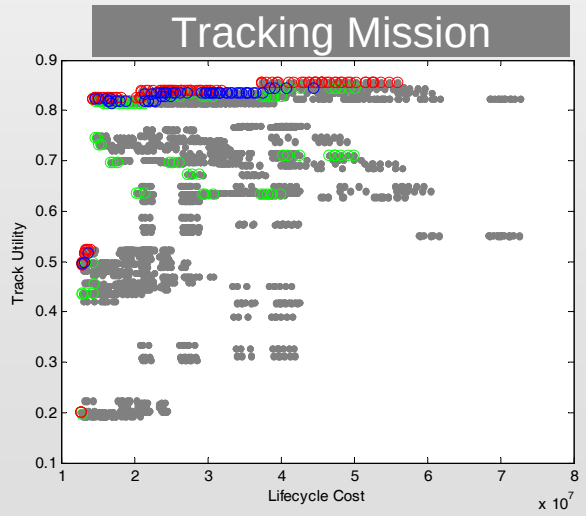
Finding "Compromises" Across Missions and Stakeholders







Method provides quantitative approach for discovering "best" mission-specific designs, as well as "efficient" (benefit at cost) compromises across missions and stakeholders

Discover "best" alternatives for individual missions, as well as "efficient" compromises

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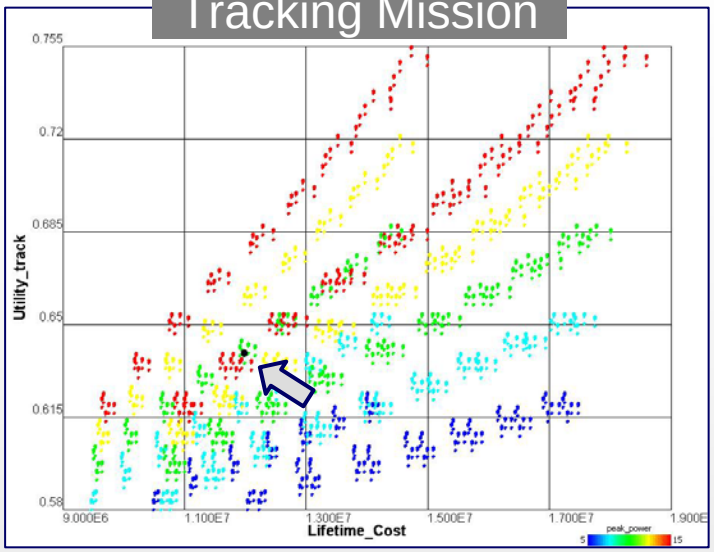
Diving Deeper onto Select Designs

- Utility can be decomposed into individual stakeholder values
- Decomposition provides insights into key system design tradeoffs across missions

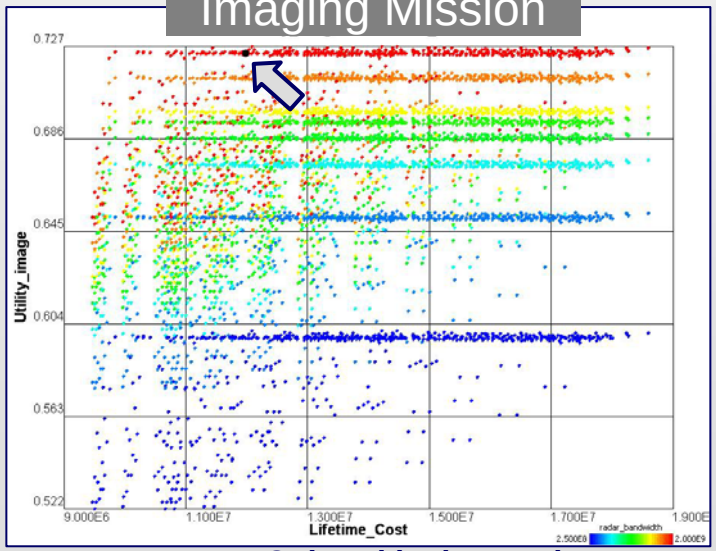
Tracking Mission



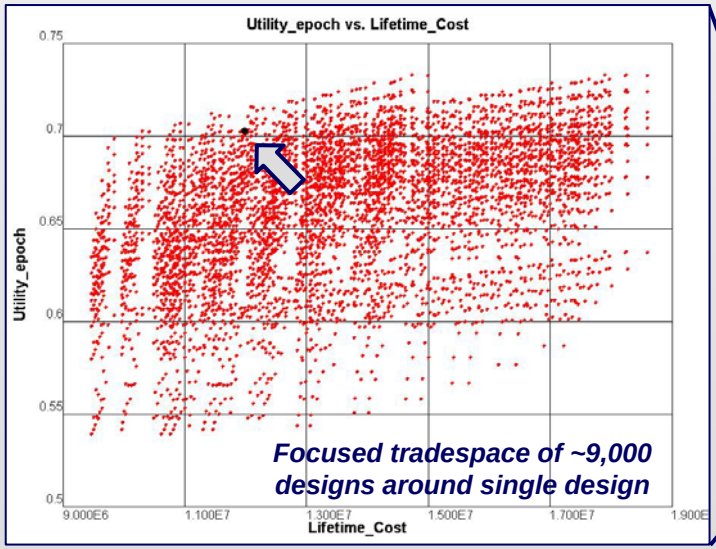
Colored by increasing peak power*

** Similar effect due to increased antenna aperture*

Imaging Mission

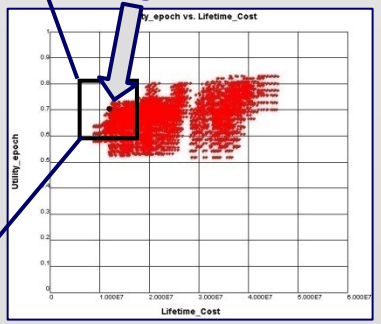


Colored by increasing radar bandwidth



Focused tradespace of ~9,000 designs around single design

Design 3435



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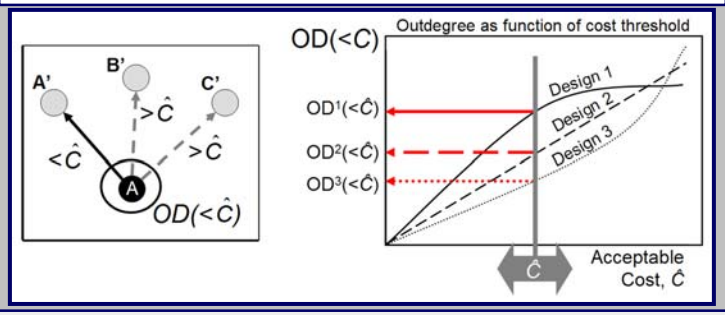
Calculating Filtered Outdegree to Identify Changeable Designs

Filtered Outdegree

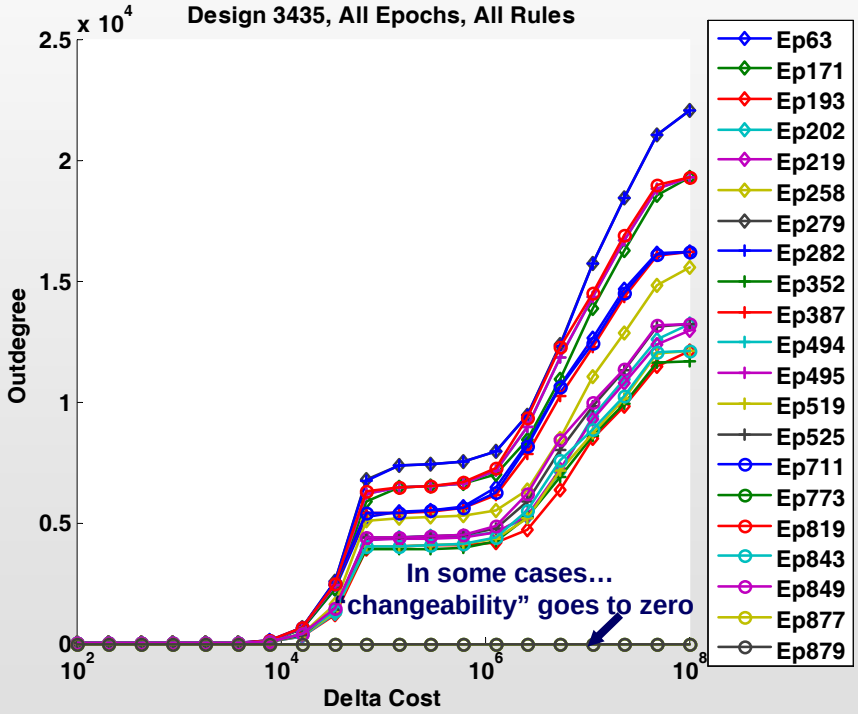
outgoing arcs from design at acceptable "cost" (measure of changeability)



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)*

Variation in design "changeability" in response to context change



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

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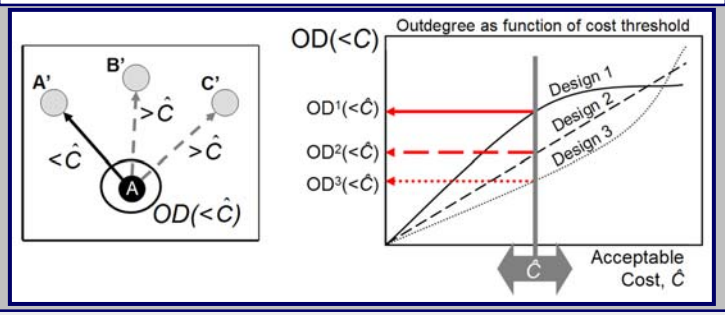
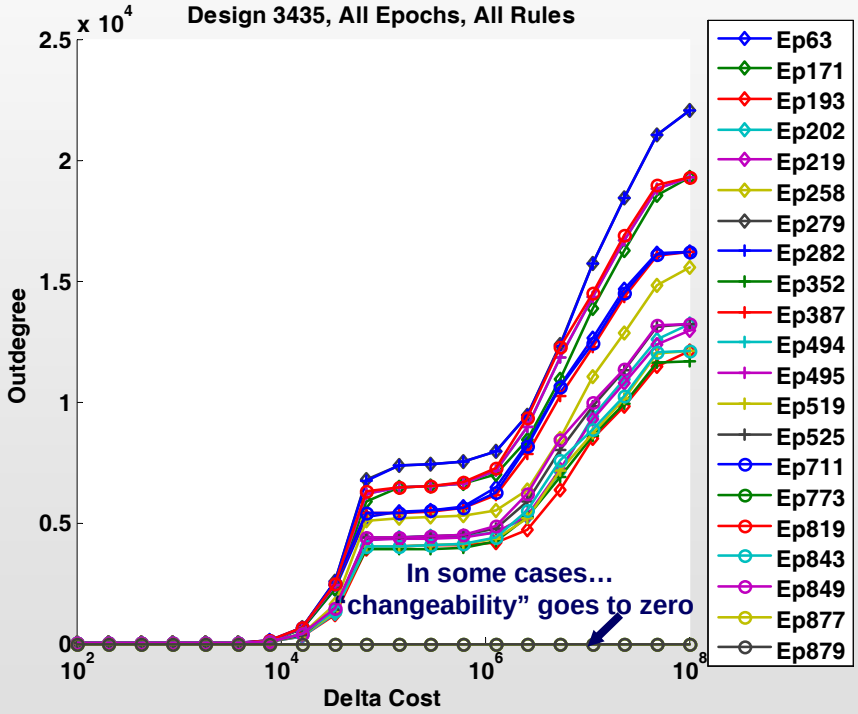
Calculating Filtered Outdegree to Identify Changeable Designs

Filtered Outdegree

outgoing arcs from design at acceptable "cost" (measure of changeability)



Variation in design "changeability" in response to context change



Quantification and specification of "ilities" can be made explicit using RSC (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

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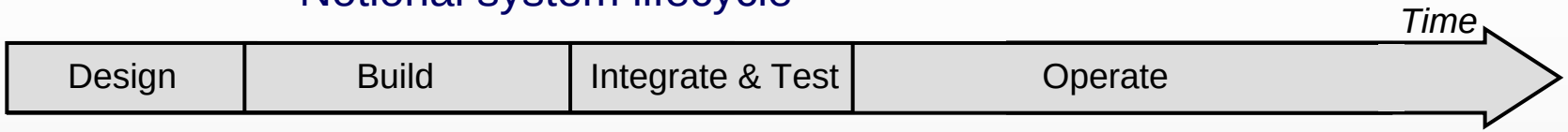
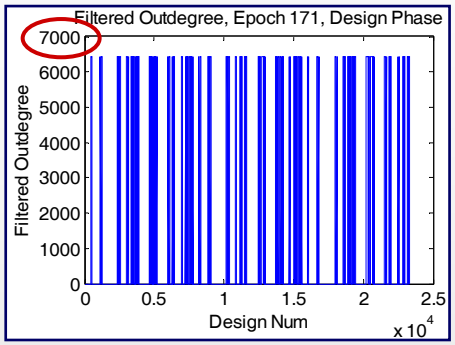
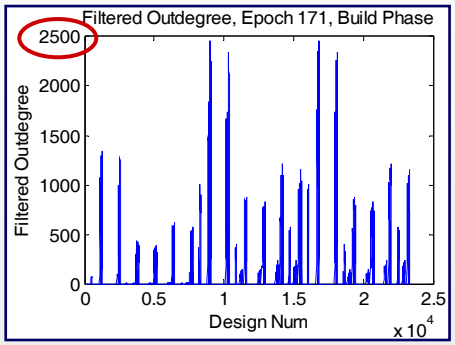
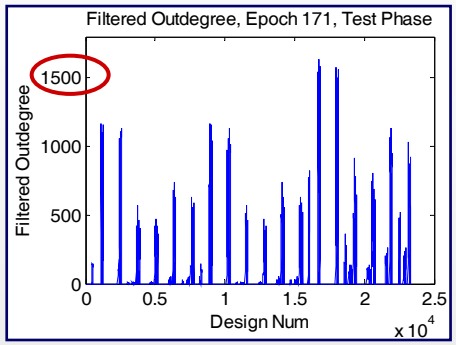
Changeability Across the Lifecycle

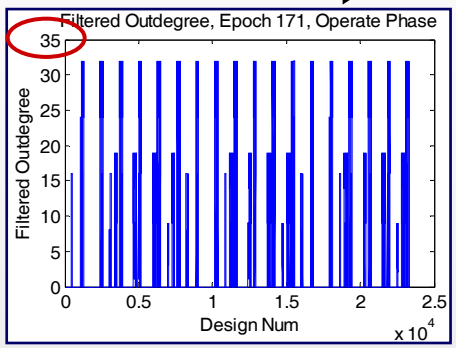
Notional system lifecycle











Changeability decreases as design moves through lifecycle

		Phase			
Epoch	Design #	Design	Build	Test	Operate
171	3435	100	0.04	0.3	0.2
171	16701	100	27.0	25.5	0.5
171	16805	100	38.2	23.6	0.4
171	Best across	100	38.2	25.5	0.5

Highly changeable designs per phase can be identified and features investigated

		16701	16805	16809	3435
Design Variables	Orbit Alt (km)	800	800	800	1500
	Walker ID (53deg, 4=20 sats, 5 planes; 3=10 sats, 5 planes)	4	4	4	3
	Tx Freq (GHz)	10	10	10	10
	Ant Area (m^2)	40	100	100	40
	Ant Type (0=AESA)	0	0	0	0
	Radar Bandwidth (GHz)	1	1	1	2
	Peak Power (kW)	20	20	20	10
	Comm Arch (0=backbone, 1=ground)	0	0	0	1
	Tactical Comm (0=yes)	0	0	0	0
Path Enablers	Tugable (1=yes)	1	1	1	1
	Maneuver package (4=baseline, 5=x2, 6=x4)	6	5	6	4
	Constellation Option (1=nothing, 3=spares built)	3	3	3	1

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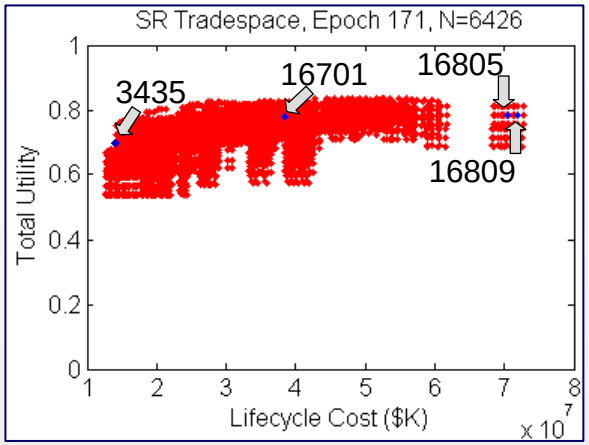
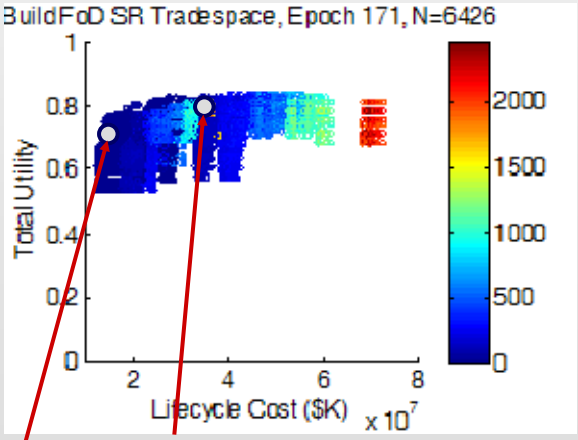
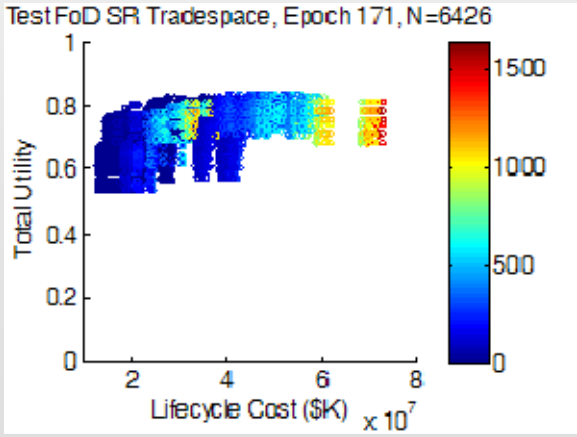
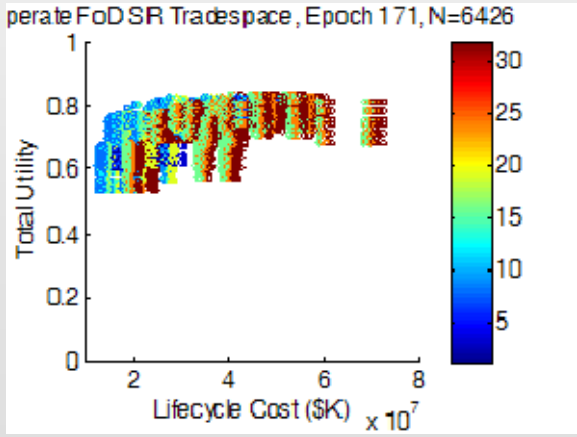
Identifying “Interesting” Designs



		16701	16805	16809	3435
Design Variables	Orbit Alt (km)	800	800	800	1500
	Walker ID (53deg, 4=20 sats, 5 planes; 3=10 sats, 5 planes)	4	4	4	3
	Tx Freq (GHz)	10	10	10	10
	Ant Area (m^2)	40	100	100	40
	Ant Type (0=AESA)	0	0	0	0
	Radar Bandwidth (GHz)	1	1	1	2
	Peak Power (kW)	20	20	20	10
	Comm Arch (0=backbone, 1=ground)	0	0	0	1
	Tactical Comm (0=yes)	0	0	0	0
Path Enablers	Tugable (1=yes)	1	1	1	1
	Maneuver package (4=baseline, 5=x2, 6=x4)	6	5	6	4
	Constellation Option (1=nothing, 3=spares built)	3	3	3	1







Most changeable (16701)
Most passive value robust (3435)

Both passive value robust and changeable designs can be identified in any epoch

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Discussion

- Insight 1: Quantitative investigation of "requirement" effect
  - Ease or difficulty in achieving "acceptable" levels
  - Identification of overly constraining expectations
- Insight 2: Quantify "value robust" and correlate to design features
  - Pareto Trace metric to identify value robust designs (across enumerated epochs)
  - Filtered Outdegree metric to identify changeable designs (for unknown epochs or for evolving systems)
  - Identify useful design features for real options
- Insight 3: Quantify key system tradeoffs
  - Illustrate tensions between missions
  - Identify good "compromise" design alternatives

Caution: Specific insights into SRS more illustrative than prescriptive (very low fidelity model used)

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Next Steps

- RSC method refinement on-going
- Application of Process 6 (Era Construction) and Process 7 (Lifecycle Path Analysis) in current research (aim to publish next year)
- Advanced metrics and approaches for incorporating survivability, SoS design, and valuing destinations for changeability

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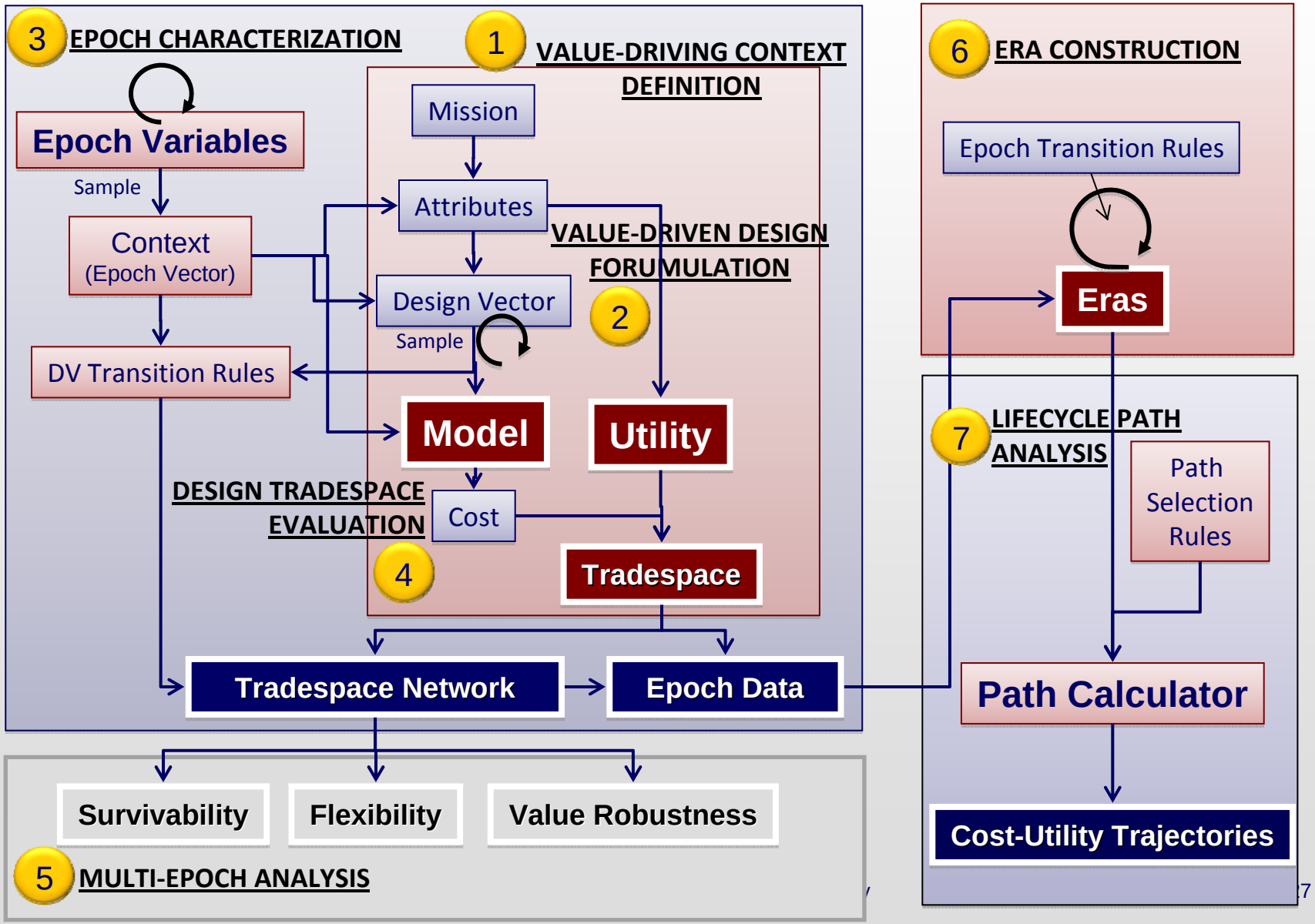
Thank you.
Questions?

Stay tuned for follow-up publications with results…

Overall Model Architecture