



**Systems Engineering Advancement Research Initiative**



2009 SEARI Annual Research Summit

## **Research Report**

“Design for Survivability: Concept Generation and Evaluation in  
Dynamic Tradespace Exploration”

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Cambridge, MA

Massachusetts Institute of Technology

**MIT ESD**

Engineering Systems Division

# Agenda

- Problem Statement
- Research Questions
- Methodology Overview
- Case Application: Satellite Radar
- Discussion
- Future Work

PhD in Engineering Systems, June 2009

Thesis Committee:

Dean Daniel Hastings (Chair)

Dr. Adam Ross

Prof. Annalisa Weigel

Dr. Donna Rhodes

# Problem Statement

Temporal system properties known as “ilities” (e.g., flexibility) are a critical design challenge for engineering systems

- Survivability is a critical challenge for aerospace system architecture

Given limitations of survivability engineering for aerospace systems,\* need design methodology that:

1. incorporates survivability as an **active trade** throughout design process
2. reflects **dynamics** of operational environments over entire lifecycle
3. captures **path dependencies** of system vulnerability and resilience
4. extends in scope to **architecture-level** survivability assessments
5. takes a **value-centric** perspective

Opportunity to build on recent research on dynamic tradespace exploration (Ross 2006)

Application of survivability methodology may address critical issue for military space

- Satellite radar architecture development

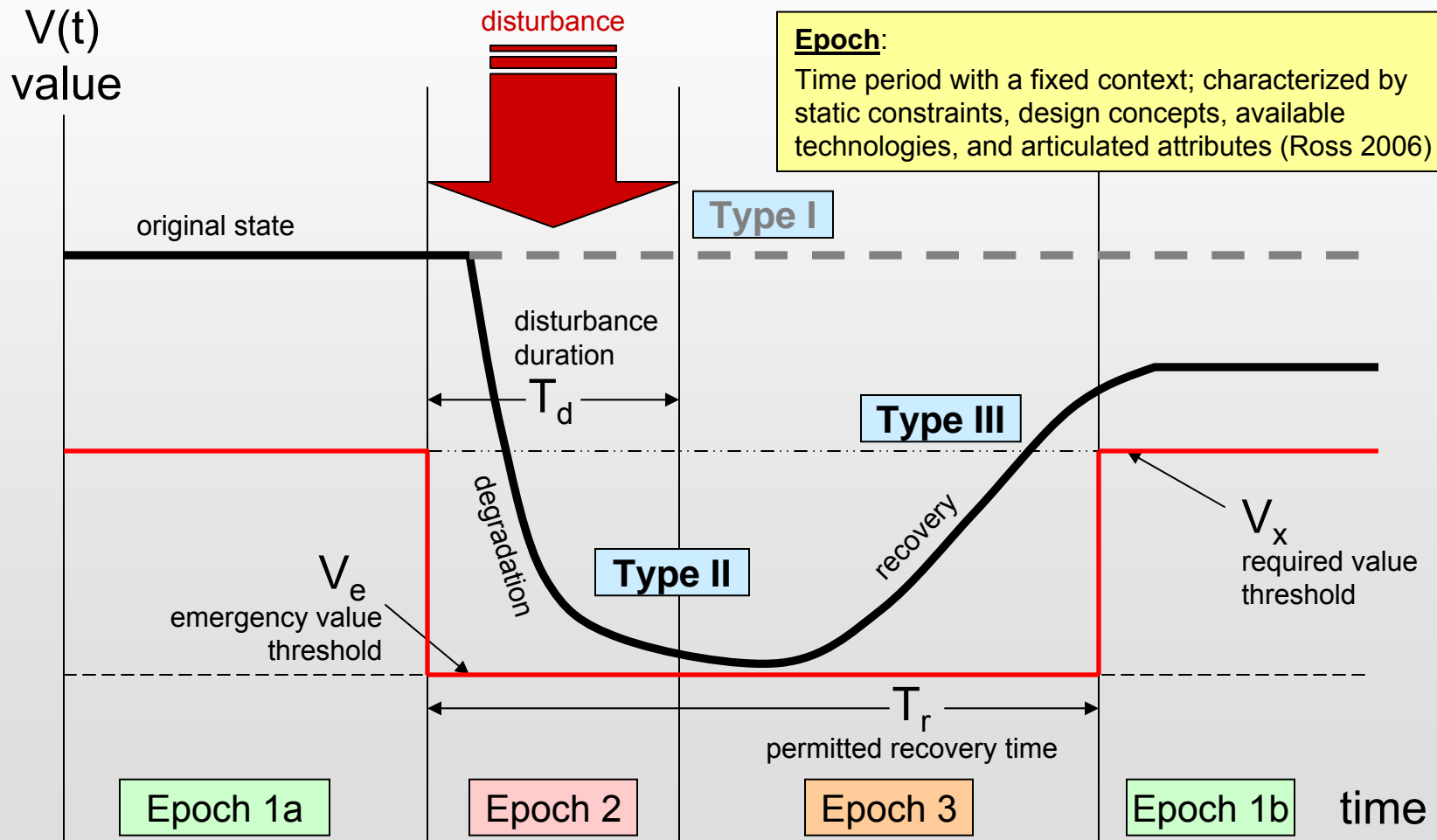
\*Richards, M., Hastings, D., Rhodes, D., and Weigel, A., “Systems Architecting for Survivability: Limitations of Existing Methods for Aerospace Systems,” *6th Conference on Systems Engineering Research*, Los Angeles, CA, April 2008.

# Research Questions

1. What is a dynamic, operational, and value-centric **definition** of survivability for engineering systems?
2. What **design principles** enable survivability?
3. How can survivability be quantified and used as a **decision metric in exploring tradespaces** during conceptual design of aerospace systems?
4. For a given space mission, how to **evaluate the survivability of alternative system architectures** in dynamic disturbance environments?

# Definition of Survivability

Ability of a system to minimize the impact of finite-duration disturbances on value delivery through (I) the reduction of the likelihood or magnitude of a disturbance, (II) the satisfaction of a minimally acceptable level of value delivery during and after a disturbance, and/or (III) a timely recovery



# Survivability Metrics

*Need to evaluate ability of system to (1) minimize utility losses and (2) meet critical value thresholds before, during, and after environmental disturbances*

**desirable attributes: value-based, dynamic, continuous**

## time-weighted utility loss

- Difference between design utility,  $U_0$ , and time-weighted average utility
- Internalizes lifecycle degradation
- Inspired by Quality Adjusted Life Years in health economics\*

$$\bar{U}_L = U_0 - \frac{1}{T_{dl}} \cdot \int U(t) dt$$

$T_{dl}$  = time of design life

## threshold availability

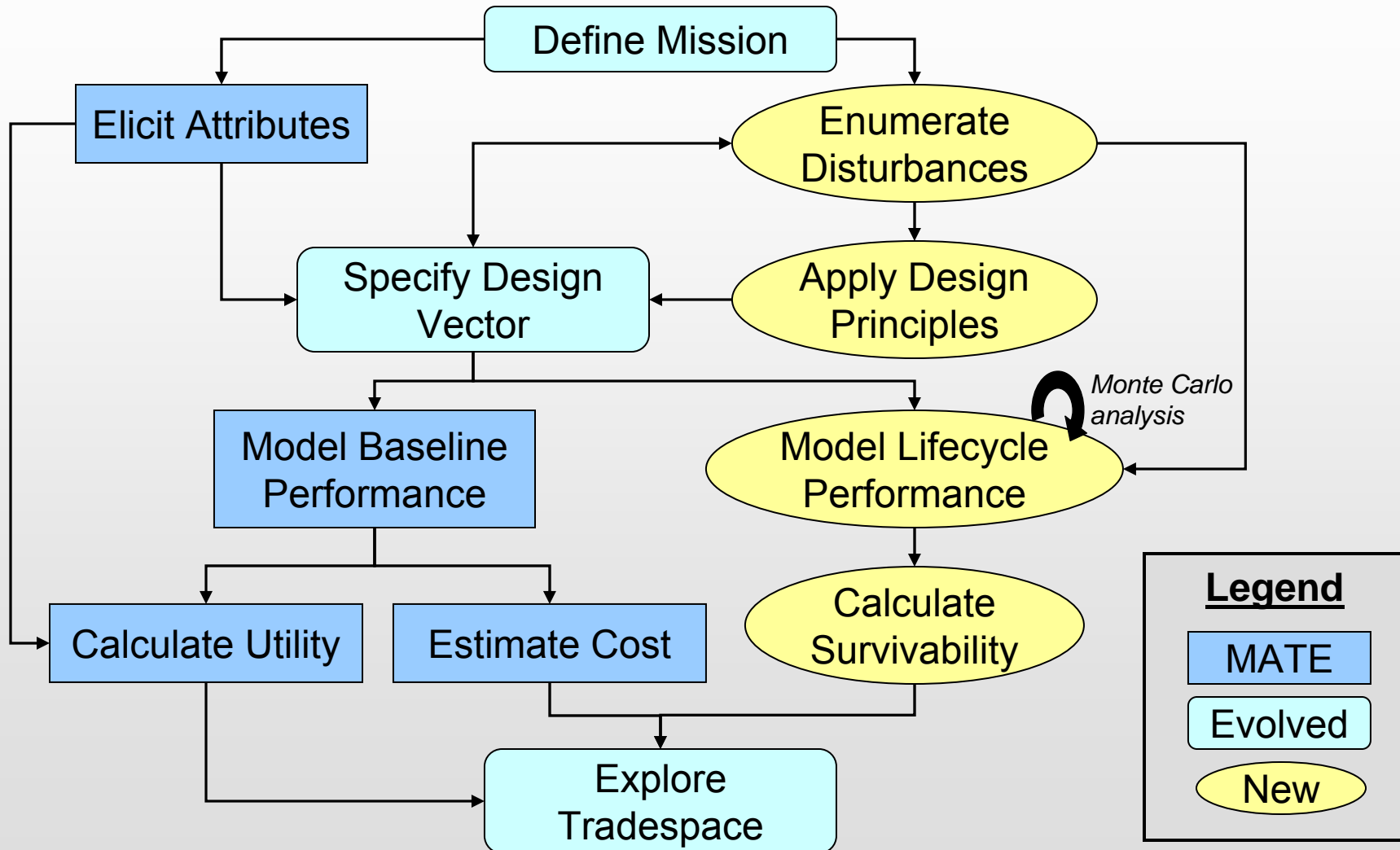
- Ratio of time above critical value thresholds ( $V_x$  during baseline Epoch,  $V_e$  during disturbance and recovery Epochs) to design life
- Accommodates changing expectations across contexts

$$A_T = \frac{TAT}{T_{dl}}$$

TAT = time above thresholds

\*Pliskin, J., D. Shepard and M. Weinstein (1980). "Utility Functions for Life Years and Health Status." *Operations Research*, 28(1): 206-224.

# Multi-Attribute Tradespace Exploration (MATE) for Survivability



# Phases of MATE for Survivability

1. **Elicit Value Proposition** – Identify mission statement and quantify decision-maker needs during nominal and emergency states.
2. **Generate Concepts** – Formulate concepts that address decision-maker needs.
3. **Characterize Disturbance Environment** – Develop concept-neutral models of disturbances in operational environment of proposed systems.
4. **Apply Survivability Principles** – Incorporate susceptibility reduction, vulnerability reduction, and resilience enhancement strategies into design vector.
5. **Model Baseline System Performance** – Model and simulate cost and performance of design alternatives to gain an understanding of how decision-maker needs are met in a nominal operational environment.
6. **Model Impact of Disturbances on Lifecycle Performance** – Model and simulate performance of design alternatives across a representative sample of disturbance encounters to gain an understanding of how decision-maker needs are met in perturbed environments.
7. **Apply Survivability Metrics** – Compute time-weighted utility loss and threshold availability for each design alternative as summary statistics for system performance across representative operational lives.
8. **Explore Tradespace** – Perform integrated cost, utility, and survivability trades across design space to identify promising alternatives for more detailed analysis.



# Case Application: Satellite Radar

Critical issue in national security space

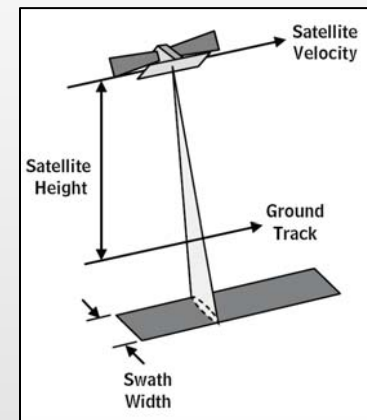
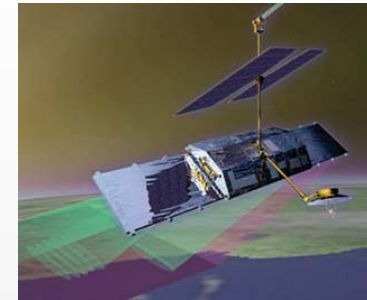
- Unique all-weather surveillance capability
- Opportunity for impact given ongoing studies
- Rich multi-dimensional tradespace

Unit-of-analysis: SR architecture

- Radar payload
- Constellation of satellites
- Communications network

Availability of data

- Systems Engineering Advancement Research Initiative (SEARI)



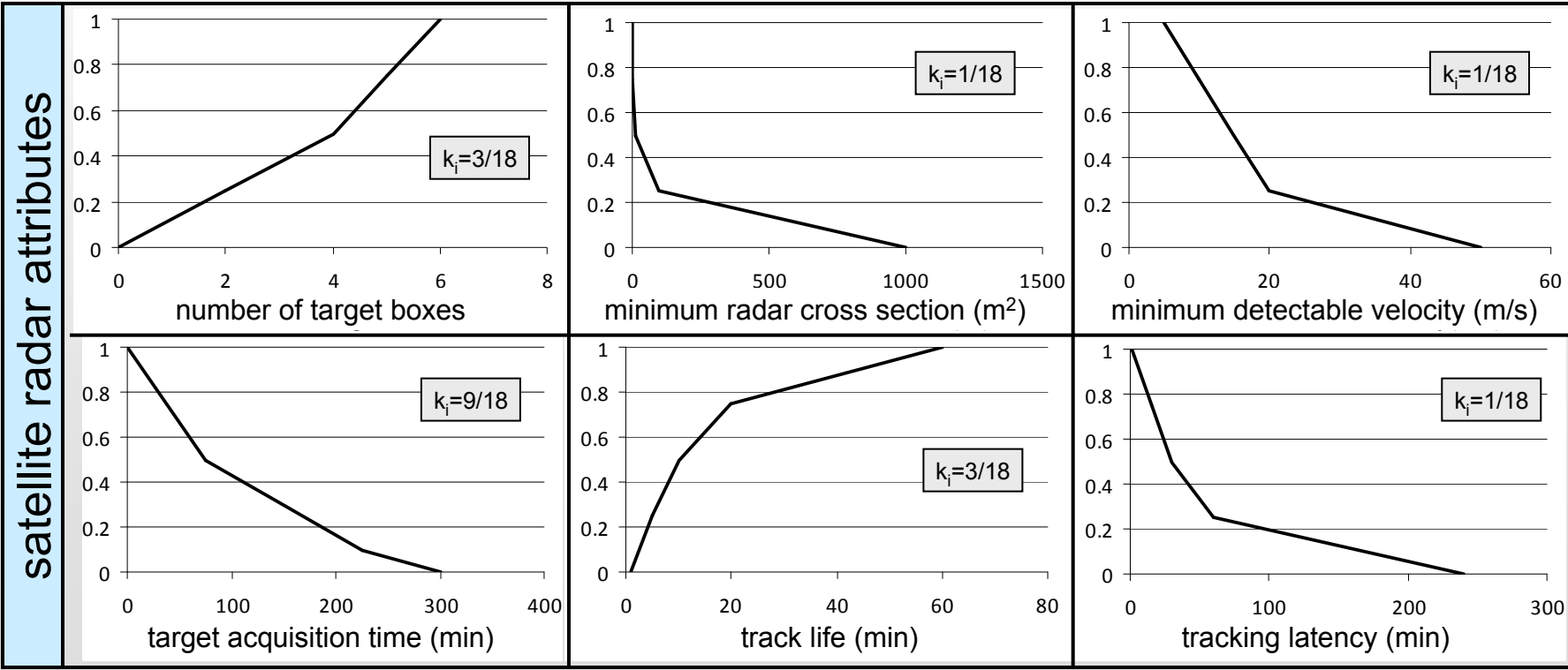
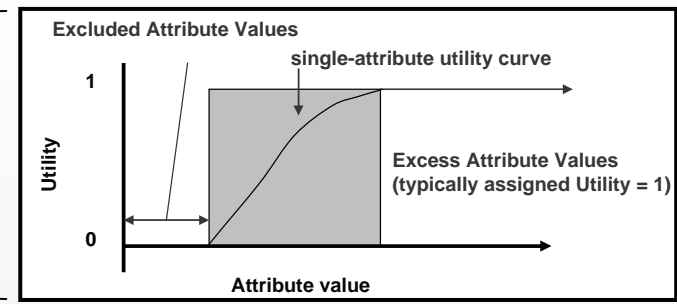
(CBO 2007)

## Case Application Goal

*To assess potential **satellite radar** architectures for providing the United States Military a global, all-weather, on-demand capability to **track moving ground targets**; supporting tactical military operations; maximizing cost-effectiveness; and **surviving disturbances** in the natural space environment.*

# Phase 1: Elicit Value Proposition

**Attributes:** *concept-neutral evaluation criteria specified by a decision maker*



# Phase 2: Generate Concepts

*Design Value Mapping Matrix establishes traceability between value-space and design-space*

		ATTRIBUTES																					
		Mission										Programmatics											
		Tracking					Imaging					Cost		Schedule									
		Minimum Target RCS	Min. Detectable Velocity	Number of Target Boxes	Target Acquisition 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		
	Radar Frequency	X	UHF	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	
	Receiver Sats per Tx Sat	0	1	2	3	4	5	9	9	3	3	1	1	9	3	3	1	1	9	9	9	9	79
	Antenna Type	Mechanical vs. AESA	9	9	9	3	3	1	9	9	9	1	1	9	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	9	73				
	Comm. Downlink	Relay vs. Downlink	0	0	0	0	0	9	0	0	0	0	9	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	9	51				
	Processing	Space vs. Ground	0	0	0	1	0	3	1	0	0	0	3	9	9	9	9	9	44				
	Maneuver Package	1x, 2x, 4x	1	1	1	1	1	0	1	1	1	1	0	9	3	3	3	9	27				
	Tugable	Yes vs. No	1	1	1	1	1	0	1	1	1	1	0	9	9	9	9	9	45				
	Constellation Option	none, long-lead, spare	0	0	0	0	0	0	0	0	0	0	0	9	9	9	9	9	36				
	Total		65	64	42	39	30	33	66	58	62	23	33	106	100	88	100						

# Phase 3: Characterize Disturbance Environment

Enumerate disturbances

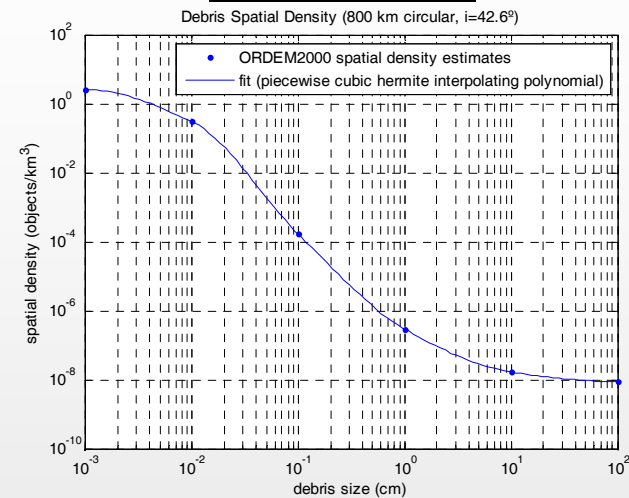
- Orbital debris
- Signal attenuation

Gather data on disturbance magnitude and occurrence

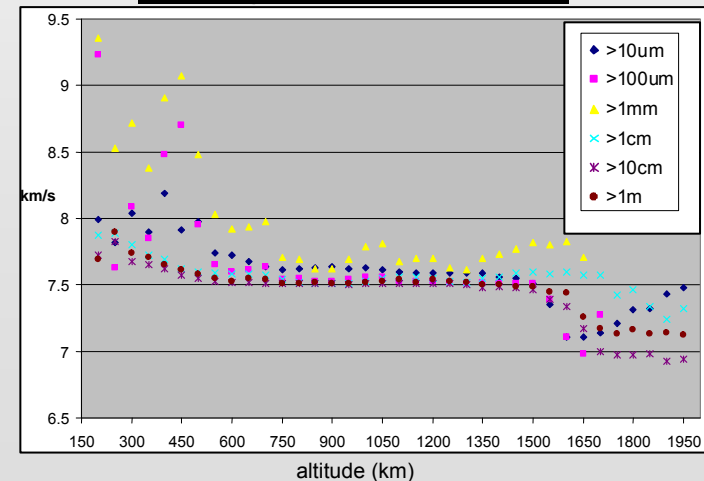
- NASA ORDEM2000 debris model
  - Space Surveillance Network
  - Haystack and Haystack radar data
  - Goldstone radar data
  - Long-Duration Exposure Facility
  - Hubble Telescope array impact data
  - Space Shuttle impact data
  - Mir impact data

Develop system-independent models of disturbance environment

## Spatial Density



## Average Orbital Velocity



# Phase 4: Apply Survivability Principles

*Survivability Variable Mapping Matrix establishes traceability between environment and design-space*

			disturbances								
design principles	concept enhancements	design variables (units)	atmospheric drag fluctuations	arc discharging	high-flux radiation	micrometeorites / debris	signal attenuation	change in target characteristics	failure of relay backbone	loss of tactical ground node	
Type I	prevention	reduce exposed s/c area	9	0	3	9	0	0	0	0	
	mobility										
	concealment										
	deterrence										
	preemption										
avoidance	s/c maneuvering	$\Delta V$ (m/s)	9	0	3	1	0	0	0	0	
	s/c servicing interface	s/c servicing interface	9	0	1	1	0	0	0	0	
	ground receiver maneuverability	mobile receiver	0	0	0	0	3	0	0	3	
hardness	radiation-hardened electronics	hardening (cal/cm <sup>2</sup> )	0	3	9	1	0	0	0	0	
	bumper shielding	shield thickness (mm)	0	0	0	9	0	0	0	0	
	redundancy	duplicate critical s/c functions	bus redundancy	0	1	9	3	0	0	0	0
		on-orbit satellite spares	extra s/c per orbital plan	0	1	3	3	0	3	0	0
margin	multiple ground receivers	ground infrastructure level	0	0	0	0	3	0	0	9	
	over-design power generation	peak transmit power (kW)	0	0	0	3	9	9	0	0	
	over-design link budget	assumed signal loss (dB)	0	0	0	0	9	0	0	0	
	over-design propulsion system	$\Delta V$ (m/s)	3	0	3	0	3	9	0	0	
	excess on-board data storage	s/c data capacity (gbits)	0	0	0	0	0	0	3	3	
	excess constellation capacity	number of satellites	0	1	3	9	0	0	0	0	
heterogeneity	interface with airborne assets	tactical downlink	3	3	3	3	3	3	3	3	
	multiple communication paths	communications downlink	0	0	1	1	9	0	9	3	
		tactical downlink	0	0	1	1	9	0	9	3	
distribution	spatial separation of spacecraft	orbital altitude (km)	1	1	3	3	0	9	0	0	
	spatial separation of s/c orbits	number of planes	0	0	3	9	0	1	0	1	
failure mode reduction	reduce s/c complexity	bus redundancy	0	0	9	0	0	0	0	0	
fail-safe	autonomous operations	autonomous control	0	0	0	0	3	0	3	3	
evolution	flexible sensing operations	antenna type	0	0	0	0	3	9	0	0	
		radar bandwidth (GHz)	0	0	0	0	9	3	0	0	
	retraction of s/c appendages	reconfigurable	0	0	9	3	0	0	0	0	
containment	s/c fault monitoring and response	autonomous control	0	1	3	1	0	0	0	0	
III I	replacement	rapid reconstitution	0	1	3	9	0	0	0	0	
I	repair	on-orbit-servicing	9	1	3	3	0	3	0	0	

# Phase 4: Apply Survivability Principles

*Survivability Variable Mapping Matrix establishes traceability between environment and design-space*

			disturbances							
design principles	concept enhancements	design variables (units)	atmospheric drag fluctuations	arc discharging	high-flux radiation	micrometeorites / debris	signal attenuation	change in target characteristics	failure of relay backbone	loss of tactical ground node
Type I	prevention	reduce exposed s/c area	9	0	3	9	0	0	0	0
	mobility									
	concealment									
	deterrence									
	preemption									
avoidance	s/c maneuvering	$\Delta V$ (m/s)	9	0	3	1	0	0	0	0
	s/c servicing interface	s/c servicing interface	9	0	1	1	0	0	0	0
	ground receiver maneuverability	mobile receiver	0	0	0	0	3	0	0	3
hardness	radiation-hardened electronics	hardening (cal/cm <sup>2</sup> )	0	3	9	1	0	0	0	0
	bumper shielding	shield thickness (mm)	0	0	0	9	0	0	0	0
redundancy	duplicate critical s/c functions	bus redundancy	0	1	9	3	0	0	0	0
	on-orbit satellite spares	extra s/c per orbital plan	0	1	3	3	0	3	0	0
	multiple ground receivers	ground infrastructure level	0	0	0	0	3	0	0	9
margin	over-design power generation	peak transmit power (kW)	0	0	0	3	9	9	0	0
	over-design link budget	assumed signal loss (dB)	0	0	0	0	9	0	0	0
	over-design propulsion system	$\Delta V$ (m/s)	3	0	3	0	3	9	0	0
	excess on-board data storage	s/c data capacity (gbits)	0	0	0	0	0	0	3	3
	excess constellation capacity	number of satellites	0	1	3	9	0	0	0	0
heterogeneity	interface with airborne assets	tactical downlink	3	3	3	3	3	3	3	3
	multiple communication paths	communications downlink	0	0	1	1	9	0	9	3
		tactical downlink	0	0	1	1	9	0	9	3
distribution	spatial separation of spacecraft	orbital altitude (km)	1	1	3	3	0	9	0	0
	spatial separation of s/c orbits	number of planes	0	0	3	9	0	1	0	1
failure mode reduction	reduce s/c complexity	bus redundancy	0	0	9	0	0	0	0	0
fail-safe	autonomous operations	autonomous control	0	0	0	0	3	0	3	3
evolution	flexible sensing operations	antenna type	0	0	0	0	3	9	0	0
		radar bandwidth (GHz)	0	0	0	0	9	3	0	0
	retraction of s/c appendages	reconfigurable	0	0	9	3	0	0	0	0
containment	s/c fault monitoring and response	autonomous control	0	1	3	1	0	0	0	0
III	replacement	rapid reconstitution	0	1	3	9	0	0	0	0
I	repair	on-orbit-servicing	9	1	3	3	0	3	0	0

# Phase 4: Apply Survivability Principles

*Survivability Variable Mapping Matrix establishes traceability between environment and design-space*

			disturbances								
design principles	concept enhancements	design variables (units)	atmospheric drag fluctuations	arc discharging	high-flux radiation	micrometeorites / debris	signal attenuation	change in target characteristics	failure of relay backbone	loss of tactical ground node	
Type I	prevention	reduce exposed s/c area	antenna area (m <sup>2</sup> )	9	0	3	9	0	0	0	0
	mobility										
	concealment										
	deterrence										
	preemption										
avoidance	s/c maneuvering	$\Delta V$ (m/s)	9	0	3	1	0	0	0	0	
	s/c servicing interface	s/c servicing interface	9	0	1	1	0	0	0	0	
	ground receiver maneuverability	mobile receiver	0	0	0	0	3	0	0	3	
hardness	radiation-hardened electronics	hardening (cal/cm <sup>2</sup> )	0	3	9	1	0	0	0	0	
	bumper shielding	shield thickness (mm)	0	0	0	9	0	0	0	0	
	redundancy	duplicate critical s/c functions	bus redundancy	0	1	9	3	0	0	0	0
on-orbit satellite spares		extra s/c per orbital plan	0	1	3	3	0	3	0	0	
multiple ground receivers		ground infrastructure level	0	0	0	0	3	0	0	9	
margin	over-design power generation	peak transmit power (kW)	0	0	0	3	9	9	0	0	
	over-design link budget	assumed signal loss (dB)	0	0	0	0	9	0	0	0	
	over-design propulsion system	$\Delta V$ (m/s)	3	0	3	0	3	9	0	0	
	excess on-board data storage	s/c data capacity (gbits)	0	0	0	0	0	0	3	3	
	excess constellation capacity	number of satellites	0	1	3	9	0	0	0	0	
heterogeneity	interface with airborne assets	tactical downlink	3	3	3	3	3	3	3	3	
	multiple communication paths	communications downlink	0	0	1	1	9	0	9	3	
		tactical downlink	0	0	1	1	9	0	9	3	
distribution	spatial separation of spacecraft	orbital altitude (km)	1	1	3	3	0	9	0	0	
	spatial separation of s/c orbits	number of planes	0	0	3	9	0	1	0	1	
failure mode reduction	reduce s/c complexity	bus redundancy	0	0	9	0	0	0	0	0	
fail-safe	autonomous operations	autonomous control	0	0	0	0	3	0	3	3	
evolution	flexible sensing operations	antenna type	0	0	0	0	3	9	0	0	
		radar bandwidth (GHz)	0	0	0	0	9	3	0	0	
	retraction of s/c appendages	reconfigurable	0	0	9	3	0	0	0	0	
containment	s/c fault monitoring and response	autonomous control	0	1	3	1	0	0	0	0	
III	replacement	rapid reconstitution	constellation spares	0	1	3	9	0	0	0	
I	repair	on-orbit-servicing	s/c servicing interface	9	1	3	3	0	3	0	

## finalized design vector (n=3888)

Orbit Altitude (km)
800
1500

Peak Transmit Power (kW)
1.5
10
20

Walker ID
5/5/1
9/3/2
27/3/1
66/6/5

Radars Bandwidth (MHz)
500
1000
2000

Antenna Area (m <sup>2</sup> )
10
40
100

Comm. Architecture
Direct Downlink Only
Relay Backbone

# Phase 4: Apply Survivability Principles

*Survivability Variable Mapping Matrix establishes traceability between environment and design-space*

			disturbances							
design principles	concept enhancements	design variables (units)	atmospheric drag fluctuations	arc discharging	high-flux radiation	micrometeorites / debris	signal attenuation	change in target characteristics	failure of relay backbone	loss of tactical ground node
Type I	prevention	reduce exposed s/c area	antenna area (m <sup>2</sup> )	9	0	3	9	0	0	0
	mobility									
	concealment									
	deterrence									
	preemption									
avoidance	s/c maneuvering	$\Delta V$ (m/s)	9	0	3	1	0	0	0	0
	s/c servicing interface	s/c servicing interface	9	0	1	1	0	0	0	0
	ground receiver maneuverability	mobile receiver	0	0	0	0	3	0	0	3
hardness	radiation-hardened electronics	hardening (cal/cm <sup>2</sup> )	0	3	9	1	0	0	0	0
	bumper shielding	shield thickness (mm)	0	0	0	9	0	0	0	0
	redundancy	duplicate critical s/c functions	bus redundancy	0	1	9	3	0	0	0
on-orbit satellite spares		extra s/c per orbital plan	0	1	3	3	0	3	0	0
multiple ground receivers		ground infrastructure level	0	0	0	0	3	0	0	9
margin	over-design power generation	peak transmit power (kW)	0	0	0	3	9	9	0	0
	over-design link budget	assumed signal loss (dB)	0	0	0	0	9	0	0	0
	over-design propulsion system	$\Delta V$ (m/s)	3	0	3	0	3	9	0	0
	excess on-board data storage	s/c data capacity (gbits)	0	0	0	0	0	0	3	3
	excess constellation capacity	number of satellites	0	1	3	9	0	0	0	0
heterogeneity	interface with airborne assets	tactical downlink	3	3	3	3	3	3	3	3
	multiple communication paths	communications downlink	0	0	1	1	9	0	9	3
		tactical downlink	0	0	1	1	9	0	9	3
distribution	spatial separation of spacecraft	orbital altitude (km)	1	1	3	3	0	9	0	0
	spatial separation of s/c orbits	number of planes	0	0	3	9	0	1	0	1
failure mode reduction	reduce s/c complexity	bus redundancy	0	0	9	0	0	0	0	0
fail-safe	autonomous operations	autonomous control	0	0	0	0	3	0	3	3
evolution	flexible sensing operations	antenna type	0	0	0	0	3	9	0	0
		radar bandwidth (GHz)	0	0	0	0	9	3	0	0
	retraction of s/c appendages	reconfigurable	0	0	9	3	0	0	0	0
containment	s/c fault monitoring and response	autonomous control	0	1	3	1	0	0	0	0
III	replacement	rapid reconstitution	constellation spares	0	1	3	9	0	0	0
I	repair	on-orbit-servicing	s/c servicing interface	9	1	3	3	0	3	0

## finalized design vector (n=3888)

Orbit Altitude (km)
800
1500

Peak Transmit Power (kW)
1.5
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Walker ID
5/5/1
9/3/2
27/3/1
66/6/5

Radars Bandwidth (MHz)
500
1000
2000

Antenna Area (m <sup>2</sup> )
10
40
100

Comm. Architecture
Direct Downlink Only
Relay Backbone

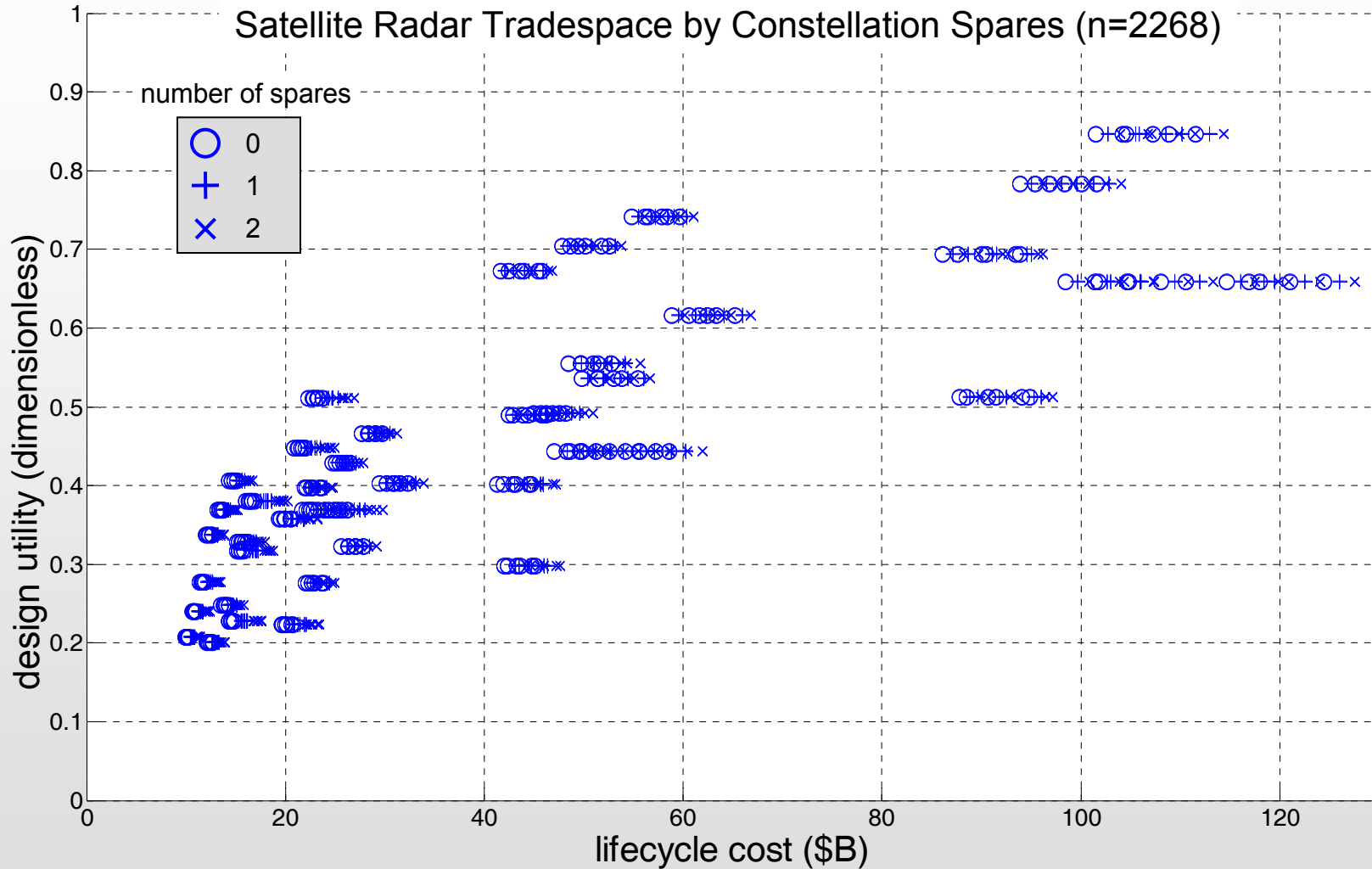
survivability variables

Constellation Spares
0
1
2

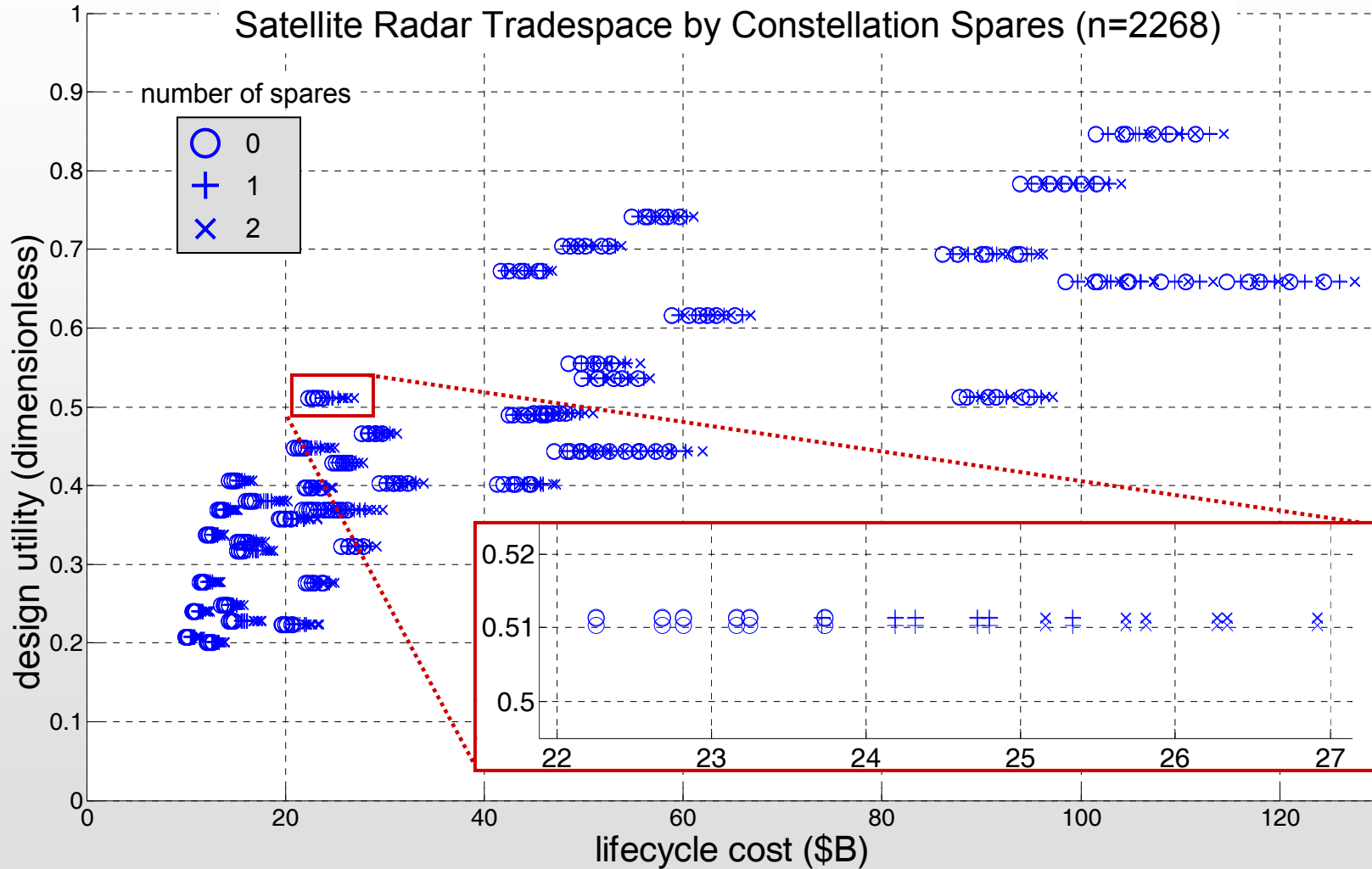
Shield Thickness (mm)
1
5
10



# Phase 5: Model Baseline System Performance

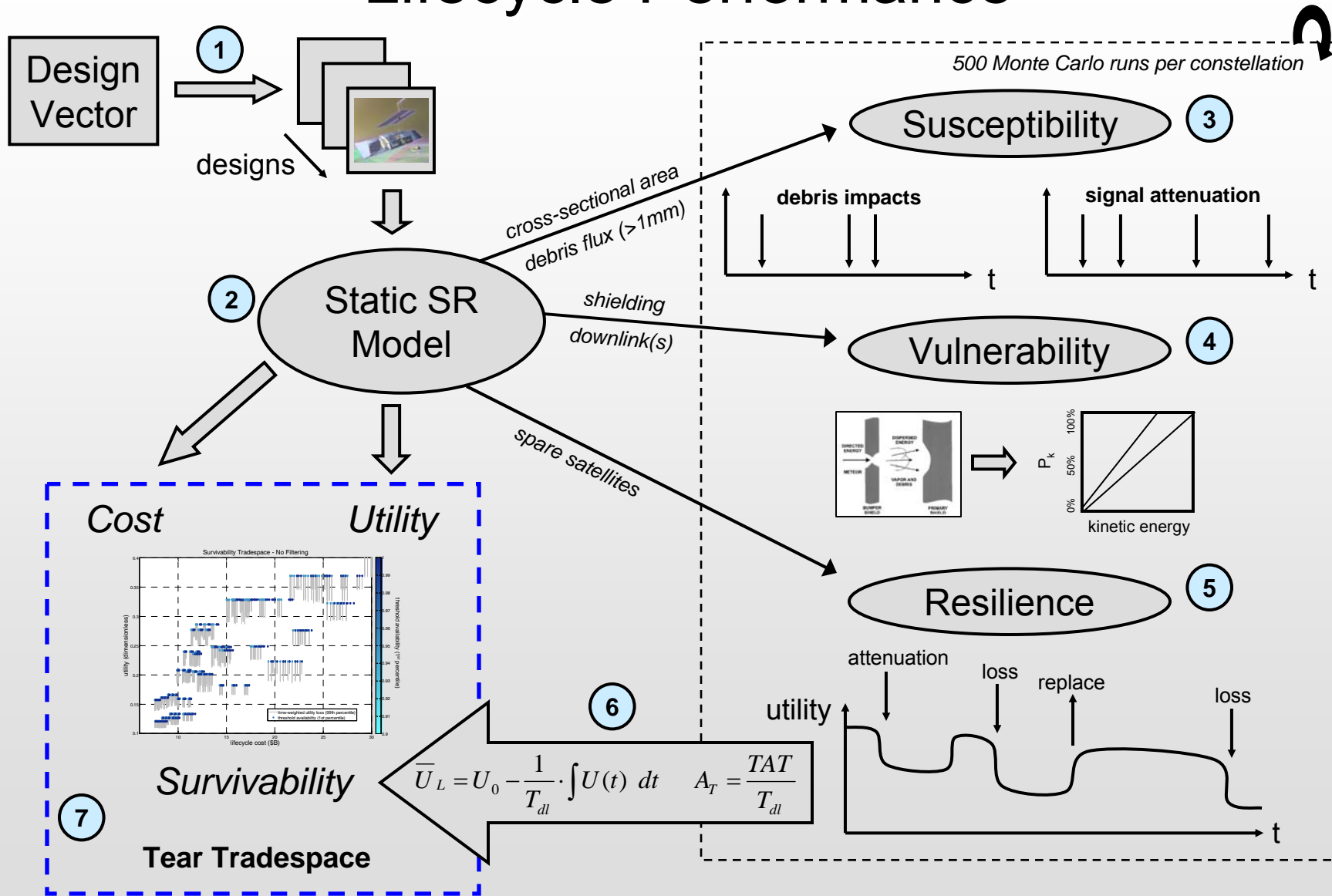


# Phase 5: Model Baseline System Performance



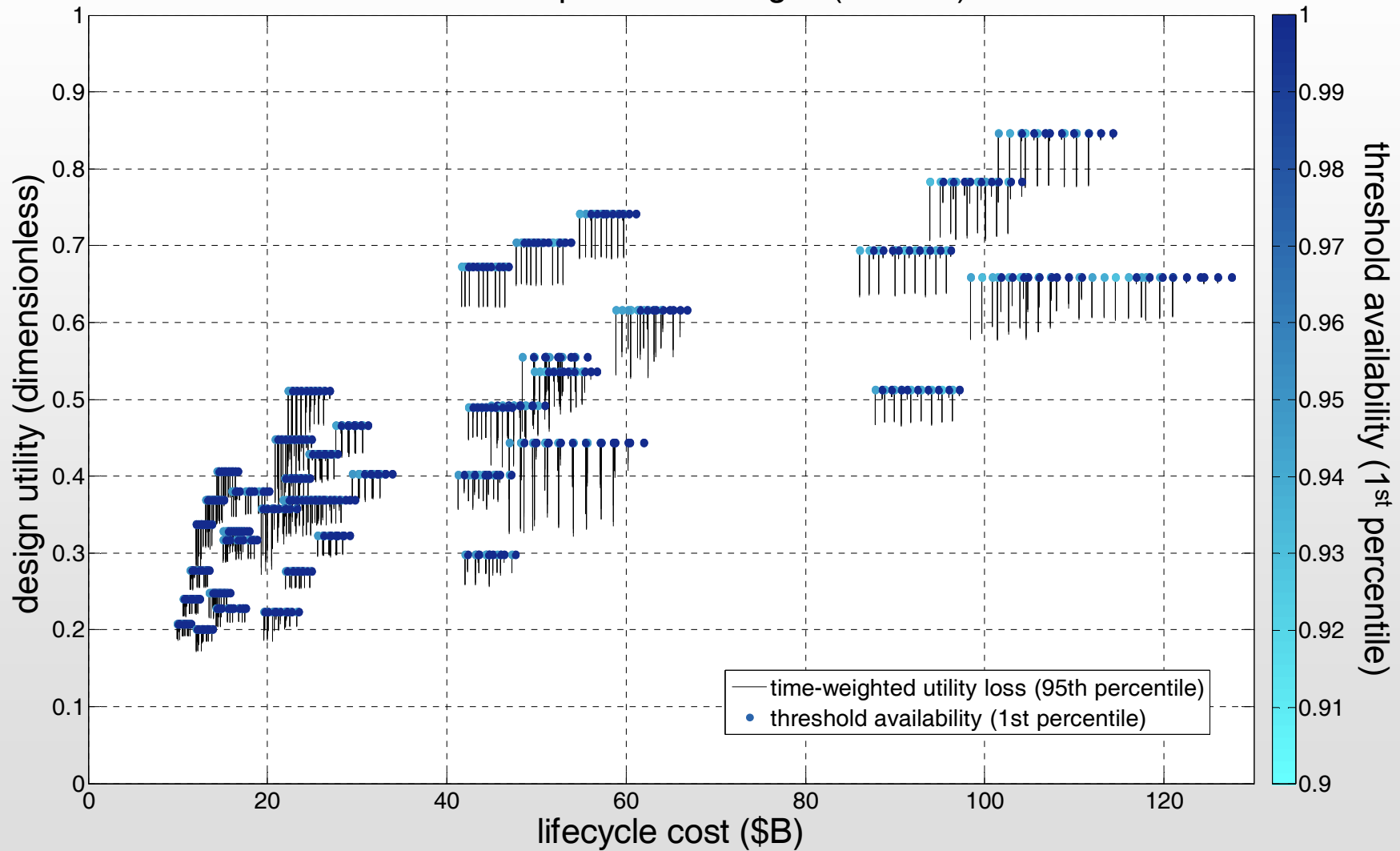
*Baseline tradespace only internalizes costs of survivability features*

# Phase 6: Model Impact of Disturbances on Lifecycle Performance



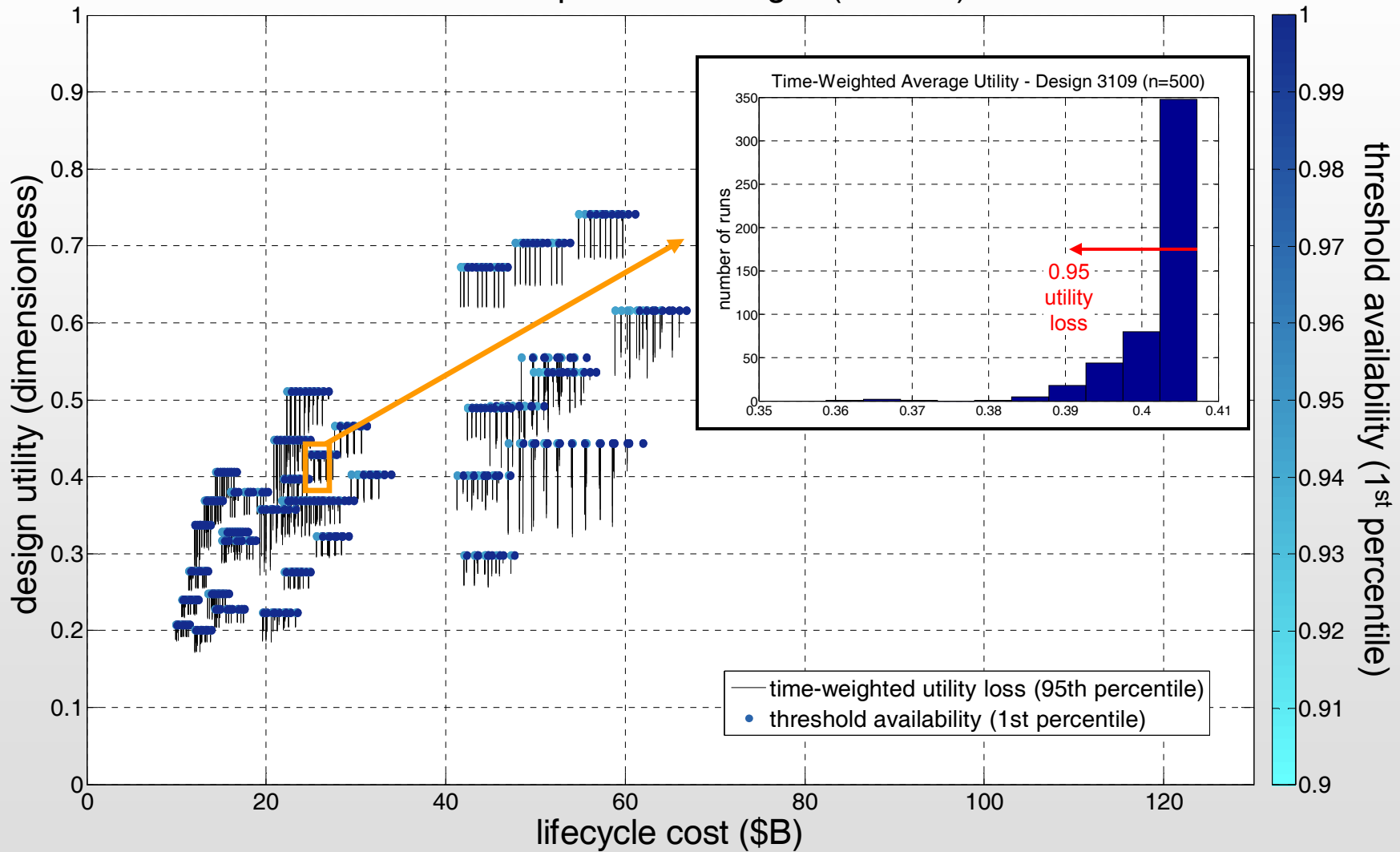
# Phase 7: Apply Survivability Metrics

Tear Tradespace - all designs (n=2268)



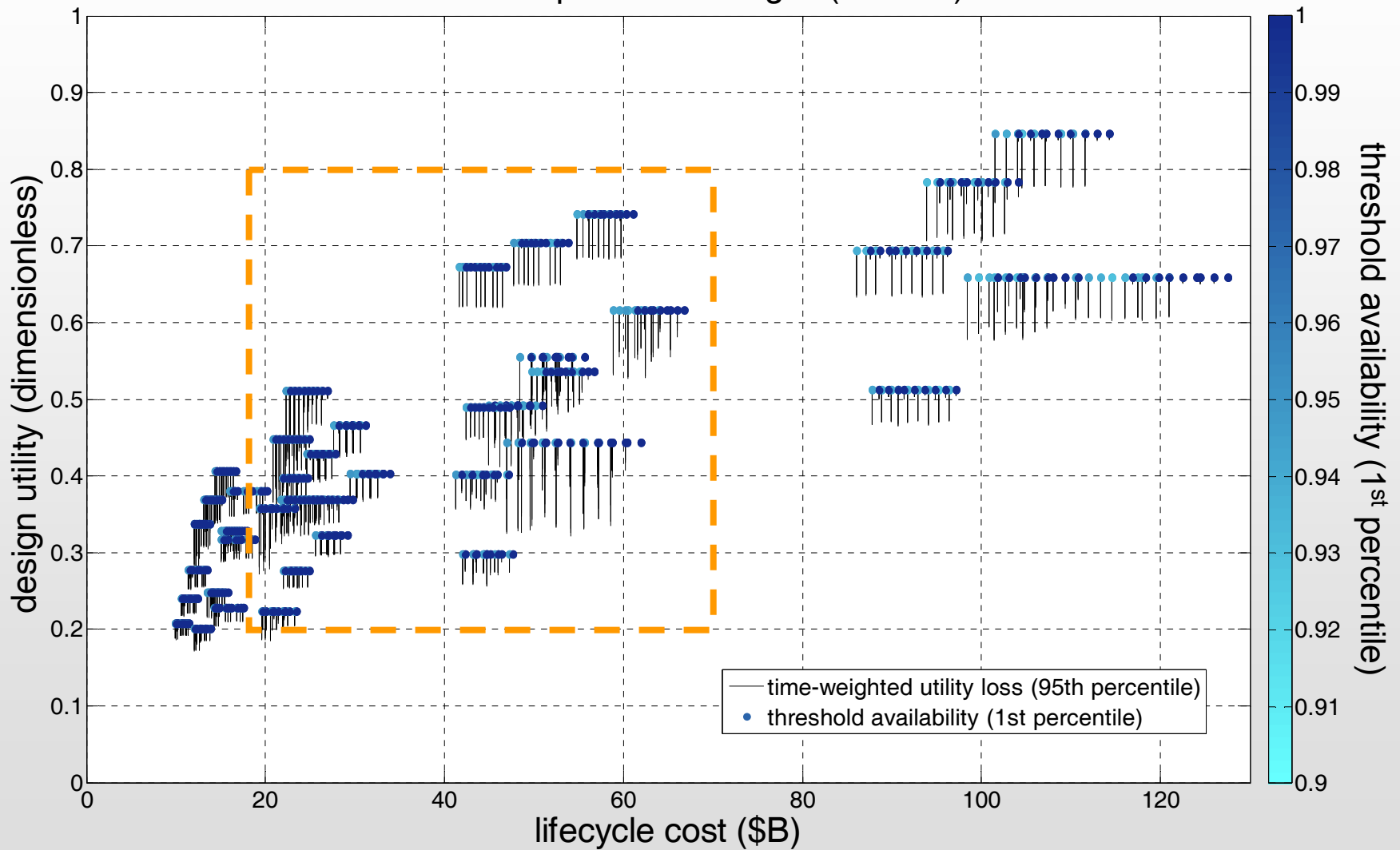
# Phase 7: Apply Survivability Metrics

Tear Tradespace - all designs (n=2268)



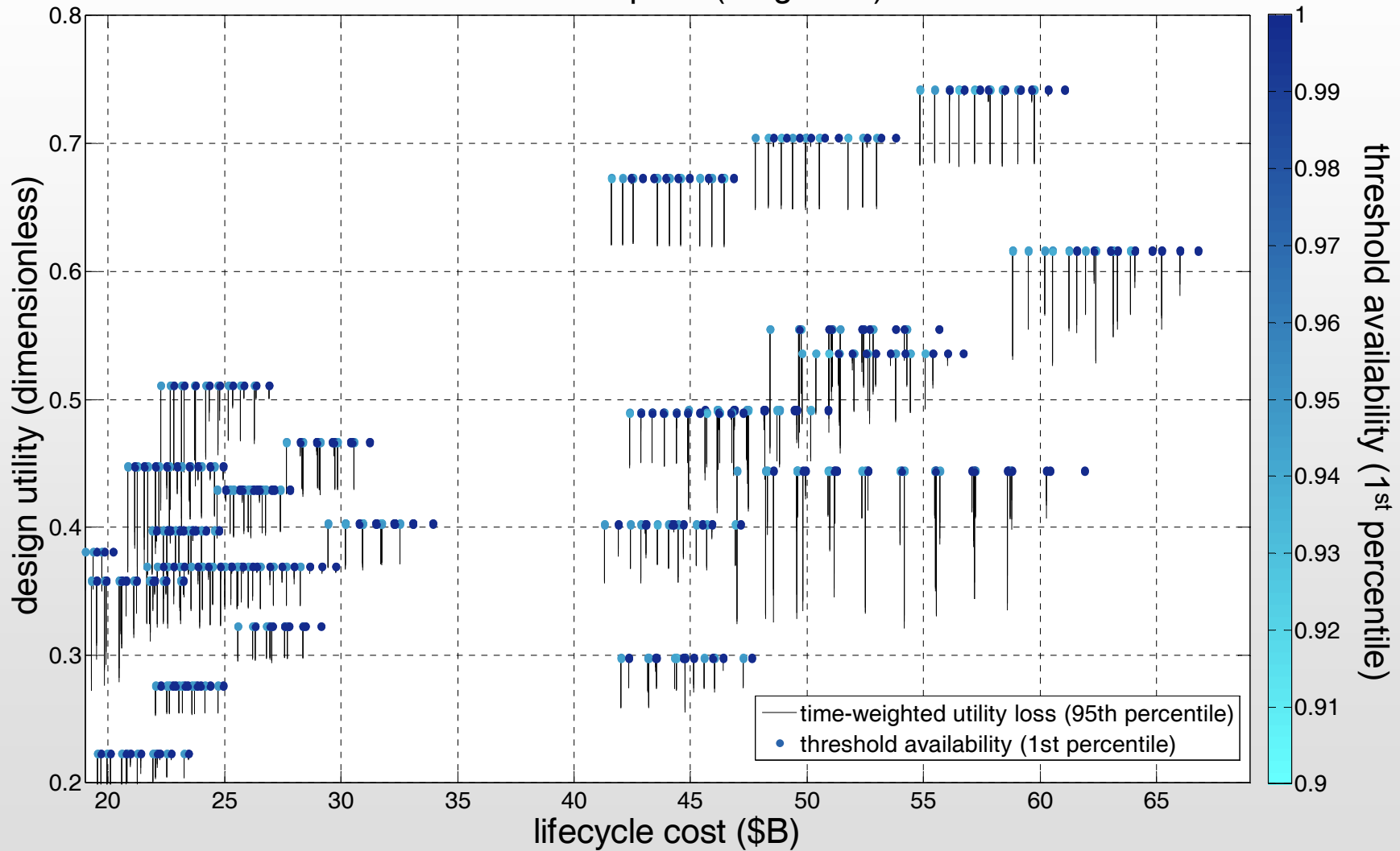
# Phase 8: Explore Tradespace

Tear Tradespace - all designs (n=2268)



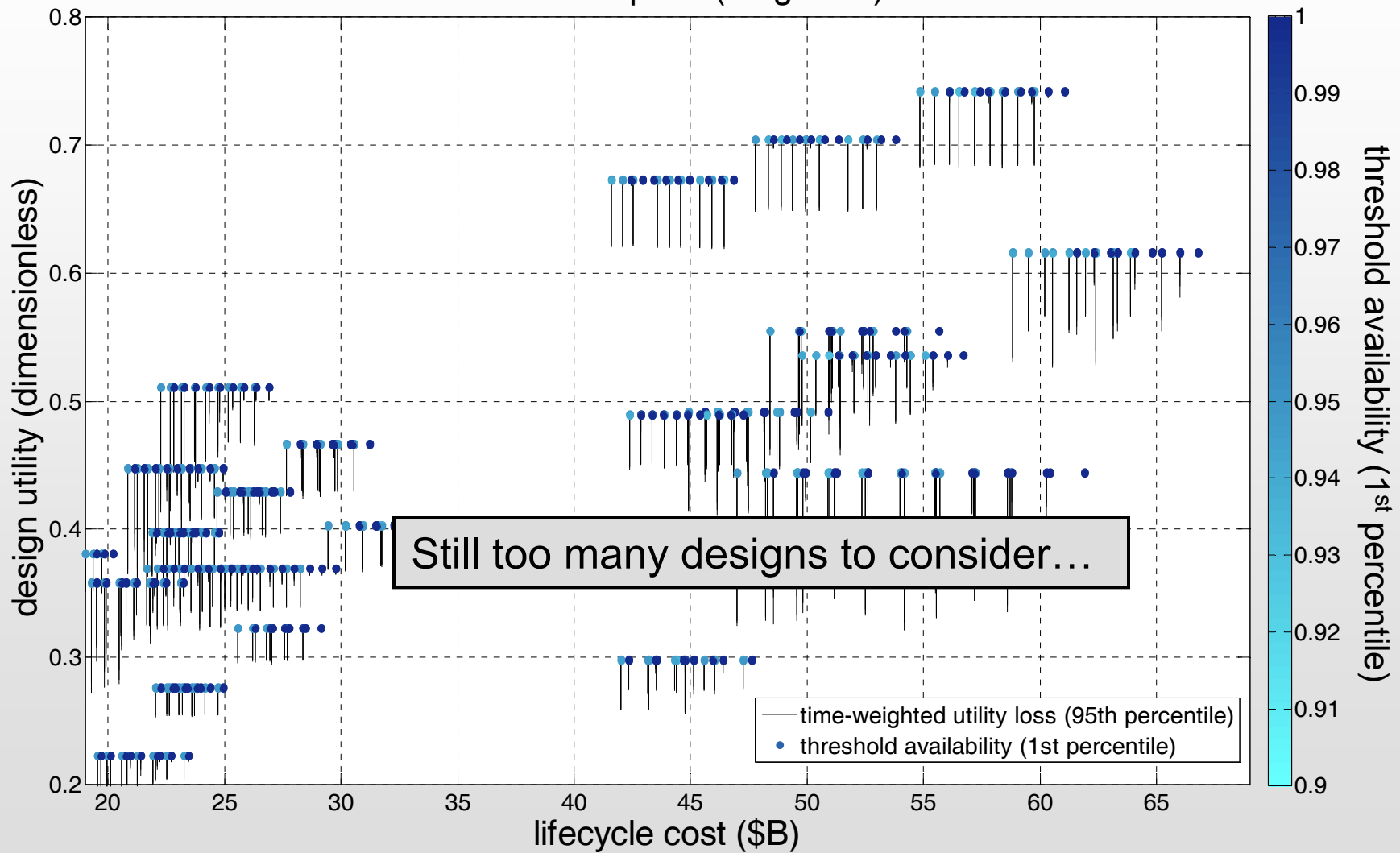
# Magnify Tear Tradespace

Tear Tradespace (magnified)



# Magnify Tear Tradespace

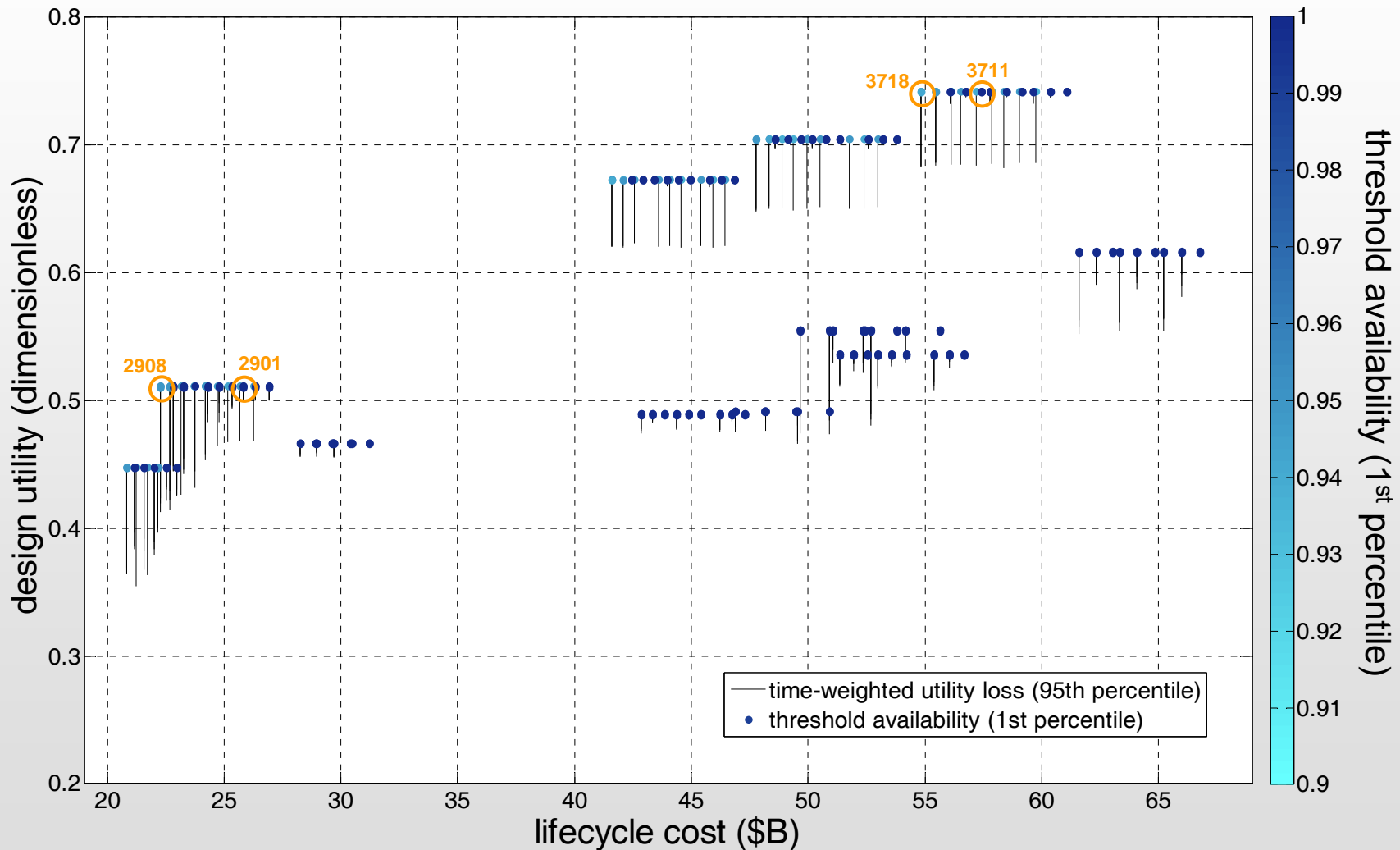
Tear Tradespace (magnified)





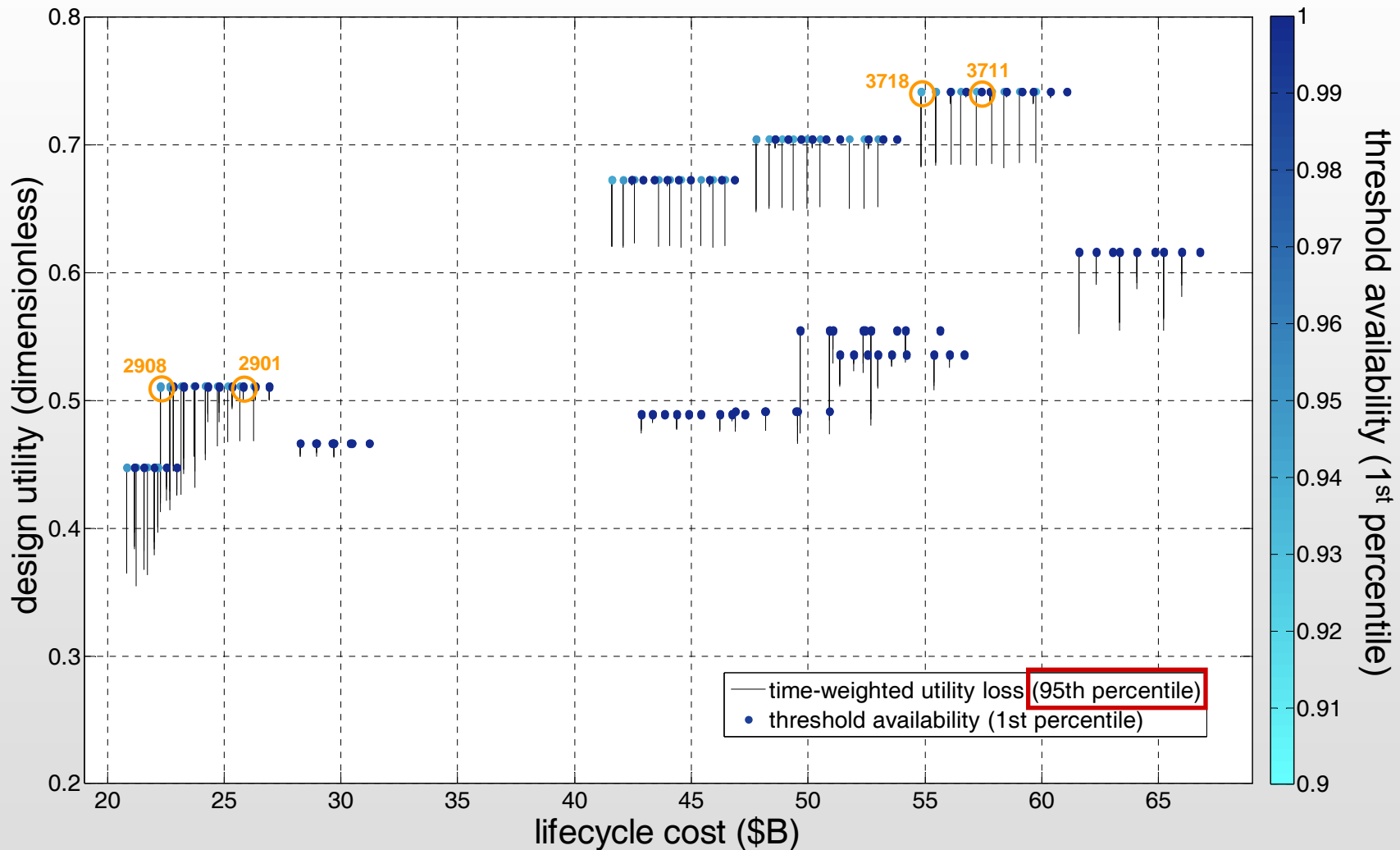
# Identify Pareto-Efficient Surface of Cost, Utility, and Survivability

Pareto Efficient Set for Cost, Utility, Utility Loss, and Threshold Availability (magnified)



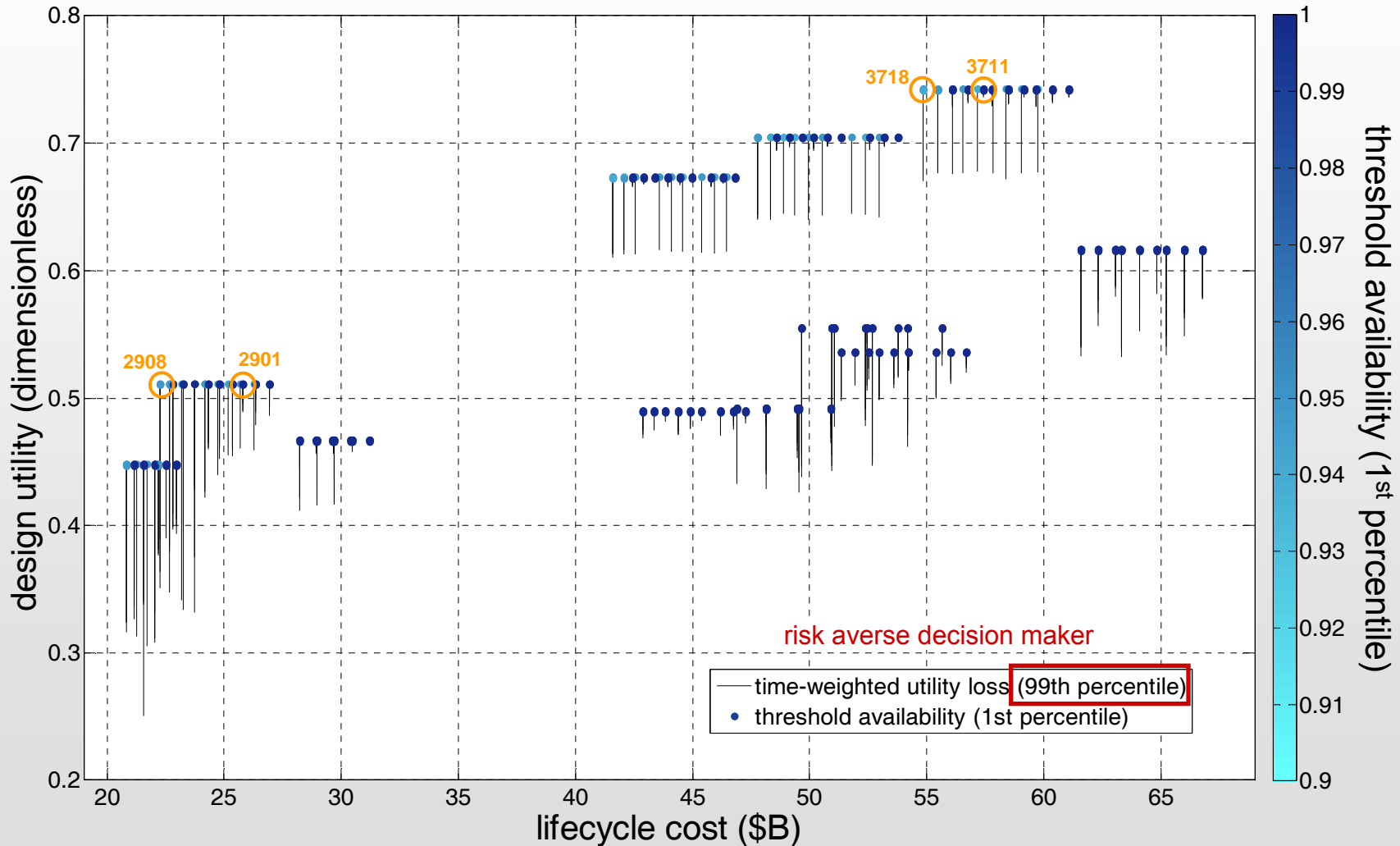
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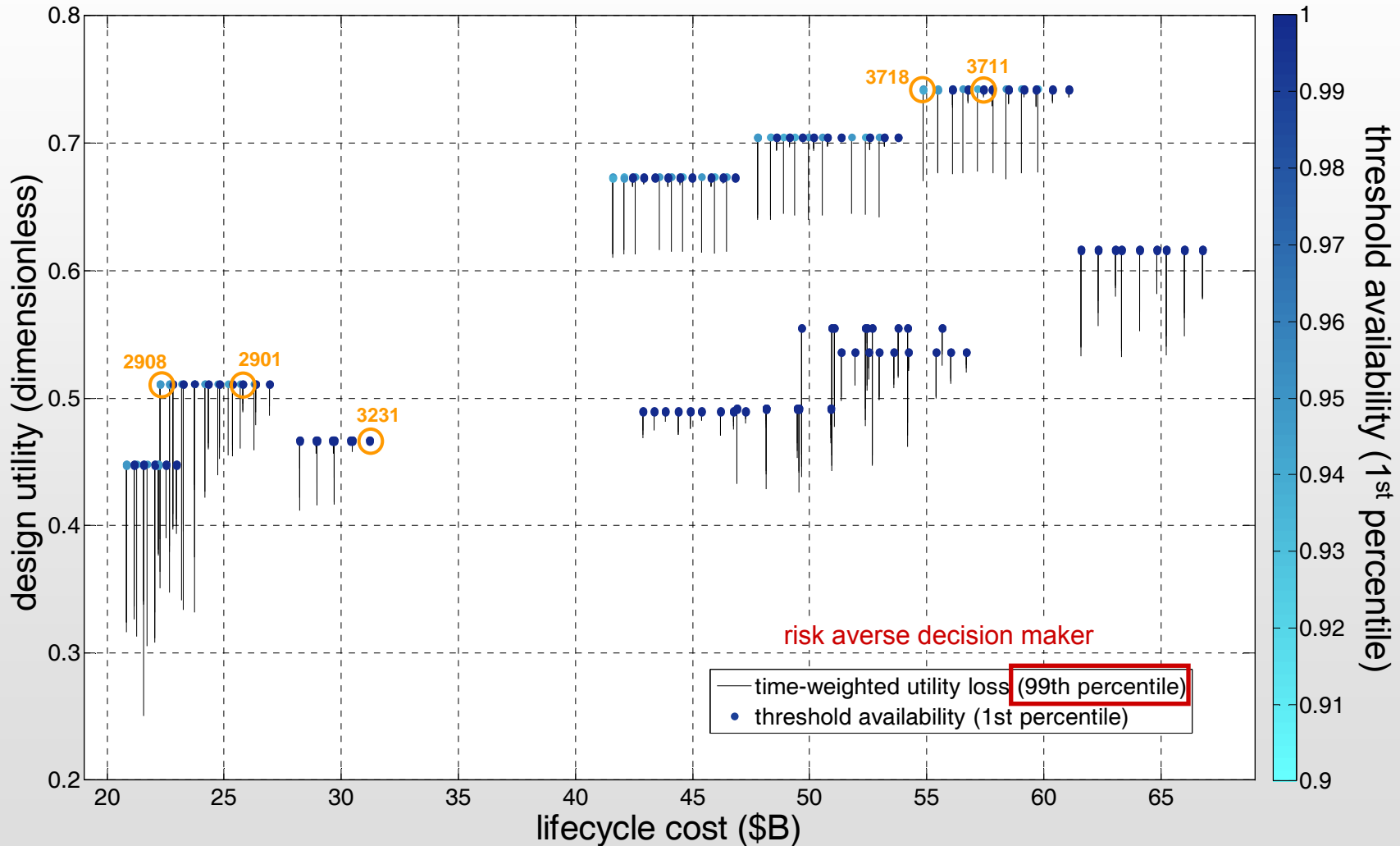
# Select Interesting Point Designs

Pareto Efficient Set for Cost, Utility, Utility Loss, and Threshold Availability (magnified)

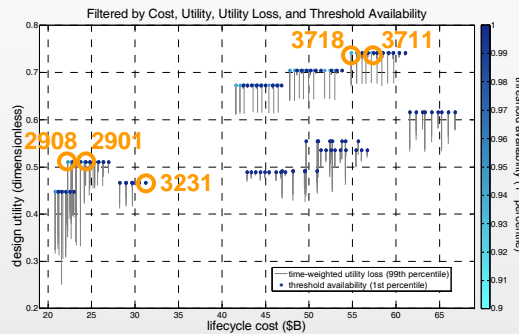
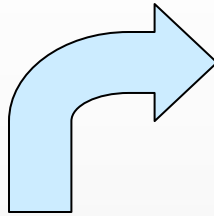


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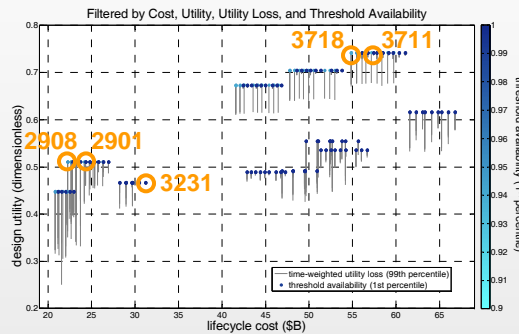
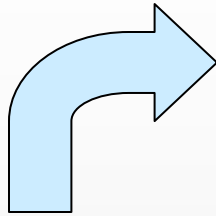
# Extract Survivability Insights from Selected Point Designs



Design Vector ID	2908	2901	3231	3718	3711
orbit altitude (km)	1500		1500		
Walker constellation	9/3/2	9/3/2	27/3/1	66/6/5	66/6/5
transmit frequency (GHz)	10		10		
antenna area (m <sup>2</sup> )	100	100	40	40	
antenna type	AESA			AESA	
radar bandwidth (MHz)	2000		2000		
peak transmit power (kW)	20		20		
tugable	no			no	
comm. architecture	direct	relay	relay	direct	relay
tactical link	yes			yes	
shield thickness (mm)	1	1	10	1	
satellite spares	0	2	2	0	2
lifecycle cost (\$B)	22.3	25.8	31.2	54.8	57.4
utility	0.51	0.51	0.47	0.74	0.74
utility loss (95th)	0.09	0.01	0.00	0.06	0.00
utility loss (99th)	0.12	0.02	0.00	0.07	0.01
threshold availability (1st)	0.95	1.00	1.00	0.95	1.00

- Survivability insights from selected point designs
  - Relay backbone critical for achieving continuous threshold availability
  - Investing in spare satellite(s) minimizes utility losses
  - Satellite shielding has limited impact in nominal debris environment
  - Distributed constellation mitigates worst-case risks

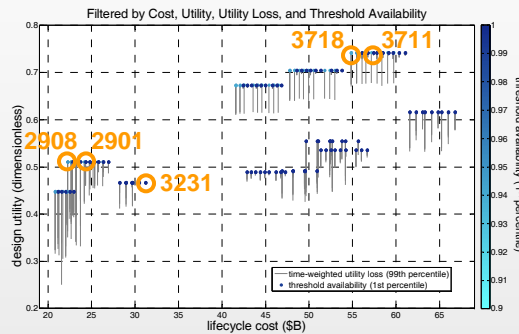
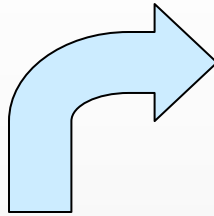
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# Methodological Insights

MATE for Survivability ***incorporates survivability as a decision metric*** into conceptual design

- Design principles reveal latent survivability trades and inform selection of survivability design variables
- Survivability metrics enable discrimination among thousands of design alternatives

Implementation considerations

- Subject percentile reporting levels to sensitivity analysis
- Balance broad exploration with selected of individual point designs

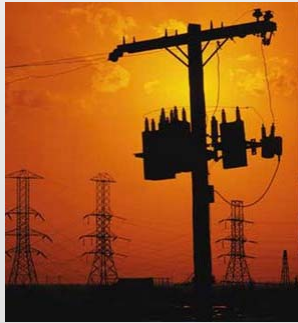
MATE for Survivability ***improves on existing tradespace approaches***

- Pareto front in traditional MATE study excludes most survivable designs
- Evaluates survivability implications for selection of baseline architecture



# Future Work

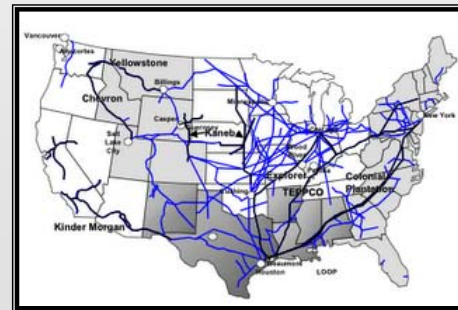
- Methodological improvements
  - Parameterize concept-of-operations in design vector
  - Extend scope for systems-of-systems (SoS) engineering
- Apply MATE for Survivability to additional systems for prescriptive insights



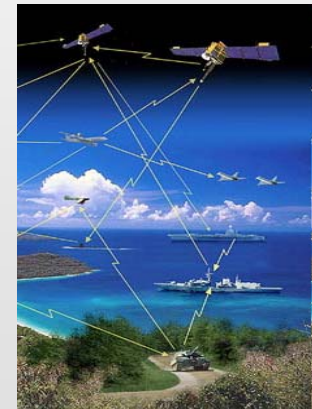
*power distribution*



*transportation*



*water distribution*



*communications*



**Systems Engineering Advancement Research Initiative**

Questions?

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