Systems Engineering Advancement Research Initiative

Metrics for Evaluating Survivability in Dynamic Multi-Attribute Tradespace Exploration

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Outline

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2. Survivability Definition
3. Survivability Metrics
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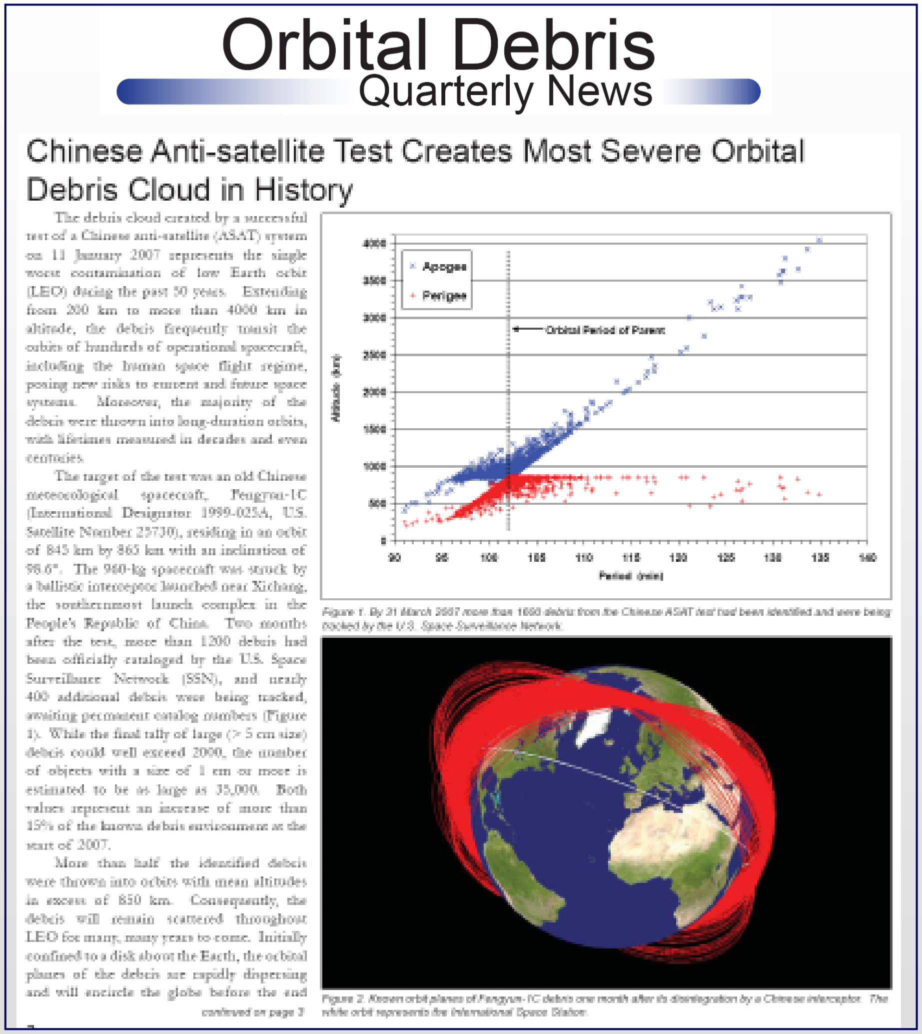
4. Application of Proposed Metrics
   A. *Dynamic Tradespace Methodology*
   B. *Design Problem: Space Tug Survivability*
   C. *Results*
5. Discussion
6. Conclusion

Motivation for Survivability


Orbital Debris
Quarterly News

Chinese Anti-satellite Test Creates Most Severe Orbital Debris Cloud in History

The debris cloud created by a successful test of a Chinese anti-satellite (ASAT) system on 11 January 2007 represents the single worst contamination of low Earth orbit (LEO) during the past 50 years. Extending from 200 km to more than 4000 km in altitude, the debris frequently transit the orbits of hundreds of operational spacecraft, including the human space flight regime, posing new risks to current and future space systems. Moreover, the majority of the debris were thrown into long-duration orbits, with lifetimes measured in decades and even centuries.

The target of the test was an old Chinese meteorological spacecraft, Fengyun-1C (International Designator 1999-025A, U.S. Satellite Number 25730), residing in an orbit of 845 km by 865 km with an inclination of 98.6°. The 960-kg spacecraft was struck by a ballistic interceptor launched near Xichang, the southernmost launch complex in the People's Republic of China. Two months after the test, more than 1200 debris had been officially cataloged by the U.S. Space Surveillance Network (SSN), and nearly 400 additional debris were being tracked, awaiting permanent catalog numbers (Figure 1). While the final tally of large (> 5 cm size) debris could well exceed 2000, the number of objects with a size of 1 cm or more is estimated to be as large as 35,000. Both values represent an increase of more than 15% of the known debris environment at the start of 2007.

More than half the identified debris were thrown into orbits with mean altitudes in excess of 850 km. Consequently, the debris will remain scattered throughout LEO for many, many years to come. Initially confined to a disk about the Earth, the orbital planes of the debris are rapidly dispersing and will encircle the globe before the end

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Figure 1. By 31 March 2007 more than 1600 debris from the Chinese ASAT test had been identified and were being tracked by the U.S. Space Surveillance Network.

Figure 2. Known orbit planes of Fengyun-1C debris one month after its disintegration by a Chinese interceptor. The white orbit represents the International Space Station.

1. Growth of military and commercial dependency on space systems

    (Gonzales 1999; GAO 2002; Ballhaus 2005)

2. Identified vulnerabilities in the U.S. space architecture

    (Thomson 1995; Rumsfeld, Andrews et al. 2001; CRS 2004)

3. Proliferation of threats

    (Rumsfeld, Andrews et al. 2001; Joseph 2006)

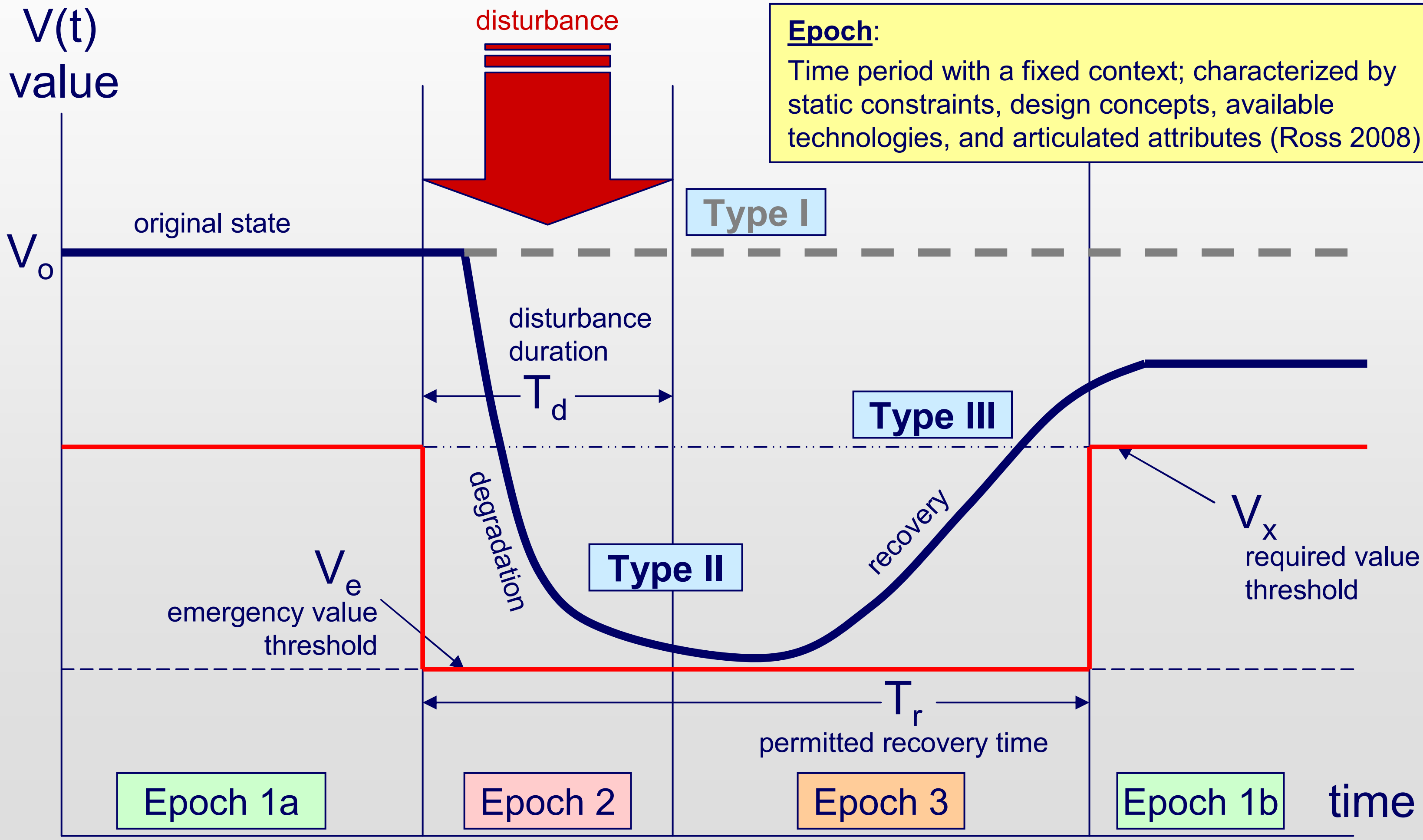
4. Weakening of the sanctuary view in military space policy

    (Mowthorpe 2002; O'Hanlon 2004; Covault 2007)

Definition of Survivability

Ability of a system to minimize the impact of a finite-duration disturbance 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) timely recovery

Epoch: Time period with a fixed context; characterized by static constraints, design concepts, available technologies, and articulated attributes (Ross 2008)



Source: Richards, M., Hastings, D., Rhodes, D., and Weigel, A., "Defining Survivability for Engineering Systems," *5th Conference on Systems Engineering Research*, Hoboken, NJ, March 2007.

Limitations of Existing Metrics

Engagement Survivability	$P_S = 1 - P_K = 1 - P_H \cdot P_{K/H}$ S = survive, K = kill, H = hit	• Binary assessment criteria fails to internalize graceful degradation
Campaign Survivability	$CS = (P_S)^N = (1 - P_K)^N$ N = number of engagements	• Binary assessment criteria • Assumes independence among shot and mission outcomes
Reliability Function (aka Survival Function)	$R(t) = 1 - F(t) = e^{t/MTBF}$ t = operating time MTBF = mean time between failure	• Construct validity • Binary assessment criteria • Time to failure assumed as exponential density function
Inherent Availability	$A_i = \frac{MTBF}{MTBF + MTTR}$ MTTR = mean time to repair	• Construct validity • Binary assessment criteria
Mission Effectiveness	$MoME = A_i \cdot P_S \cdot Capability$	• Survivability preferences confounded with availability and capability

(Ball 2003; Blanchard and Fabrycky 2006)

Proposed 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 average utility

- Difference between design utility and aggregate utility loss
- Internalizes lifecycle degradation
- Based on Quality Adjusted Life Years (QALYs) in medicine*

$$\overline{U}_t = \frac{1}{T_{dl}} \cdot \int U(t)\ dt$$

*Johannesson, M. (1995). "The Ranking Properties of Healthy-Years Equivalents and Quality Adjusted Life-Years Under Certainty and Uncertainty." *International Journal of Technology Assessment in Health Care,* 11(1): 40-48.

threshold availability

- Ratio of time above critical value threshold (V_x during baseline Epoch, V_e during disturbance and recovery Epochs) to total time
- Accommodates changing expectations during disturbances

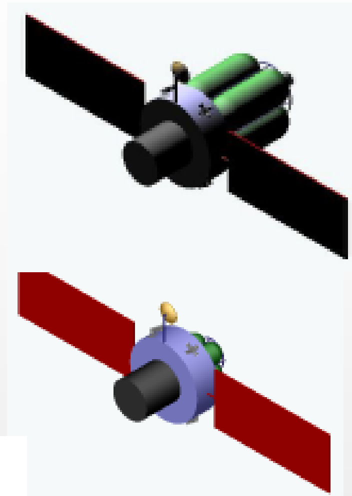
$$A_T = \frac{MTAT}{T_{dl}}$$

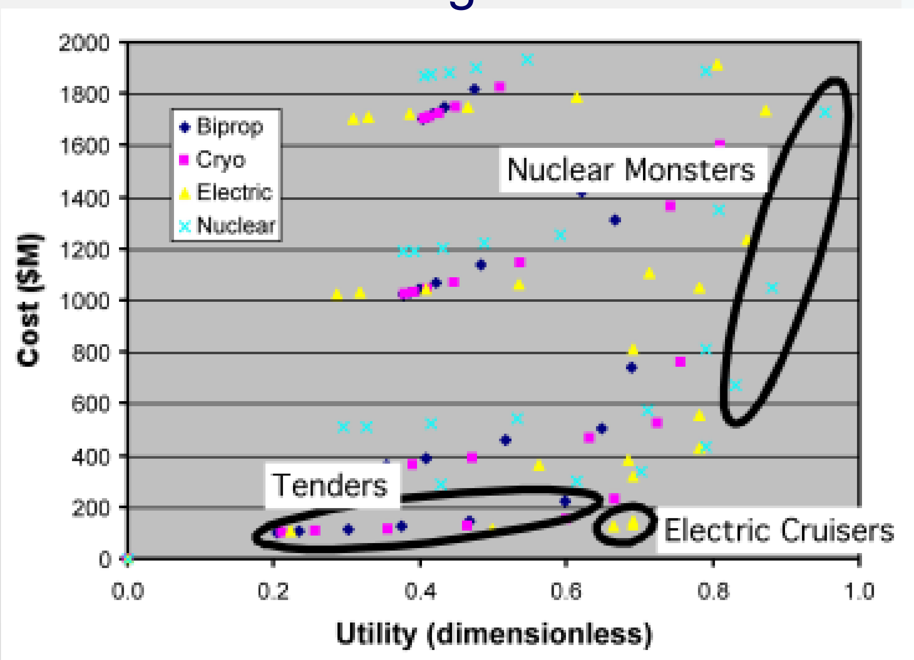
MTAT = mean time above threshold

T_{dl} = time of design life

Baseline Study: Space Tug

- Existing study of space tug tradespace*
  - Three attributes
    - Delta-V
    - Capability
    - Response time
  - Three design variables





Design Space

>Manipulator Mass
- Low (300kg)
- Medium (1000kg)
- High (3000 kg)
- Extreme (5000 kg)

>Propulsion Type
- Storable bi-prop
- Cryogenic bi-prop
- Electric (NSTAR)
- Nuclear Thermal

>Fuel Load - 8 levels

- Simple performance model
  - Delta-V → rocket equation
  - Binary response time
  - Capability solely dependent on manipulator mass
  - Cost calculated from vehicle wet and dry mass

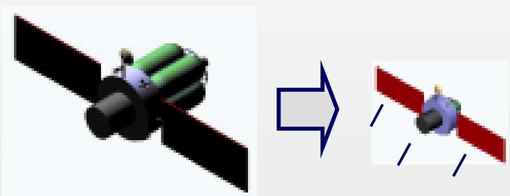
* McManus, H., and Schuman, T., "Understanding the Orbital Transfer Vehicle Tradespace," AIAA-2003-6370, Sept. 2003.

Adding Survivability to Design

Type I

Susceptibility reduction

- Active collision avoidance
- Reduced cross-sectional area (derived)

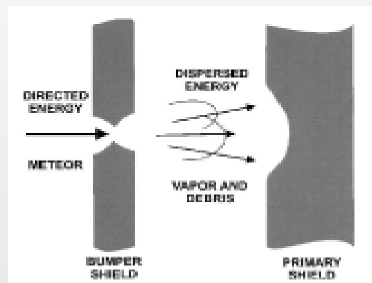


45 m^2 5 m^2

Type II

Vulnerability reduction

- Bumper shielding
- Increased capability margin (derived)



(Lai 2002)

Type III

Resilience enhancement

- On-orbit servicing insurance for timely repair

Design Variables

Manipulator Mass
Low (300kg)
Medium (1000kg)
High (3000 kg)
Extreme (5000 kg)

Propulsion Type
Storable bi-prop
Cryogenic bi-prop
Electric (NSTAR)
Nuclear Thermal

Fuel Load (kg)
30
100
300
600
1200
3000
10000
30000

Shield Mass (kg)
30
100
300
500
1000

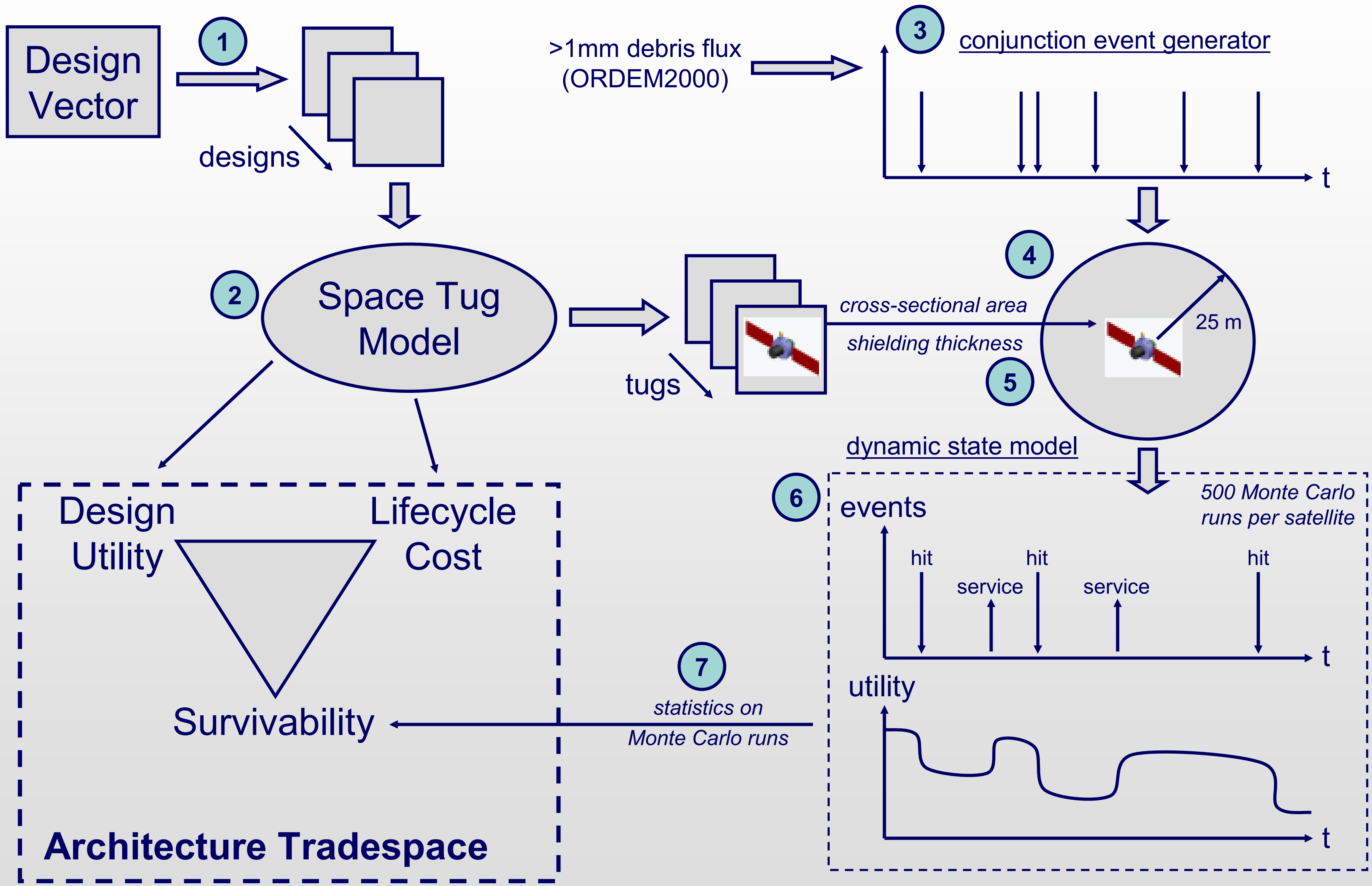
Servicing
no
yes

Collision Avoidance
no
yes

survivability features

1 of 2560 possible design vectors (full-factorial)

Model Overview

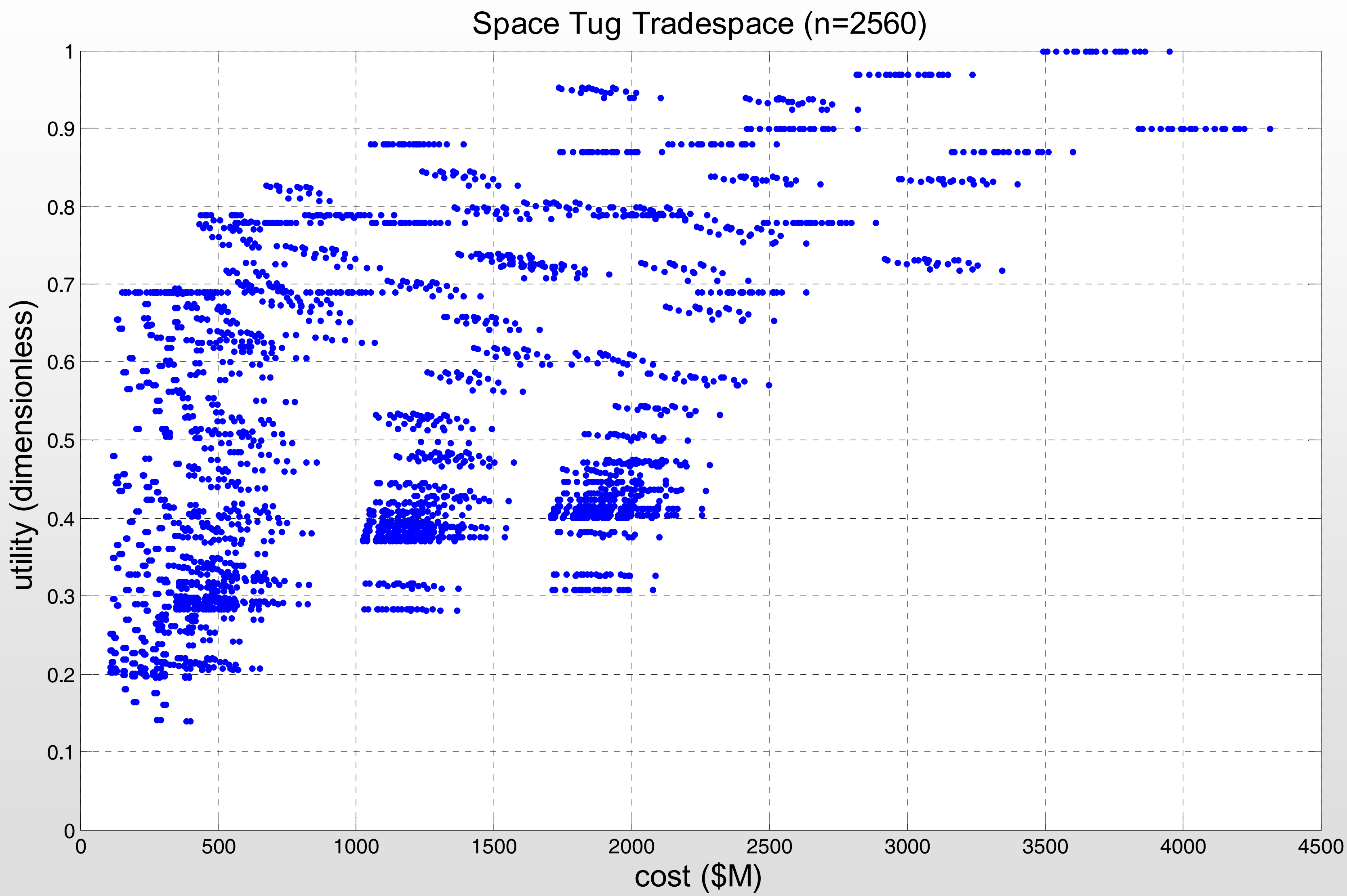


Impact Outcomes

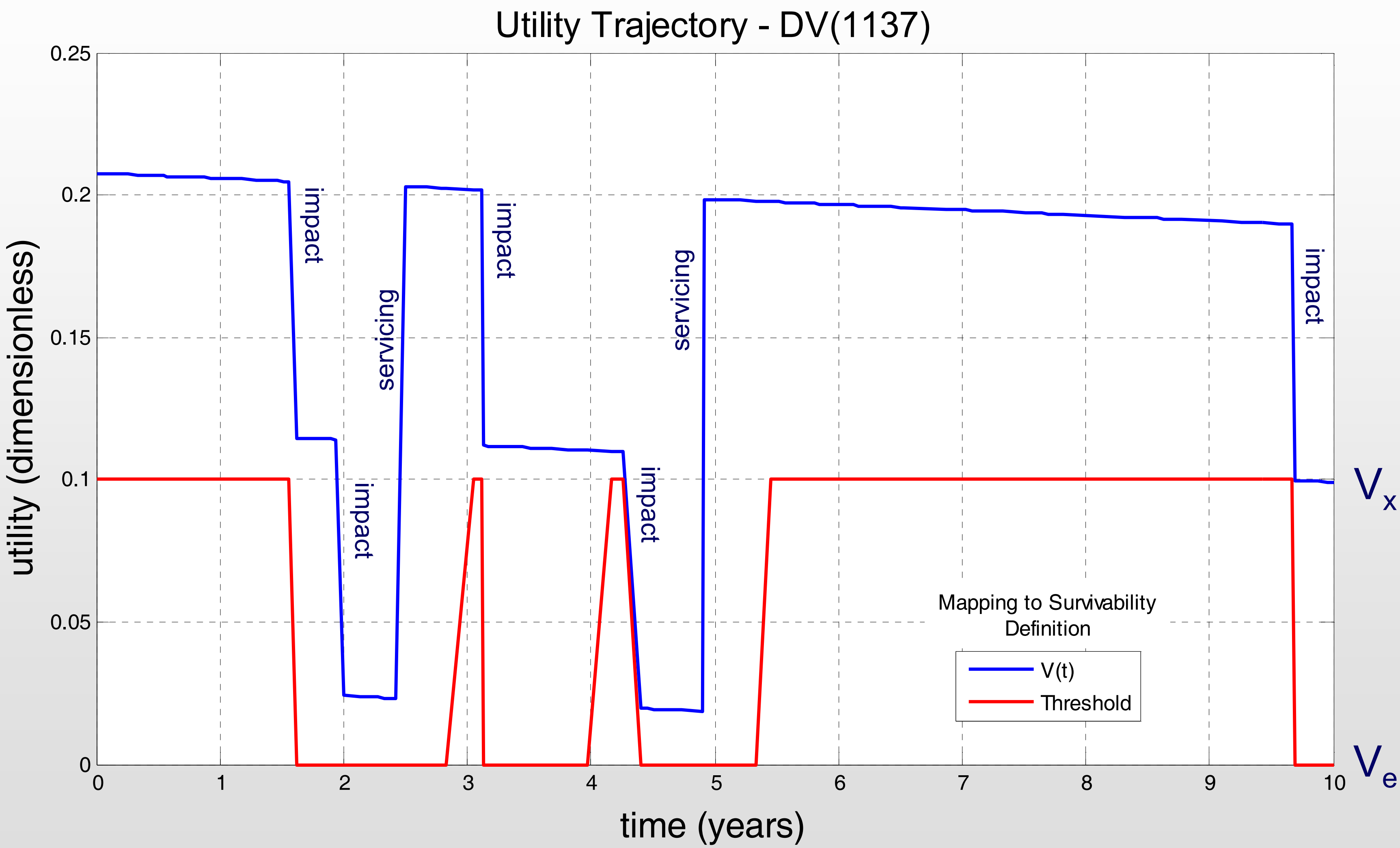
debris diameter	1 mm ⟵ x cm ⟶ 10 cm micro	small	medium	large
impact outcome (Remo 2005)	degradation	damage	severe damage	satellite loss
modeling assumption (7 km/s)	no impact	10% chance of loss in capability level	loss in capability level	end-of-life / collision avoidance with 99% success

- Threshold between satellite degradation and loss regime, x cm, is a function of bumper thickness
- Bumper thickness is a function of shield mass design variable and satellite body area

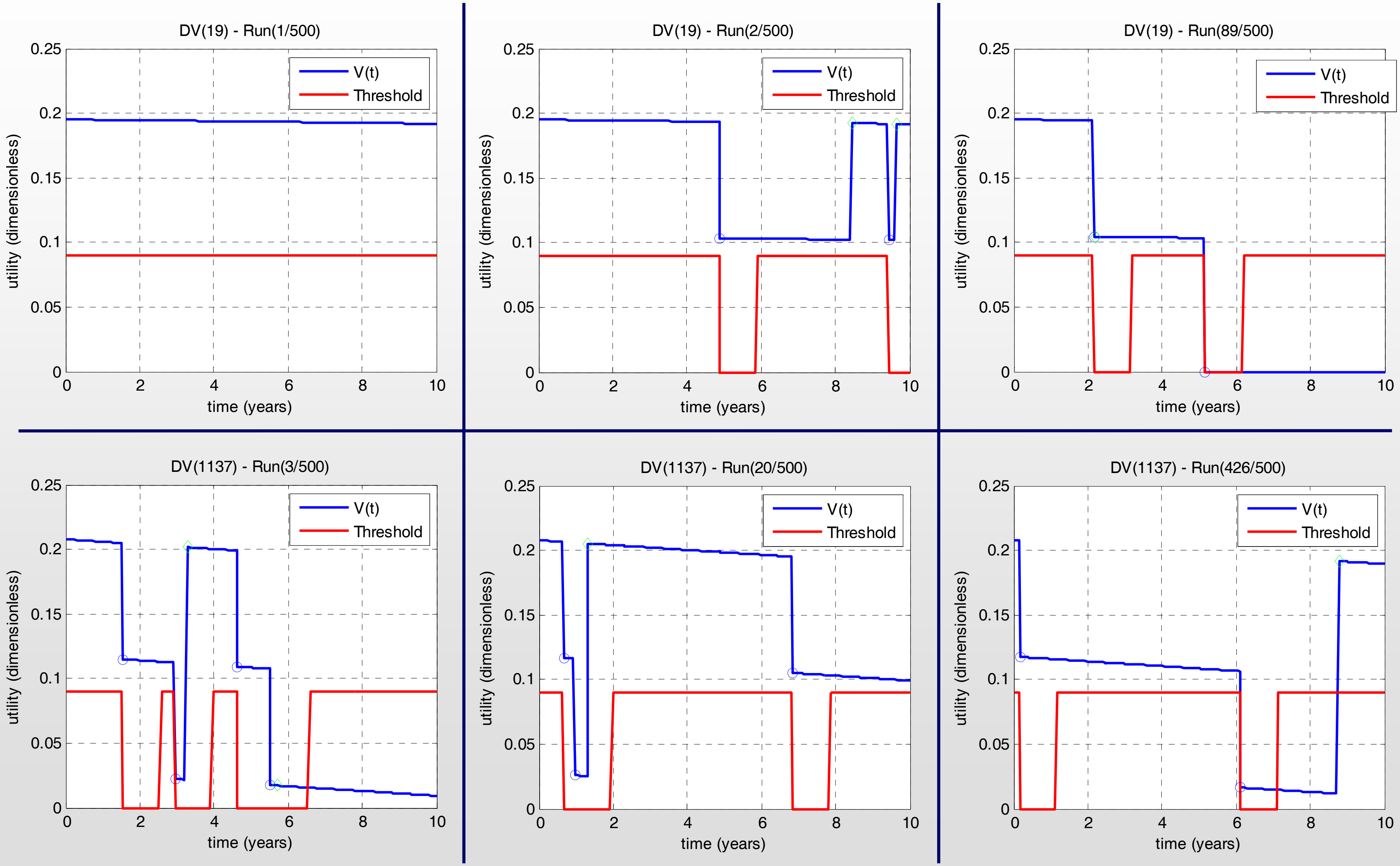
Baseline Tradespace



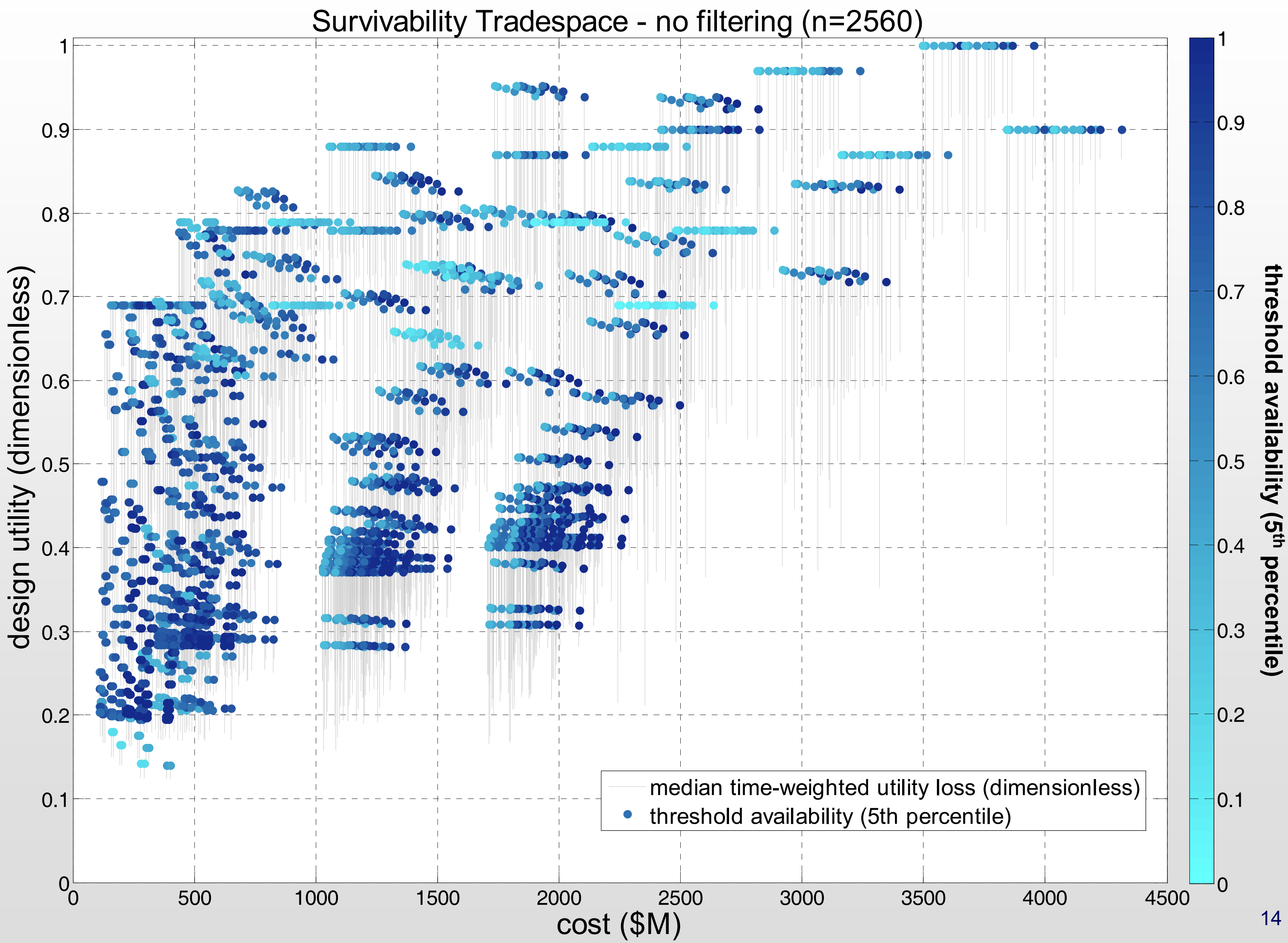
Utility Trajectory Provides Data for Dynamic Survivability Assessment



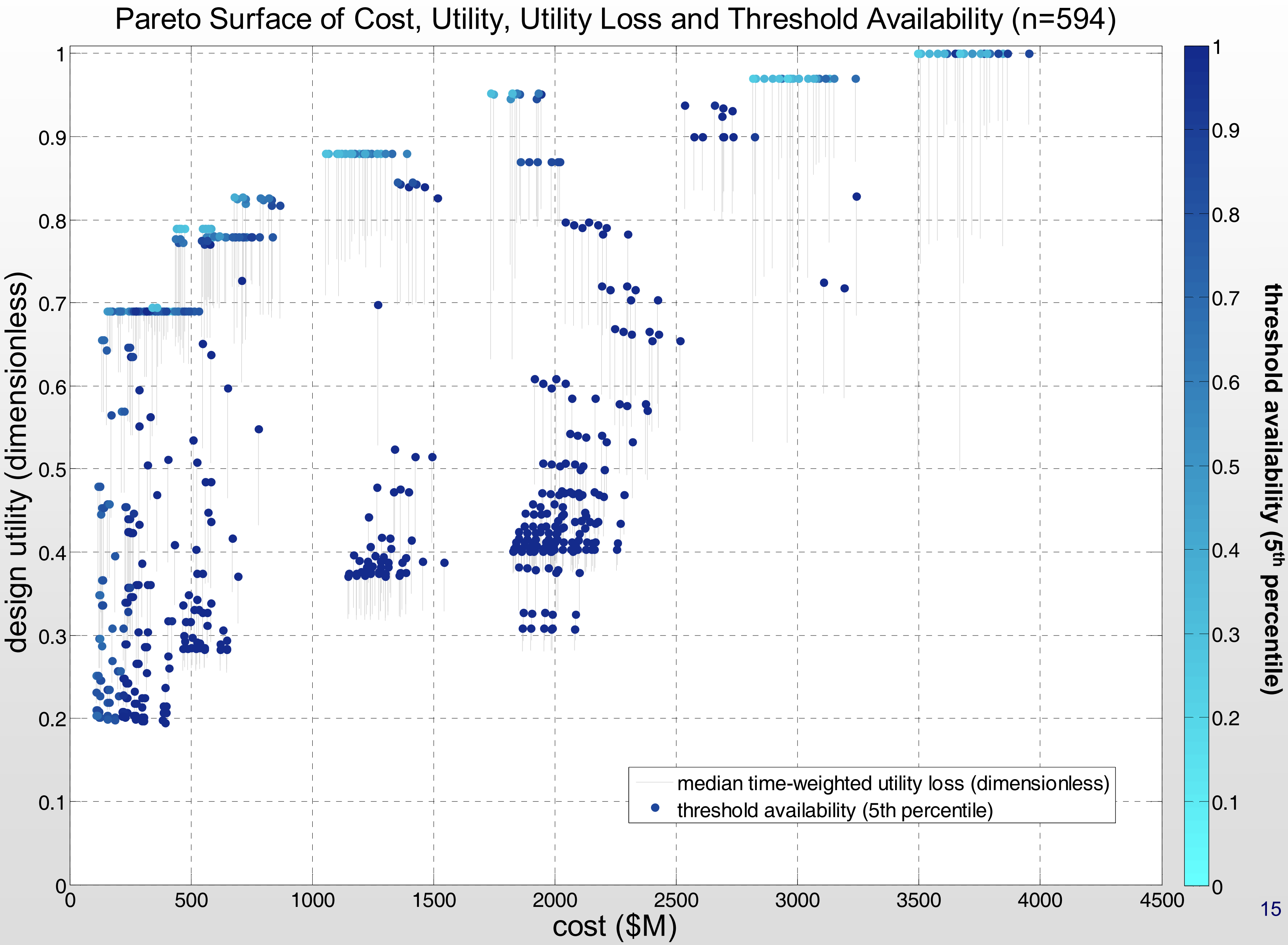
Need Measures of Central Tendency Across Runs



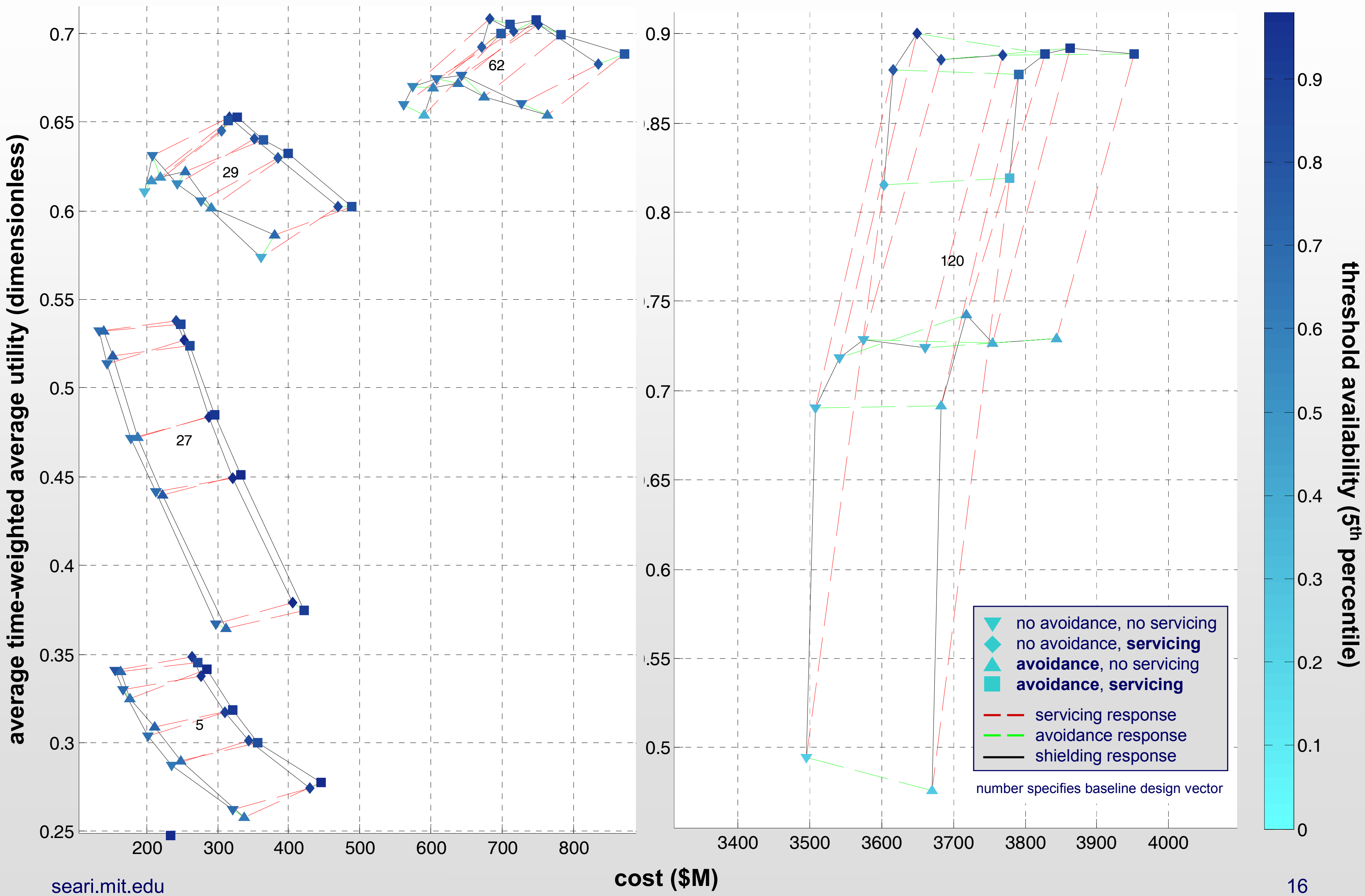
Survivability Tear Tradespace



Pareto Surface (Filtered)



Survivability Response Surfaces



Insights from Model

- Criticality of survivability derived from baseline design
  - Impact sometimes greater than dedicated survivability design variables
- Results highly sensitive to damage model
- Many highly survivable designs only slightly dominated in terms of cost and utility
  - Traditional Pareto-optimal designs exhibit poor survivability
  - Pareto surface of cost, utility, utility loss, and threshold availability increases size of optimal set by factor of 5
- Mixed impact of survivability design variables
  - Moderate shielding valuable only for mid-range and large tugs
  - Avoidance appropriate for only most risk-averse decision maker
  - Servicing has large positive impact

Conclusion

- Survivability engineering critical for U.S. space architecture
- Proposed metrics to operationalize dynamic, continuous, and value-centric definition of survivability
- Demonstrated metrics in dynamic tradespace study
- Developed survivability “tear” tradespace for integrated evaluation with cost and utility
- Future opportunities to improve model fidelity and incorporate environmental path-dependencies

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Questions?