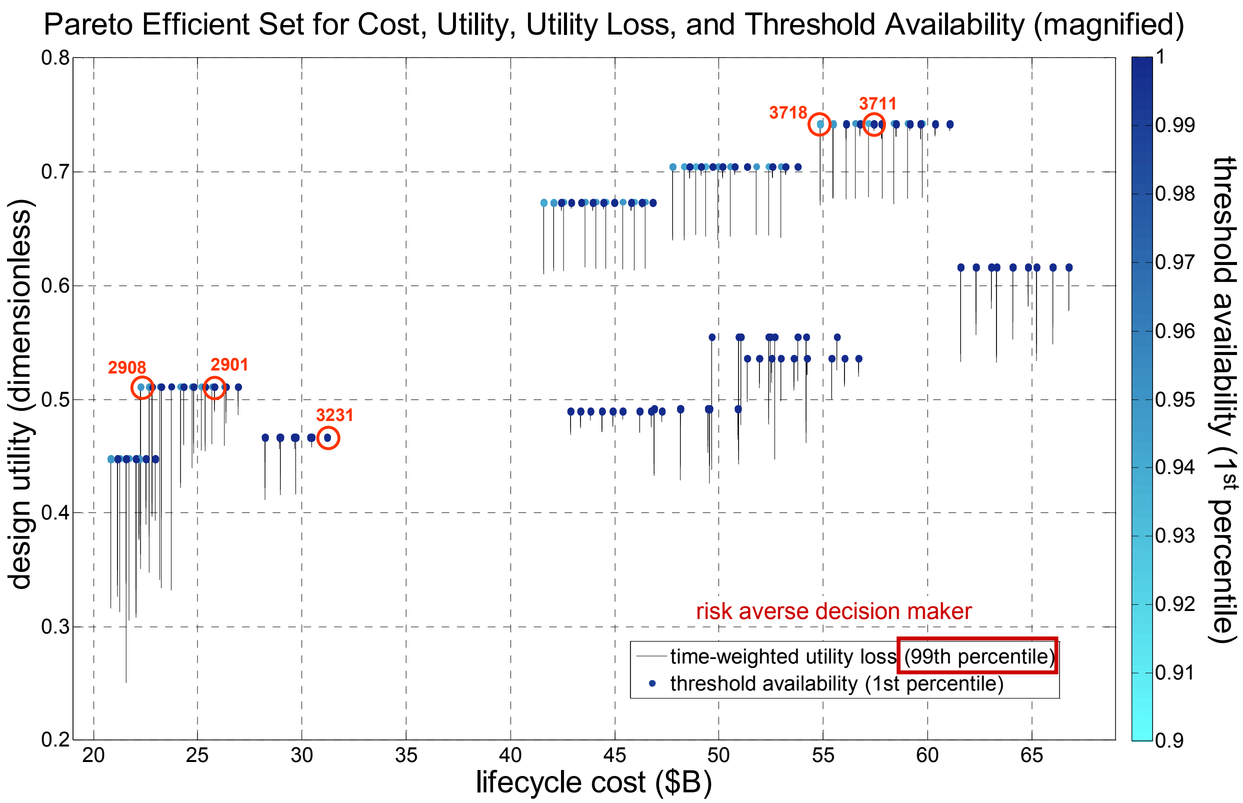

Figure 7. Magnified and Filtered Survivability Tear Tradespace - Risk Averse Decision-maker

Figure 7 applies a four-dimensional filter to a magnified region of the tear tradespace (*i.e.*, high-utility designs between $20B and $65B). In particular, only designs belonging to the Pareto-efficient set of lifecycle cost, design utility, utility loss, and threshold availability are plotted. (In contrast to Figure 6 which reported utility loss at the 95th percentile, Figure 7 reports utility loss at the 99th percentile for a highly risk-averse decision-maker.) While the filtering has greatly reduced the number of designs under consideration, dozens of "optimal" design remain within this central region of the tradespace. Five designs of particular interest are circled and labeled in Figure 7 for further investigation. Two of the designs, DV(2908) and DV(3718), are selected given their location in the traditional Pareto front. The other three designs are selected given their strong performance in the traditional metrics of cost and utility while also achieving high survivability. To complement the examination of DV(2908) and DV(3718), DV(2901) and DV(3711) are selected as alternatives within the same constellation cluster that exhibit better survivability performance. In addition, DV(3231) is selected as a highly survivable alternative located in the interior region.

Table 8. Properties of Circled Design Vectors in Figure 7

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^2)	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

Table 8 shows the design variable inputs and decision metric outputs of the satellite radar model for the five designs of interest. The designs are divided into two groups, with DV(2908), DV(2901), and DV(3231) located in the lower-left of the Pareto region, and DV(3718) and DV(3711) located in the upper-right region. Comparing columns allows explicit trades to be made between cost and survivability. For example, selecting DV(2901) in lieu of DV(2908) increases cost by $3.5B (through the addition of a relay communications system and the purchase of two satellite spares) but reduces utility loss to 0.01 and increases threshold availability to 1.00. Similarly, the additional $3.6B cost of DV(3711) reduces utility loss to effectively zero and increases threshold availability to 1.00.

Rather than improving the survivability of a Pareto front design (*i.e.*, optimal in terms of lifecycle cost and design utility) exclusively through survivability enhancements, substituting DV(3231) for DV(2908) also improves survivability through the benefits afforded by a different system architecture. Although located close to the cost and utility values of DV(2908), DV(3231) has a different constellation structure consisting of more numerous, less-capable satellites. In particular, the Walker constellation is increased from 9/3/2 to 27/3/1, and the antenna area of each satellite is decreased from 100 to 40 m^2. The more distributed constellation structure combined with the investments in shielding and satellite spares yields a design that is highly survivable to even the most risk-averse decision-maker

While the primary goal of the tear tradespaces is to identify designs that achieve a good balance of cost, utility, and survivability, the preceding analysis also yielded prescriptive insights regarding the impact of the survivability design variables on a couple of point designs. Given that the fundamental goal of tradespace exploration is to gain a broad understanding of the design space, this analysis on two point designs is applied to the entire tradespace through the construction of survivability response surfaces.

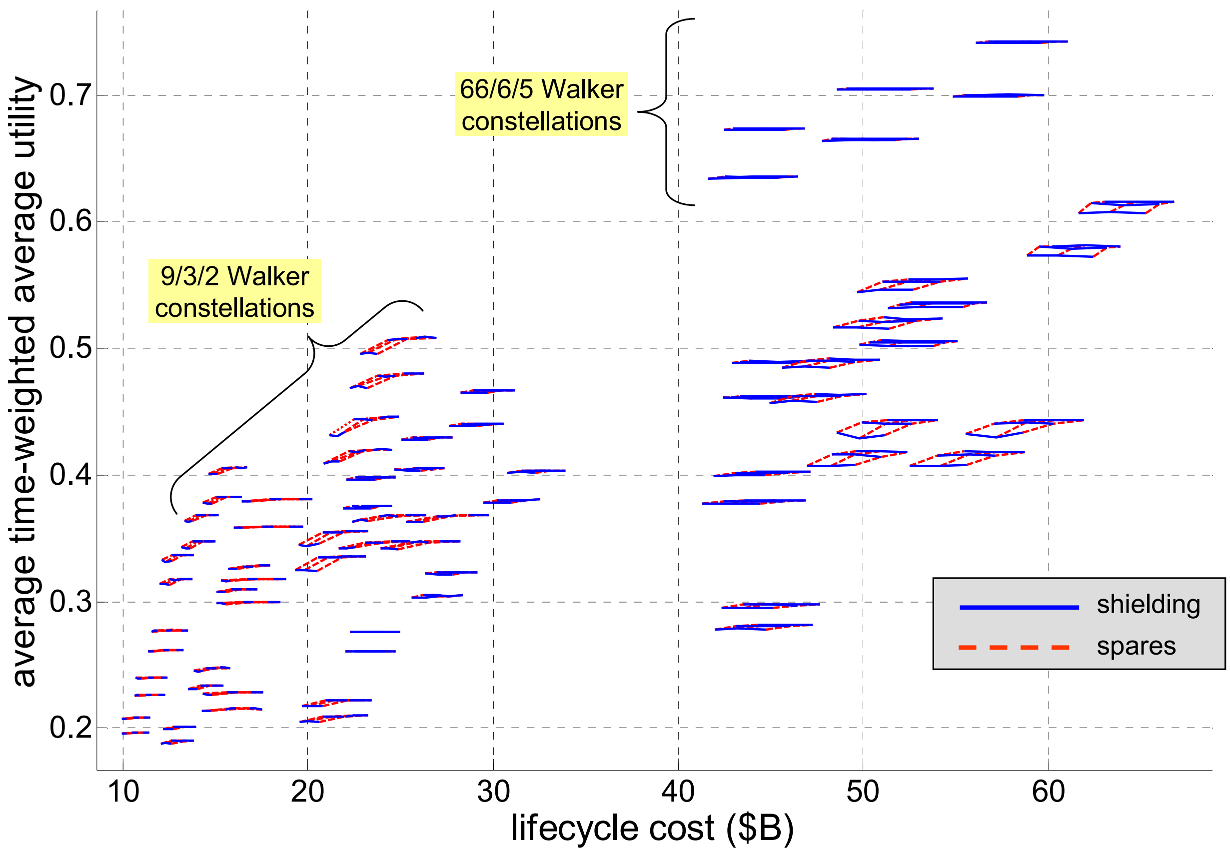

Figure 8. Survivability Response Surfaces for Satellite Radar

Figure 8 shows survivability response surfaces for each of the baseline designs. Each design point is located in terms of cost and average time-weighted average utility *(i.e.*, average value of time-weighted average utility over all Monte Carlo trials). Linked clusters indicate a common baseline design of constant Walker constellation type, altitude, antenna area, peak transmit power, and communications architecture. Each cluster consists of nine points, representing the full range of possible combinations of the two survivability design variables. The impact of survivability features may be observed by finding the lowest-cost point in each cluster to identify the baseline satellite radar design (which incorporates only 1 mm of shielding and no spares). Then, the response surfaces for shielding and spares may be viewed by examining the solid and dashed lines, respectively.

General prescriptive insights may be extracted from Figure 8 regarding the impact of shielding and sparing on the average utility achieved by design alternatives. Whether increasing to 5 mm or 10 mm, shielding universally adds cost but offers limited survivability benefits given the natural debris flux present in the orbits under consideration. The response surfaces for constellation spares are more interesting, revealing variable impact of the purchase of one or two additional satellites on average utility. For example, in the lower-left Pareto region of the tradespace featuring 9/3/2 Walker constellations, designs with spare satellites have higher average utility values. The impact is not linear, however, with diminishing returns associated with the purchase of the second spare. Different behavior is observed in the upper-right Pareto region consisting of 66/6/5 Walker constellations. While the same relative trend of increasing average utility with the purchase of spares may be observed under high magnification, the impact is extremely small. The response surfaces show similar behaviors in the interior region of the tradespace. With rare exceptions, shielding for natural debris adds cost with limited benefit to average utility while the impact of satellite spares varies as a function of constellation density.

V. Discussion

Having applied MATE for Survivability to an analysis of military satellite radar, this section offers general insights for the system under investigation and for the methodology itself.

A. Satellite Radar Insights

Before providing specific insights on satellite radar, it is important to note two caveats. First, in addition to the survivability considerations that add complexity to the acquisition of any military system, attempts to acquire a military satellite radar capability over the past decade have been further characterized by fractured management, competing stakeholder needs, immature technology, and uncertain cost estimates. Therefore, the scope of this system analysis addresses only one part of what would be a complex development program. Second, cost estimation and performance modeling of complex system can only be conducted at low to medium fidelity during conceptual design. The results, accordingly, reveal broad trends and provide general insights. The results may be valuable for a comparative analysis to guide the selection of a few promising alternatives for more detailed design (provided that there is agreement with the elicited value proposition). However, it would be unwise to associate certainty with any of the projected cost, utility, and survivability values.

From the baseline performance modeling, the satellite radar case application revealed an extremely broad tradespace, with alternative designs varying in cost by an order-of-magnitude. Performance in the six GMTI attributes varied tremendously as a function of Walker constellation, power-aperture product of the radar sensor, and downlink options.

Given the results from the dynamic tradespace model, the satellite radar alternatives are survivable to the space environment (of orbital debris and signal attenuation). The survivability metrics applied to the utility trajectory outputs indicate that the enumerated constellations are able to meet the acceptability criteria for GMTI as specified in the utility functions. While time-weighted average utility is reduced following satellite losses in small and medium sized constellations, the reductions are small and the distributions of threshold availabilities remain above 90% at even the 1st percentile. However, when applied to sparse constellations, this finding is sensitive to changes in the decision-maker's acceptability ranges for target acquisition time and track life.

Although the satellite radar constellations are found to be survivable, the tear tradespace analysis shows that the rank-order preferences of the decision-maker on alternatives are subject to change when environmental disturbances are taken into account. By adding time-weighted average utility and threshold utility as additional decision metrics, designs in the interior region of the tradespace join the Pareto front designs in the "optimal" set. Resolution of these integrated cost, utility, and survivability trades requires dialogue with the decision-maker.

The tradespace model yielded several insights regarding the cost and survivability implications of the design variables. Counterintuitively, maximizing survivability design variable levels (and hence constellation cost) does not necessarily equate to the most survivable satellite radar system. In fact, shielding is found to have a very limited impact on time-weighted average utility. In contrast, supplementing direct downlink communications with a relay option is important in the model for mitigating signal attenuation. Investments in satellite spares have a variable impact, with sparse constellations benefitting the most from the option to rapidly reconstitute. There are diminishing returns, however, when purchasing additional spares.

Most interestingly, survivable designs that are most insensitive to decision-maker risk preferences (*e.g.*, percentile reporting level for time-weighted average utility) mitigate disturbances architecturally. The tear tradespace identified constellations that are co-located in the baseline tradespace (of cost and utility) with variable survivability performance. In particular, by sacrificing individual satellite performance and accepting moderate growth in lifecycle cost through selecting a more distributed constellation of less-capable satellites, it is possible to achieve higher levels of survivability.

B. Methodological Insights

MATE for Survivability was successfully applied to a satellite radar system. Building on a static MATE analysis, the methodology allowed survivability considerations to be incorporated into concept generation and tradespace evaluation. In concept generation, the designs principles revealed latent survivability trades in the initial design space and informed definition of a new design vector incorporating explicit survivability enhancements. In tradespace evaluation, the survivability metrics were applied to probabilistic utility trajectory outputs from a dynamic state model, enabling discrimination of thousands of design alternatives in terms of survivability.

Many recommended practices for implementing MATE for Survivability emerged from the satellite radar case application. First, given that the survivability metrics are dependent on the percentile reporting levels, it is important to examine the sensitivity of the results to the selected percentile of the distribution (*e.g.*, stability of set of designs on four-dimensional Pareto surface when reporting time-weighted average utility loss at the 95^{th} and 99^{th} percentiles). Second, the broad insights that may be derived from the design variable impact tradespaces, tear tradespaces, and response surfaces, should be complimented by querying individual point designs. Close inspection of individual designs (including design variables, intermediate variables, calculated attributes, and performance metrics) allows the analyst to gain a deeper understanding of the causal relationships in the performance model as well as to verify model accuracy. Third, producing the filtered tear tradespace should not mark the end of the survivability analysis but rather mark a departure point for navigating the tradespace with the decision-maker. Although the 760 designs that arise along the four-dimensional Pareto surface in the satellite radar tear tradespace[1] are less than the 2268 in the unfiltered tradespace, they are significantly more than the 198 designs along the traditional Pareto front of cost and utility. Therefore, having identified the region of optimal trade-offs among cost, utility, and survivability, it is particularly important to engage with the decision-maker in the process of selecting a small number of alternatives for more detailed design.

The application of MATE for Survivability also reinforces the benefits of the methodology relative to existing approaches. The analysis shows that that using tradespace exploration solely to identify designs on the traditional Pareto front of cost and utility excludes the most survivable designs. Furthermore, the methodology allows system-level and architecture-level survivability trades to be made in concert rather than delaying survivability considerations until after selection of a baseline system concept. As demonstrated by the response surfaces for the survivability design variables, incorporating survivability considerations into the definition of the system concept is important if the dedicated survivability design variables (*e.g.*, shielding) are less critical to achieving survivability than the fundamental system architecture (*e.g.*, constellation type). By applying the concept-neutral criteria of lifecycle cost, multi-attribute utility, and the survivability metrics, the tear tradespaces may be used to identify promising design alternatives among thousands of technically-diverse systems.

VI. Conclusions

Multi-Attribute Tradespace Exploration for Survivability seeks to address the motivation outlined in Section II by enhancing the generation and evaluation of design alternatives that maintain value delivery in the presence of finite-duration disturbances. While existing survivability engineering techniques optimize the physical survivability of individual systems, the evolution of engineering systems to higher levels of complexity necessitates architectural solutions to emerging threats. Accordingly, MATE for Survivability complements existing survivability approaches focused on detailed design trades by allowing survivability considerations to be incorporated into the selection of the baseline architectural concept. It is hoped that the survivability design principles and metrics introduced in this thesis may be applied prescriptively as analytic tools, shifting one aspect of the systems architecting process from an art to a science.

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