# Revisiting the Tradespace Exploration Paradigm: Structuring the Exploration Process

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**A number of case applications of tradespace exploration have further extended the types of analyses and knowledge insights that can be gained about tradeoffs between design choices and perceived utility and cost of alternatives. These extensions include application beyond its heritage aerospace domain to the transportation domain, comparing distinct concepts on a common tradespace, considering the impact of changing needs and contexts over time, evaluation of alternatives in a "light effort" manner. In parallel with these case applications, a formalization of the tradespace exploration process has emerged, using a question-driven approach to ensure the knowledge generated is practical and useful to decision makers. These questions are introduced and applied to three example space systems in order to illustrate insights gained in answering the questions. The insights include identifying "good" designs, the strengths and weakness of selected alternatives across a tradespace, limiting constraints and requirements that could allow for less expensive solutions. Additionally, advanced insights include understanding the sensitivities of designs to changes in contexts and needs, and consideration of the differential impact of uncertainty across a set of alternatives with potential opportunities for risk mitigation.**

## I. Introduction

The architects and designers of a complex system, or of a system of systems, have many possible design solutions to choose from, and many potential stakeholders to satisfy. Worse, they face the problem that changes in stakeholder needs, available technologies, and political and technical contexts are inevitable during the system lifetime. Five years ago, Ref. 1 summarized work on this problem and proposed a *Tradespace Exploration Paradigm*: the systematic calculation of the performance of many possible designs, evaluated against the elicited needs of multiple stakeholders, and the consideration of many possible future contexts.[1] Since then, the increasing power and decreasing cost of computing resources, the wide availability of flexible tools for creating technical models, additional tradespace exploration case studies[2,3] and analysis approaches,[4,5,6,7,8] and the ability to store and access large databases on desktop equipment have greatly facilitated the analytical aspect of the tradespace exploration paradigm. The open-ended problem of understanding multiple, preference-unstable stakeholders, and changing contexts, has been at least partly brought under control using structured processes.[9] Emerging graphical tools, some of them specifically developed for the tradespace exploration problem, have aided in the display of the resulting masses of data.[10] However, techniques used to extract the desired knowledge from the large amount of available data have lagged, while dealing with the uncertainties inherent in both the method and the typical state of knowledge in preliminary design.

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This paper will review progress towards creating a systematic method for tradespace exploration. In order to advance tradespace exploration methods, it is assumed that a database has been created using a tradespace analysis, which includes a large number of possible designs and their analyzed performances (see Fig. 1). The designs are expressed parametrically by varying the elements of a *design vector*. The performance is expressed in terms of *attributes*, metrics of interest to, and chosen by, the stakeholders. It is also assumed that some set of computational, graphical tools are available to interrogate the database.

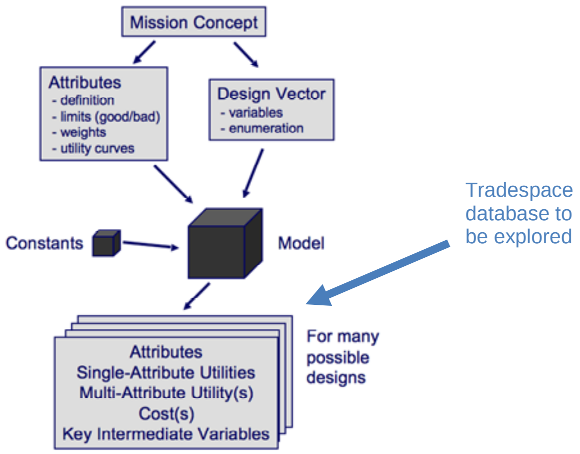

**Figure 1. Creation of a tradespace**

## II. Advances in Tradespace Exploration

Reference 1 introduced the idea of tradespace exploration as a structured means for considering a large number of design alternatives in terms of concept-neutral benefits and costs, while avoiding prematurely focusing on point solutions. Instead of identifying the "optimum" or "best" solution, the approach sought to evaluate even so-called "bad" designs in order to reveal the multi-dimensional tradeoffs inherent in a complex design problem. Typically represented as a utility-cost plot, the tradespace concisely reveals the structure of high-order benefit-cost information of many alternatives (Fig. 2). Illustrated emergent benefits of using this approach included seeing the immediate effects of changing needs, comparing point designs to alternatives in a tradespace, and the ability to readily identify both physical and preference constraints on feasible solutions. Less mature, but promising advanced uses of the tradespace included using the representation to illustrate the differential impact of uncertainty across a tradespace of alternatives, as well as differentiation of alternatives in terms of their ability to change state (i.e., "flexibility"). Application areas included using tradespaces to inform spiral acquisition, as well as to assess policy robustness of alternative solutions. Since 2005, additional research has further developed these advanced uses, as well as illustrated the ability to apply tradespace thinking to domains other than aerospace and across time.

### A. Multiple Concepts and Domains using Tradespaces

The tradespace exploration paradigm is based fundamentally on concepts from decision analysis, which is domain independent, so it was expected that the approach should apply to non-aerospace domains. A case application to transportation planning, specifically the planning of an Airport Express transit option for connecting downtown Chicago to its airport, was conducted and found to display similar benefits as seen in aerospace: preventing premature reduction of design alternatives that may provide superior value.[3,11] Additionally the approach differed from current techniques in transportation planning in that it forced the explicit linking of value propositions to alternatives, which may be obfuscated by politics, time, and misrepresentation.

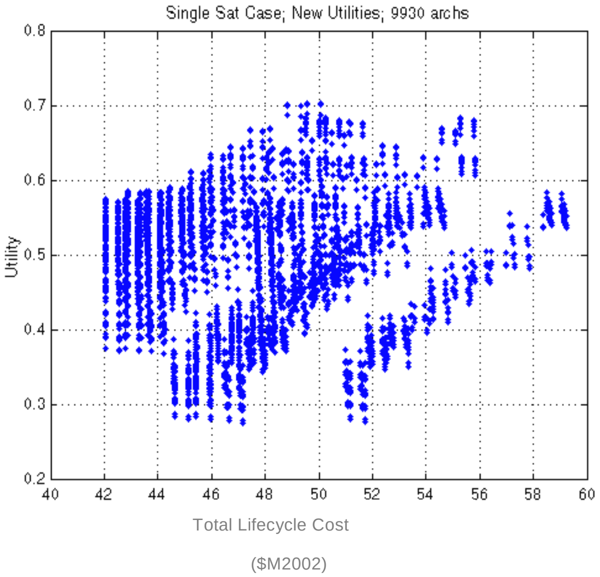

**Figure 2. Typical tradespace representation (Ref 1)**

Since tradespaces are constructed using concept-neutral criteria (perceived benefits and costs), one should be able to compare vastly different concepts on the same tradespace. A case application evaluating sensor swarms, manned-aircraft, unmanned aircraft, and spacecraft for performing an operationally responsive disaster surveillance mission was done to demonstrate cross-concept comparisons in a tradespace.[2] Figure 3 illustrates the multi-concept tradespace for the owner of the system (ORS), showing aircraft, satellites, swarms, and combinations of these assets (SoS) for achieving this mission.

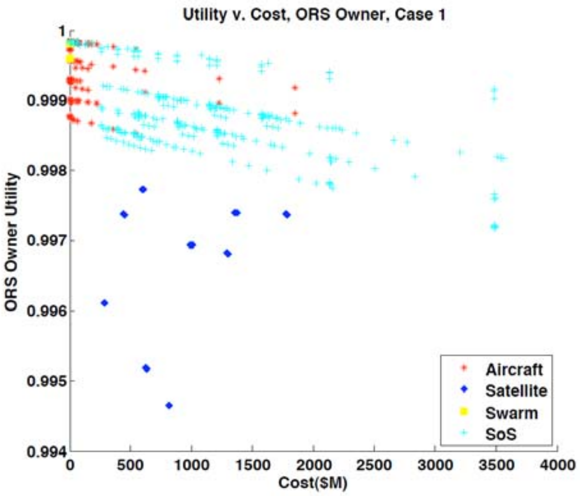

**Figure 3 Multi-concept tradespace (Ref. 2)**

## B. Tradespaces over Time

Generalizing the basic tradespace exploration approach (Multi-Attribute Tradespace Exploration, MATE), Dynamic MATE[12] relaxed assumptions regarding static preferences and constraints, adding the ability to consider changing contexts and needs (epochs) over the short and long run (eras) using Epoch-Era Analysis.[1314] Additionally, a quantification of changeability in the tradespace[4] allowed for the evaluation of a system's ability to be altered in order to respond to changing definitions of utility and cost over time. A number of metrics were developed in order to help identify "good" designs in the temporal context. These metrics fall into several categories for achieving system value robustness[15] -- maintaining system value in spite of changing contexts and needs – which include highly changeable designs (Filtered Outdegree),[4,16] and highly versatile or passively value robust designs (Pareto Trace, Normalized Pareto Trace, Fuzzy Normalized Pareto Trace).[17]

As temporal considerations entered tradespace exploration approaches, temporal system properties beyond changeability could be considered. As an example, the survivability of a system to finite duration disturbances could be determined using the value-centric, concept-neutral approach of Dynamic MATE.[18] Metrics for survivability[5] were proposed and derived through the computation of system utility trajectories across their lifecycle, illustrated through case applications to a SpaceTug system and a Satellite Radar System (SRS) mission[7].

Using the epoch construct to discretize system timelines, allowing for the calculation of tradespaces for periods of fixed contexts and needs, a series of case applications were developed including Joint Direct Attack Munition

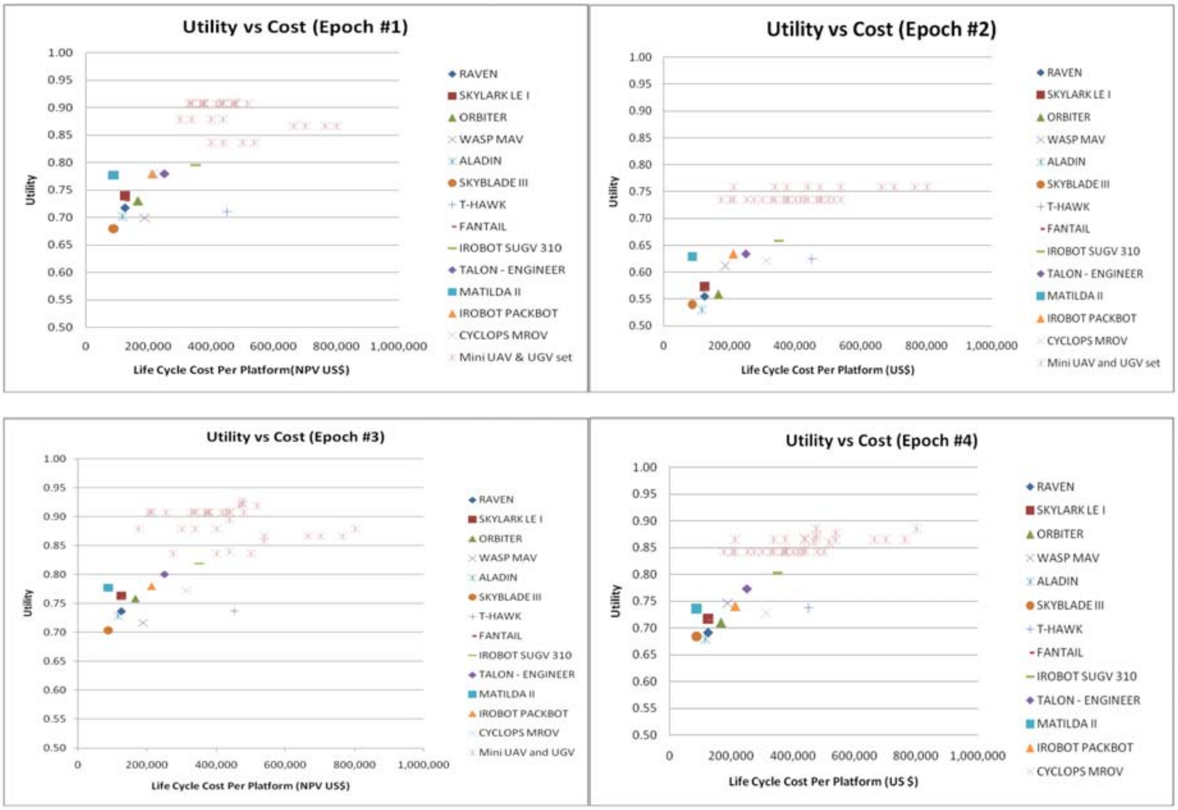

**Figure 4 Tradespaces for ISR ground and air systems, four epochs (Ref. 19)**

(JDAM),[4,12] Terrestrial Planet Finder (TPF),[4,12] and a Satellite Radar System (SRS).[7,9,14,22] Not all studies had the resources available in order to develop full tradespaces, so a "lighter" version of Epoch-Era Analysis was applied to an ISR Army System of Systems using both ground and air unmanned vehicles,[19] and to an Offshore Patrol Cutter (OPC) study for the Coast Guard.[20] Figure 4 illustrates the ISR case application results with tradespaces across four epochs, representing periods with differing stakeholder needs (i.e., utility functions).

## III. Structured Procedures for Tradespace Exploration

Parallel to the research contributions through case applications, there was an on-going effort to encapsulate tradespace exploration knowledge into a more formalized approach. Called the "Responsive Systems Comparison Method" (RSC), the method ties together insights from a decade of tradespace exploration research, including newer dynamic advancements, into a series of processes.[9,22] Given the generation of a large set of tradespace data, encapsulating a repeatable approach to generating insights, knowledge, and trust from the overall method became necessary.

In the course of tradespace exploration, both decision makers and analysts will have a series of practical questions that will be answered using this data. Emerging through the course of ten years of tradespace exploration studies, question-driven approach has shown to be a useful construct for structuring the exploration process.

When considering high-level decision makers who will make critical decisions concerning large, complex systems, the following questions provide a starting point for organizing the tradespace exploration effort:

1. Can we find good value designs?
2. What are the strengths and weaknesses of selected designs?
3. Are lower cost designs feasible? What compromises are needed to lower costs?
4. What about time and change?
5. What about uncertainty?
6. How can detailed design development be initiated in ways that maximize the chance of program success?

Procedures for answering these questions have been developed both "top down" by tradespace experts and "bottom up" by interacting with decision makers at various levels, leveraging how they think about the designs in the tradespace. These procedures have been refined through the case studies cited in this paper and Ref. 1. Considering the role of both designers and decision makers as "humans in the loop," the result is a set of suggested procedures that, while not overly prescriptive, guide the tradespace exploration analyst attempting to answer practical questions. The important application of supporting multiple stakeholder negotiations is explored in a separate paper.[21] Use of the procedures will be shown not only to quickly recreate the lessons of prior tradespace exploration work, but also to provide emergent knowledge not found in earlier ad-hoc explorations of tradespaces.

The starting point for following any of the procedures is with a tradespace database that has been populated using MATE or a similar method, as shown in Fig. 1. The relationships among the data in the database will be interrogated and explored using computational and graphical tools.[*] The tools used in this paper are summarized in Table 1 and Table 2.

**Table 1. Input and Calculation Tools**

| Name | Function |
|---|---|
| Pareto Calculator | Find the Pareto front on any plot. Multi-dimensional Pareto capability also useful. |
| Preference Input | Ability to accept changes in the Worst and Best values, and the Weights, for Attributes. Also ability to change the utility curves. |
| Preference Calculator | Ability to recalculate the single- and multi-attribute utilities using the new preferences, and use them as the basis for all of the above displays. |

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[*] For clarity, the tools will be referred to as if they were implemented as computer programs or macros, but no specific implementation will be assumed. Almost all of the tools could be implemented using an Excel® spreadsheet simply by creating a custom plot with the information desired each time the tool is needed. The particular tools used in this research were built using MATLAB® by The MathWorks™.

**Table 2. Display Tools**

| Name | Function |
|---|---|
| Tradespace Plot | Plot single- or multi-attribute utilities versus cost. Use color to represent a third dimension (e.g., design vector values). |
| Strength/Weakness Plots | Multiple plots showing physical attributes and their associated utilities, against cost or other factors. Use color for a third dimension. |
| Sensitivity Plots | Multiple plots showing sensitivities of one factor to another (e.g., attributes to design vector values). |
| Design Definition | Ability to pick a point on any of the above plots and find out what design it is associated with. |
| Favorites List | List of favored designs, with key information and a symbol or icon. Display these designs on all plots using their special symbol. |
| Comparison Table | Display and compare the physical characteristics (design vector values) and performance (attributes and utilities) of selected designs. |
| Era Viewer | Multiple plots showing a tradespace under a variety of conditions (epochs) that together represent a scenario for changes over time. |
| Era Animator | Animation of the era; a single plot that shifts as conditions change across epochs. |

Before a tradespace exploration exercise can begin, the tradespace database needs to be created. During the exploration, the explorer needs ready access to the key concepts being considered, including definitions of what is considered “good value,” and what is meant by “designs.” These concepts were defined in the course of generating the tradespace data and are reflected by the mission concept, the attributes and the design vector. Illustrations defining these key tradespace input definitions should be printed, or displayed in some other manner, so that they can be readily referenced during the exploration activity. Important definitions include:

1. a simple definition and graphic of the mission concept,
2. a list of the stakeholder attributes, with units, best desired and worst acceptable values, and swing weights. If there is more than one stakeholder, the attributes for each stakeholder need to be separately defined, with a clear description of each stakeholder’s name and value proposition, and
3. a list of the design variables that define the design vector, along with their enumeration, definitions (particularly if they are binary or listed-choice variables), and sampling strategy used to populate database.

## A. Case Study Systems

The procedures will be illustrated using case studies of existing aerospace system tradespace databases: a constellation of Satellite Radar System vehicles (SRS[22]), a single-vehicle atmospheric research satellite (X-TOS[23]), and an orbital transfer vehicle (SpaceTug[24]). These systems are briefly described here; more detail is available in the references.

X-TOS (Terrestrial Observer Satellite X) is a single-satellite science-based mission, with three instruments, that makes direct in situ measurements of Earth’s neutral atmospheric density. The stakeholder (an atmospheric physicist) cares about the data collected, which is characterized by five attributes: the lowest altitude at which data is sampled, the data lifespan, the time spent near the equator, the diversity of latitudes sampled, and the data latency (time from data collection to delivery). These attributes will be used to calculate a single attribute utility (SAU) -- converted to a scale of 0 for the worst acceptable value to 1 for the best desired, (not necessarily linearly) and aggregated (combined, taking the weights into account). The result is a measure of overall “goodness” to the stakeholder referred to as a multi-attribute utility (MAU). The X-TOS design variables are the orbital parameters, including apogee, perigee, and inclination, and five of the basic spacecraft parameters – antenna gain, communication system, propulsion, power, and delta-V (how much the satellite can maneuver once it is in orbit).

The Satellite Radar System (SRS) is a constellation of multiple identical radar-equipped satellites designed to provide global, all-weather tracking and imaging for a variety of stakeholders under a variety of conditions. SRS has a total of 12 attributes, which various stakeholders care about to differing degrees, and 16 design variables covering orbital and spacecraft design parameters. SRS’s multiple stakeholders, long projected lifetime, and multiple potential missions made it particularly appropriate for studying the effects of changing contexts and stakeholder needs.

A final example system was SpaceTug, a single general-purpose orbital transfer servicing vehicle. SpaceTug had only three attributes: capability of equipment carried (measured in kg of equipment), delta-V the vehicle could impart over its lifetime (measure in km/sec) and speed (a binary value, fast or slow). The design variables included fuel load, propulsion type, and equipment payload carried. This simple system was ideal for studies that involved customized models or customized graphical presentation types.

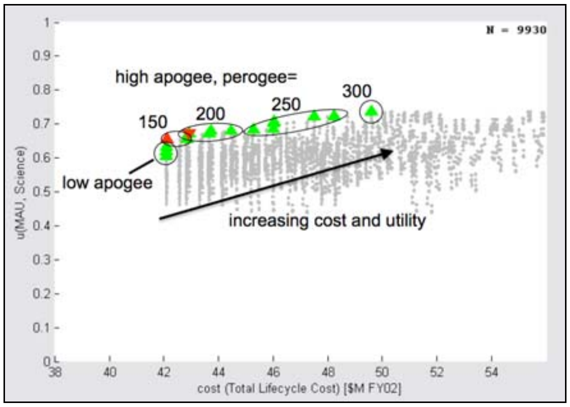

**Figure 5. X-TOS tradespace initial exploration**

### B. Decision Maker Questions

This section will provide a suggested procedure to answer each question using the database and tools. The procedure will not be explained in depth, but will be illustrated through one or more of the case studies. The early steps will be given as a fixed procedure that we have found it helpful to follow, while later steps are more situation-dependent and will be discussed without a rigid procedure.

*1. Can we find good value designs?*

For a given stakeholder, the plot of that stakeholder's Multi-attribute Utility (MAU) versus cost provides the starting point for answering this question. Figure 5 illustrates MAU versus cost for the X-TOS example system. MAU is on the y-axis, with higher utility designs higher up the plot; cost is on the x-axis, with higher costs to the right. Each point on the plot represents an analyzed design. More desirable (higher utility, lower cost) designs are therefore on the upper-left boundary of the "cloud" of possible designs; this is the Pareto front.

***Procedure for this addressing this question:***

First indentify what good value designs might look like:

- Find a few attractive (high utility and/or low cost) points and list their design vector values to understand the physical designs they represent.

Next, get an understanding of the utility versus cost tradeoff(s):

- Pick out or calculate the Pareto front of the MAU versus cost tradespace.
- List the design vector values and attributes of the designs on the front, from low-utility/low-cost to high-utility/high-cost.
- Group by families of similar designs, which share many design vector values (if possible). Find factors that change along the front to understand the major utility versus cost trades.

Begin to understand the details:

- Look in detail at the utility/cost patterns on the Pareto front.
- Look at changes in the individual attributes along the front.
- Try to understand the "why" of the trades. Interpretation may involve subject matter expertise not inherent in the tradespace data.
- Start asking questions that will lead to further explorations.

Things to watch out for:

- In order to effectively explore, trust must be developed in the model and the tradespace representation, which is built through questioning what is seen on the tradespace. "Gut-checking" should be done through relating the tradespace data to expected physical system (design vector values) to performance (attributes) relationships of the systems. Disagreements between data and expectations should be reconciled with those knowledgeable of how the tradespace data was generated.
- Conversely, avoid anchoring on the first couple of designs investigated. These designs are a starting point for further exploration, not the final solutions.
- Do not assume the Pareto front contains all of the good designs. Other stakeholders or other contexts may favor designs not on the current front.

Figure 5 shows the result of this procedure for the X-TOS tradespace. The red triangles represent the selected, highly attractive designs. Investigated in detail, these designs are short-lifetime, low-perigee vehicles with a high delta-V and conventional choices of power and propulsion systems. The trade to move along the Pareto front was to move to higher perigee, which produced longer system lifetime at the expense of low altitude data.

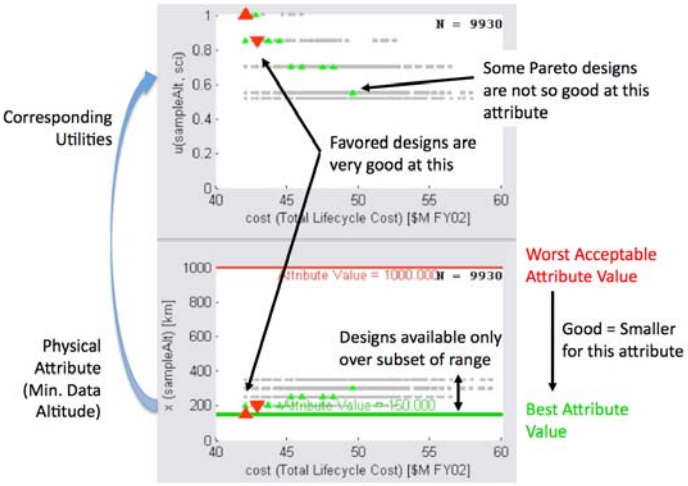

**Figure 6. Min. Data Altitude attribute and its utility versus cost**

*2. What are the strengths and weaknesses of selected designs?*

This question is most meaningfully answered by looking at the calculated attributes of the selected designs, and comparing them to the desired range of attributes specified by the stakeholder. In the previous step, this data may have been tabulated to some degree, but a graphical representation reveals even more information.

Figure 6 illustrates a good form for such a graphical display. The figure has two stacked plots, with the lower showing one attribute ("Min. Data Altitude") plotted against cost. The upper plot is an optional but useful display of the corresponding single attribute utility (SAU) versus cost, which presents the data in a normalized, filtered[*] form (0 to 1, where 1 is good). The entire tradespace is shown (grey points); several picked designs (red triangles), and the set of designs in the MAU versus cost Pareto front (green smaller triangles). The stakeholder-specified worst (red line, SAU=0) and best (green line, SAU=1) values for the attribute are shown on the lower plot. The strength of this representation is that it shows the range of values and costs that are achieved in the tradespace; the placement of the favored designs within this range; the attribute acceptability limits; and how the attribute values translate into stakeholder utility all on one plot. This representation allows for greater contextual understanding for "strengths and weaknesses" than either an attribute value or a utility number alone.

***Procedure for this addressing this question:***

For a quick look at the strengths and weaknesses of some designs:

- Tabulate the attribute values of the favored designs and the corresponding SAUs, and note their strengths and weaknesses relative to both the acceptable bounds for the attribute and the values achievable from other designs.

For an understanding of the other options in the tradespace:

- From the above plots, observe and tabulate the ranges of each attribute achievable from all designs in the tradespace.
- Observe and tabulate the ranges of the attributes achievable considering only favored or Pareto front designs. Determine if the value of each attribute is sensitive to choice between favored or Pareto front designs.

Things to watch out for:

- Strengths and weaknesses are relative to the tradespace evaluated, not absolute.
- Performance in the attributes may be coupled, perhaps antagonistic, where improving one may make another worse, so one may not be able to find "weak" attributes and find an alternative that improves on these. Tradeoffs likely will be needed; however these tradeoffs could inspire new designs to be evaluated.

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[*] The filter is the acceptability range for the attribute. Attribute values at the "worst" acceptable level receive a 0, while attribute values at or above the "best" desired level receive a 1. A single attribute utility function maps the attribute values in between these values. Attribute values below the worst acceptable value are deemed infeasible and excluded.

*3. Are lower cost designs feasible?*

Often, having chosen a technical approach to a problem, one is confronted with a request to provide similar capability for less money. On the tradespace, costs can be rationally minimized by selecting designs from the existing Pareto set that are lower cost and lower utility. If this is not sufficient, one may be able to expand the tradespace to include more low-cost designs. This expansion may be accomplished by either relaxing the worst acceptable value of attributes (equivalent to relaxing attribute requirements) or adding more designs to the design space under consideration, or both.

The X-TOS system provides a simple example of the first strategy. Figure 5 shows the families of designs on the Pareto front. The low perigee designs provide only slightly lower utility than higher perigee designs, at very close to the lowest cost in the tradespace, so simply selecting the “knee” design is a sound cost minimizing strategy in this case. There are several low apogee designs that are even cheaper, although in this case one should be wary – the designs are only very marginally cheaper, a result that is probably not significant given the low fidelity and uncertainty of the cost calculations.

The next step is to consider if stakeholder-specified bounds on the attributes are over-constraining the tradespace and excluding more economical designs. The SRS system provides a good example. For a particular stakeholder, the tradespace was found to have a relatively low “yield” – the fraction of the total designs considered that appears on the tradespace. The discarded designs had unacceptable MAU values, as they failed to deliver attributes in the acceptable ranges specified by the stakeholder. In particular, low cost designs were absent from the tradespace. Assessing the attributes using the techniques of section B.2 above, two attributes are found to be eliminating cheaper designs from consideration. Figure 7 shows that the attribute “Minimum Detectable Velocity” (MDV) excludes designs with small antennas (that are cheaper); the attribute “Target Acquisition Time” (TAT) excludes system designs with fewer than 10 satellites (also cheaper). If the stakeholder concurs, it may be possible to relax the limits of these attributes to achieve lower cost alternatives. In the figure, the points are colored by the most affected design variable, aiding the identification of which design feature led to alternatives being eliminated.

The final strategy for finding lower cost designs is to expand the design space. If the attribute ranges are not restricting the tradespace, and lower cost designs are not part of the original tradespace enumeration, these designs possibly can be added to the design vector and their performance calculated, if one has access to the original tradespace data-generating models. Evaluation of new alternatives requires at least a partial re-running of the design vector to attribute calculation models. In the SRS example, if one relaxes the restrictive attribute constraints further, one might consider systems with even fewer satellites and/or even smaller antennas. One would have to add these design variable values to the design vector and re-run the model.

***Procedure for this addressing this question:***

First, find economical designs on the current Pareto front (where “economical” is specified by stakeholders)

Determine if attribute acceptability ranges are excluding low cost designs:

- Use yield numbers and attribute versus cost plots to check for excluded designs.
- Experimentally relax an attribute limit, and re-plot the MAU versus cost tradespace to include the new designs allowed.
- Pick and assess new candidate designs, tabulating these designs noting the relaxed constraint.
- Repeat as needed.

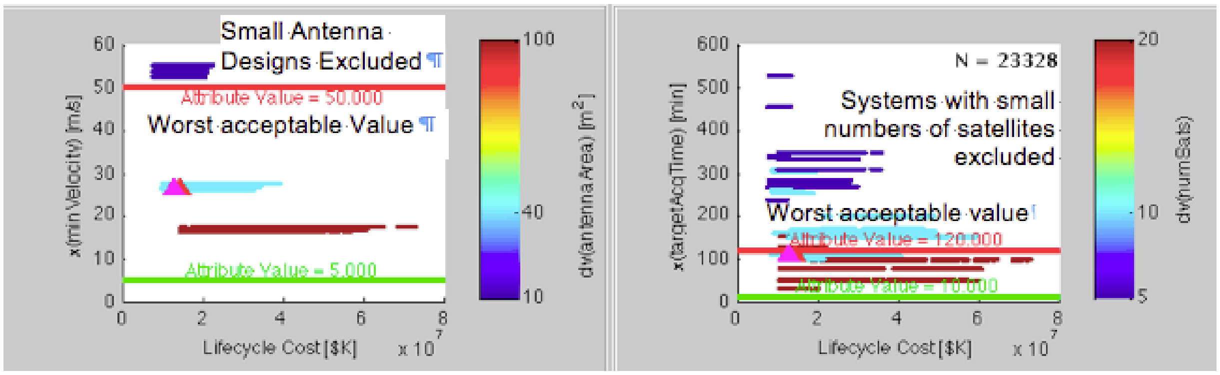

**Figure 7 Attribute versus cost plots with limits included show designs eliminated from the tradespace**

Expand the design space to include more low-cost designs:

- Add lower-cost alternatives to the design vector; recalculate tradespace.

If the expanded tradespace is substantially different than the old one (i.e. new Pareto front, new trades):

- Reassess tradespace from the beginning.

Things to watch out for:

- On the Pareto front, the utility versus cost tradeoffs can be made only by the affected stakeholders.
- Beware of "cliffs" at the low-cost end of the Pareto front – radical changes in designs and/or steep drops in utility with very little cost savings.
- "Small" utility differences may not be small in the mind of the affected stakeholder; it is important to show the attribute differences to the stakeholder to determine if "small" utility differences are meaningful.
- Decisions to relax attribute acceptability ranges can only be made by the affected stakeholders.

### 4. *What about time and change?*

The basic conceptual approach for gaining insight into time and change in a tradespace is through using Epoch-Era Analysis.[13,14] From a tradespace point of view, imposed contextual or need changes are modeled by recalculating the tradespace under the new conditions. Each distinct set of stakeholder needs and external conditions considered is referred to as an *epoch*. A set of epochs considered in a time-ordered sequence forms an *era*.

Given a set of tradespaces, one calculated for each epoch, visualizations can help to understand the effects of changing contexts and needs. For example, the shape of the basic MAU versus cost tradespace may change, or the relative performance of favored designs and the designs on the Pareto front may change. All of this can be tracked visually by observing differences between the tradespaces. One approach to help indentify differences between tradespaces in the shift from one epoch to another is to use animation for the transition. Unless the impact on utility and cost in reality is a smooth and gradual transition from one state to another, this animation does not represent anything real, but it is a useful way to engage the human visual perception ability for indentifying differences.

Another technique for understanding the impact of change, especially across large numbers of unordered epochs, is through calculating multi-epoch metrics.[9] The Pareto Trace is a multi-epoch metric defined as the number of times, across all epochs considered, that a design appears on the Pareto front. A variant on the Pareto trace is to count designs that are "close" to the Pareto front, a *Fuzzy Pareto Trace*. We define a *K-percent fuzzy Pareto front* as including all designs within both *K* percent of the total cost range, and *K* percent of the total utility range, of a Pareto front design. Another simple metric that should be considered is the fraction of acceptable designs (the *Yield*) found in each epoch. Low yields indicate difficult conditions or demanding needs; epochs with these characteristics may require extra attention.

Figure 8 illustrates a simple case of an epoch shift. In this example, the stakeholder's needs have changed for the X-TOS system, with greater emphasis placed on low altitude data. The initial epoch (the previous example tradespace) has a region of cost-utility tradeoff. The second epoch has a single optimum design. More expensive designs actually have lower utility than the design on the "knee." An immediate question is how previously favored designs fare across the change in needs. One favored design (red triangle) appears "optimal" in the second epoch, dominating all other designs. In this case the previously selected design is robust in utility to the changed needs.

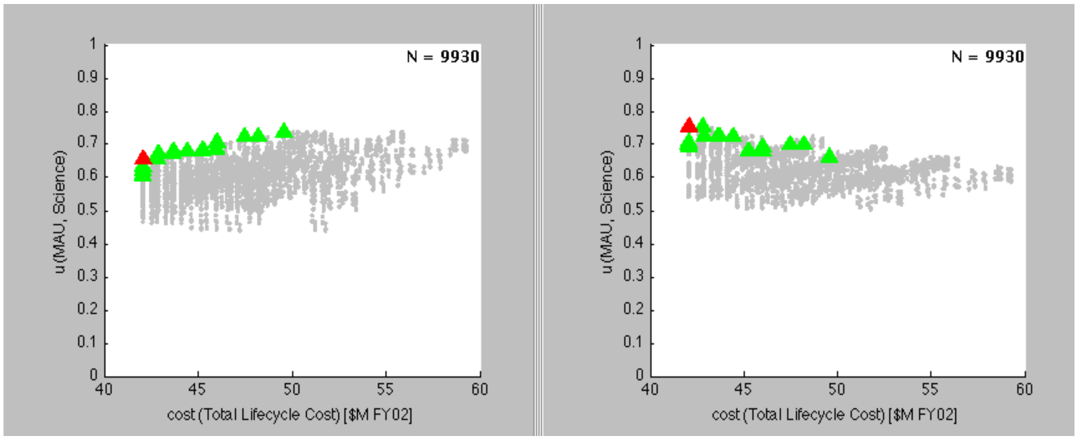

**Figure 8. Change in tradespace with change in stakeholder needs**

***Procedure for this addressing this question:***

Define epochs, which are periods of time characterized by static stakeholder needs and contexts:

- Define stakeholder needs, expressed as utility functions with ranges and weights for the attributes.
- Define context conditions, expressed as constraints and constants in the model.
- Run the model and store the tradespace for each epoch.

Use multi-epoch metrics to find identify promising designs and directions for further investigation:

- Use Pareto Trace and Fuzzy Pareto Trace to find designs that perform well (or at least adequately) over a wide variety of conditions.
- Use the Yield of each epoch to identify “difficult” epochs for further study.

Iterate as needed with new favored designs and/or new epochs for study.

Define an era, a time-ordered series of epochs for study:

- Compare the apparent structure of the tradespace across the different epochs.
- Compare the performance of favored designs in different epochs.

Use techniques, as necessary, to understand the differences (utility, cost, attributes, etc.) from one epoch to another in the era:

- Use color to find design variables and/or attributes whose effects or contributions to the overall utility change.
- Use animation (from one epoch to the next) to help visually identify these changes.

Things to watch out for:

- Choose epochs and eras wisely, as indiscriminate specifying of many epochs will result in excessively large databases. Sparse sampling of potential epochs can be done, along with probability weighting of likely epochs.[25]

*5. What about uncertainty?*

Addressing this question is an area of active tradespace research and therefore suggestions in this section are still preliminary. However, current tradespace exploration capabilities can be used to shed some light on several forms of uncertainty.

First, the tradespace intrinsically contains a large amount of information on the sensitivity of the attributes to the design variables. An example of the use of this knowledge of sensitivities to understand uncertainty issues is presented in Fig. 9. This plot shows a tradespace for the SpaceTug system, with designs differentiated only by fuel load connected by lines. The figure is useful for understanding the non-linear effects of adding fuel to an otherwise identical vehicle. The figure can also be used to infer the effects of uncertainties in the fuel load, propulsion system efficiency, and performance modeling. For heavily-fuel-loaded vehicles, uncertainties may cause drastic increases in costs, indicating this is a major risk factor. For lightly loaded vehicles, on the other hand, uncertainties in the use of the much smaller fuel load may have wide effects on stakeholder satisfaction; fortunately in this region of the tradespace extra fuel may be added as insurance at very little cost. The uncertainty effects can be identified on the “up side” as well; improved propulsion system performance may save a lot of money on one end of the spectrum, and result in much greater stakeholder satisfaction on the other.

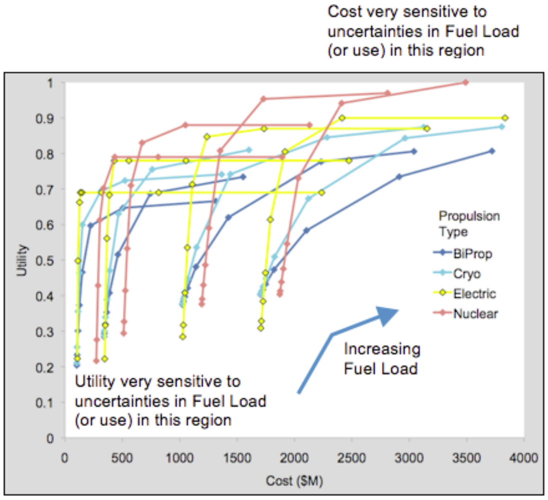

**Figure 9. Sensitivity studies give insight into uncertainty issues**

A more general approach to uncertainty involves looking at sensitivities to many modeled parameters, not just the design vector elements and attributes. This approach, in general, requires modification and re-running of the tradespace model. In order to understand the effects of changes in defined sets of stakeholder needs, context effects, or modeling relations, these can be altered and the model recalculated. Practically speaking from a tradespace exploration point of view, this approach may look similar to the Epoch-Era Analysis used for time and change in the previous section. In fact, the changes in context and stakeholder needs discussed in the previous section can be thought of as a subset of possible uncertainties that could be studied in a similar manner.

Uncertainties can be studied even more generally by assigning a range and statistical distribution to many factors in the analysis, and performing a Monte Carlo analysis using the tradespace mode.l[25] Monte Carlo analysis generates an extremely large amount of data if the whole tradespace were modeled statistically, since the analysis requires a generation of tradespace data for each sampling of an uncertain parameter, possibly increasing the dataset size by many orders of magnitude. A more modest approach is shown in Fig. 10, where six representative SpaceTug designs are selected for investigation. A full Monte Carlo analysis is performed on these six designs, varying all uncertain model parameters over reasonable but wide ranges. The results are plotted as a “cloud” of possible locations for each design, showing the effects of different values for uncertain factors in the model.

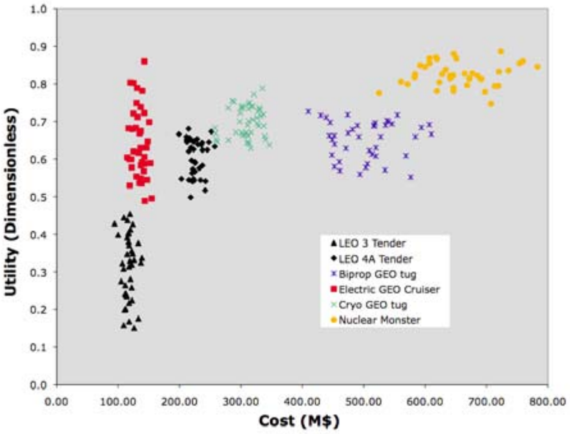

**Figure 10. Monte Carlo simulation of general uncertainty in the SpaceTug tradespace**

***No detailed procedure is yet proposed for answering this question, but possible approaches include:***

- Understand the sensitivity information already available in the tradespace. Uncertainty in sensitive factors may indicate areas risk.
- Use Epoch-Era Analysis to understand uncertainties due to discrete changes in contexts and needs.
- Use Monte Carlo analysis to understand the general uncertainty in performance of a *subset* of designs.

6. *How can detailed design development be initiated in ways that maximize the chance of program success?*

Presently, this question can only be answered at the level of expert opinion. The holistic answer is that the overall knowledge generated during tradespace exploration activities should help program managers and technical leaders better understand the system they are trying to develop. More specifically, tradespace exploration appears to have promise in addressing critical known program planning issues, including:

- *Picking good projects.* At the most basic level, tradespace exploration shows what is possible and practical in terms of tradeoffs and costs. Projects focused on creating something approaching the “favored” design on tradespaces are more likely to succeed than those aiming for an arbitrary set of requirements, which may correspond to a dominated, or even empty, region of the tradespace.
- *Specifying good requirements*. Prior to defining requirements, utility metrics and attributes with acceptability ranges are used in tradespace exploration to allow for simultaneous consideration of many alternatives. Gaining an understanding of attribute sensitivities and the effects of attribute bounds might avoid the creation of “bad” requirements that unnecessarily restrict the tradespace. Tradespace knowledge would also focus requirements on attainable systems, avoiding requirements that are excessively costly or physically difficult to meet. On the opportunity side, this knowledge can help set higher stretch goals in areas where capability is available that exceeds the current needs (or imaginations) of the stakeholders.
- *Understanding risk areas*. Tradespace exploration as defined in this paper lacks a formal procedure for risk assessment, but the tradespace has relevant information related to its consideration. Sensitivity information reveals design variables that will have the most impact on cost and utility, and attributes that will be the most difficult to achieve. Exploration often reveals difficult trades of one attribute for another that must be resolved. Epoch-Era Analyses can be used to identify the impacts of changes in future contexts or needs, including designs that are insensitive to such changes. These insights can be used as input into any risk mitigation plan.
- *Understanding alternatives*. Given that risks may threaten the success of the project, it is useful to understand ahead of time the options that are available to respond to these threats. Knowing available alternate designs, including their strengths and weaknesses, and the advantages and necessary compromises in switching between alternatives is valuable information for creating contingency (or expansion) plans.

# IV. Discussion

A series of tradespace exploration research efforts from 1999 to 2004 resulted in a proposed new approach for considering potential system solutions in the conceptual design phase.[1] This new approach, the "tradespace exploration paradigm" was depicted in contrast to the "classical paradigm" in that it sought to minimize the premature application of constraints, both on the potential solution systems and on the potential expectations of stakeholders. Putting off focus on "point designs," this new paradigm sought to take a "value-centric" approach where alternatives are evaluated in terms of stakeholder-defined metrics, rather than designer determined metrics, thereby creating a proxy "voice" for the stakeholders during generation, evaluation, and, ultimately, selection of alternatives. Early works on Multi-Attribute Tradespace Exploration (MATE)[26,27], a synthesis of value-centric[28] tradespace exploration leveraging Multi-Attribute Utility Theory[29], suggested a wide array of possible applications for the approach, such as designing a car, aerospace systems[27], and even a wedding[30]. Advances in tradespace exploration, developed through case studies since Ref. 1 was published, have raised demonstrated new capabilities for the approach, as well as some new issues:

- The importance of representing different cost types other than dollars, predicted by Ref. 26, was verified in Ref. 3 through an application of tradespace exploration to transportation planning problems. Transportation planning projects tend to seek to minimize costs, rather than maximize benefits. Example generalized "costs" include cost sharing constraints, contractual limits, and environmental externalities such as pollution or noise. In order to aggregate the net cost, a *multi-attribute expense function* was used as a "cost" analogy equivalent to the "benefit"-representing multi-attribute utility function.
- As predicted in Ref 27, multiple different system concepts can be compared on the same tradespace since the alternatives are evaluated in terms of utility and cost, which are concept-independently defined.[2,19]
- Systems of systems require higher order modeling of SoS-value, including sophisticated combining of component system attributes[31], as well as consideration of the impact of inheritance of legacy systems[6].
- Dynamic considerations are difficult to visualize and analyze, especially with the large growth of dataset size (a tradespace per epoch and many such orderings of these to generate the eras), but metrics can be used to screen through the dataset to identify "interesting" designs for further consideration.[8,9,17] Ongoing research seeks to better characterize dynamic tradespace techniques, as well as develop concepts and metrics around system properties that enable systems to maintain value across changing needs and contexts.[5,8,9,16]

The opportunity to mature tradespace exploration techniques into the Responsive Systems Comparison (RSC)[9,22] method also resulted in an effort to capture tacit knowledge gathered by tradespace researchers over the past decade. Up until this concerted effort to encapsulate and formalize tradespace exploration techniques and representations, each case study relied upon orally transmitted techniques, as well as imitation-based approaches for generating visual representations of the tradespace data (e.g., reusing analysis software code from one project to the next, or copying of figure templates from reports). But across multiple projects, it became apparent that each case study's unique aspects and the research goals of participants resulted in differences in data representation and increasing sophistication of metrics. This *ad hoc* examination of the tradespace did slowly accumulate knowledge, but it was often the case that representations developed for analyses in one project were unknown to analyses in other projects[*]. The question-guided tradespace exploration set of approaches outlined in this paper is a first step in codifying this knowledge in order to make repeatable and consistent tradespace exploration analyses possible, along with allowing researchers to focus on pushing the state of the art, rather than redeveloping past applied techniques.

Some observations emerged from the question-guided tradespace exploration applied to the three case applications in this paper (X-TOS, SRS, and SpaceTug):

- A systematic process, aided by appropriate graphical tools, is much faster and more complete than *ad hoc* examination of the tradespace.
- A characteristic of tradespace analyses is that the information created, although large in quantity, often has uncertainties or approximations in both elicited stakeholder needs and technical modeling of the system. Therefore, the inclusion of both stakeholders (or their proxies) and technical subject matter experts in the tradespace exploration process is critical.
- Information collected during the exploration often calls into question the stakeholders' preferences and requirements. The ability for stakeholders to change these, and track the resulting change in the tradespace, is critical, particularly in multi-stakeholder negotiations.[21]

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[*] Observation by the lead author, as only common participant in all MATE case applications since 2000.

- Tradespace exploration analyses can display *correlations* between various elements of the tradespace; *causation* can only be determined by subject matter experts and system modelers (who should be present during the exploration).

The overall outcome of a systematic approach to tradespace exploration is an understanding of not only good designs, but also the trades between them, their strengths and weaknesses, the sensitivities that might be exploited to find improved designs, and a sense of a selected design's robustness to change. This overall knowledge, not just the choice of a "good design," is an excellent starting point for a successful system development effort.

## V. Conclusion

Tradespace exploration has progressed since the publication of "The Tradespace Exploration Paradigm," with a broadening of application areas, development of new metrics, as well as new representations and constructs for considering time and change. Equal to the importance of the expansion of the techniques for working in this paradigm, is also the maturation of the process of exploration itself through an effort to codify the tacit knowledge of tradespace exploration researchers. The overall outcome of this effort is structured guidance for systematically exploring tradespaces to extract answers to practical questions and to generate other forms of useful knowledge from the data in a tradespace dataset. This structured exploration guidance is a key enabler to the successful use and broad applicability of the tradespace exploration paradigm.

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