

The Tradespace Exploration Paradigm

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Abstract. Over the past five years, researchers working on a number of system design projects in the Space Systems, Policy, and Architecture Research Consortium (SSPARC) at the Massachusetts Institute of Technology (MIT) have developed a process of value-focused, broad tradespace exploration for the development of space systems. The broad tradespace framework has provided insights into communicating and quantifying the impact of changing requirements, uncertainty, and system properties such as flexibility and robustness. Additionally, insights have been made in applications to more complex cases, such as analyzing policy effects on system cost and performance, as well as understanding the time-dependent effects of architecture and design choices for spiral development. The tradespace exploration paradigm both broadens the perspective of designers in conceptual design to better understand the “physics” of the proposed solutions relative to one another, and focuses the designer on delivering systems of value to key system stakeholders.

Introduction

Motivation

Conceptual design is a special point in the development process for products. During this phase, the key mapping of function to form is specified. The physical form selected then determines a majority of the cost and schedule for the ensuing development process. Making a poor decision at this point will have significant cost and schedule ramifications as changes become more difficult to make later in the process. The selection of the design concept and high level specifications are the outputs of this phase and inform the preliminary design phase to follow. The design choice space from which the concept is selected must be carefully considered in order to mitigate the risk of later costly changes, and maximize the value created for the stakeholders of the system. Intentional or unintentional premature reduction of the design choice space may take away valuable information from the designer, preventing realization of more robust and valuable systems.

Glossary

The terms in this paper were developed by the Space Systems, Policy, and Architecture Consortium in order to effectively conduct internal communication. These terms often hold different meanings for different people. For the sake of this paper, the following definitions will apply. Most definitions that follow are directly or derived from (Ross 2003a).

Architecture. Is the level of segmentation for analysis that represents overall project form and function. It is also used to describe design alternatives identified by a particular design vector.

Attribute. Is a decision maker-perceived metric that reflects how well a decision maker-defined objective is met.

Decision maker. Is a type of stakeholder that makes or significantly influences the decisions that impact a system at any stage of its lifecycle. Typically these people have significant influence over the allocation of resources for the system (including money, labor, equipment, operational expertise, etc).

Design variables/vector. Includes variables that are designer-controlled quantitative parameters that reflect an aspect of a concept. Typically these variables represent physical aspects of a design, such as power subsystem type. The set of design variables form the design vector, which contains all of the parameters that will be explicitly traded. (Example: the satellite system concept design vector {single vs. dual satellite, perigee altitude, apogee altitude, orbit inclination, propulsion subsystem type, power subsystem type, communication architecture, antenna gain, available delta v} was used for an atmospheric density sampling mission tradespace study.)

MATE-CON. Multi-attribute tradespace exploration with concurrent design. MATE without – CON typically refers to the lower fidelity broad tradespace exploration phase of the MATE-CON process. The two key concepts within the process are *broad tradespace exploration* coupled with and driven by *explicit decision maker value function elicitation*. The MATE-CON process was developed by (Diller 2002) and (Ross 2003b).

Tradespace. Is the space spanned by the completely enumerated design variables, which means given a set of design variables, the tradespace is the space of possible design options. The expansion of this tradespace is a “creative recombination of current resources or systems to create a new system,” which would involve generation of either new design variables or reconfigurations of existing combinations of variables. (Example: if the design variables are circular orbit altitude (km) and inclination (degrees), where altitude is in the range of 200-300 km in 50 km increments, and inclination is either 0 or 90 degrees, then the tradespace would be {(200,0), (250,0), (300,0), (200,90), (250,90), (300,90)}, with (X,Y)=(altitude,inclination).) Using models and simulation, the full set of design options—the tradespace—can be evaluated in terms of benefits and costs to decision makers. Often the Utility-Cost plot will be referred to as the tradespace as well since it is a useful representation for making “best” system value trade decisions. (Example: Continuing the previous example, the Utility-Cost coordinates are calculated to be {(0.7,20), (0.8,25), (0.9,30), (0.75,30), (0.85,35), (0.95,40)}, with (X,Y)=(Utility,Cost).) The *Pareto Front* is the set of points that are the best in a given metric with all other metrics held fixed, i.e., the highest utility for a fixed cost. *Dominated solutions* are those that are not on the Pareto Front. The Pareto Front is the tradeoff curve between metrics. In the prior example, (0.75,30) and (0.85,35) are dominated solutions, while the other points are on the Pareto Front. Typically, one would not choose dominated solutions *unless* they perform better in an uncaptured metric.

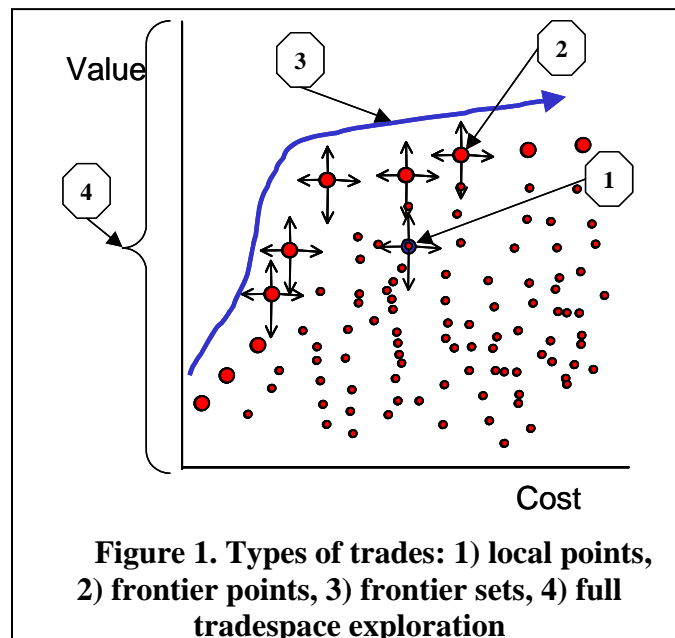
Utility. Is a dimensionless parameter that reflects the ‘perceived value under uncertainty’ of an attribute. Often used in economic analysis, utility is the intangible personal goal that each individual strives to increase through the allocation of resources. For most of the projects studied using the MATE-CON process formal Utility Theory has been used. A utility function is an axiomatically defined quantity that explicitly captures a subset of the preferences of a decision maker (Keeney and Raiffa 1993). Typically varying from zero (minimal acceptable) to one (most desirable), utility is a useful quantitative proxy for representing benefit.

Value. Is a metric that captures the goodness of something to a stakeholder. Value metrics are specified by someone with knowledge of the need and/or use of the system. Attributes and functions of the attributes are examples of value metrics (a utility function as a special case of such a function).

Old Paradigm

According to official system engineering handbooks, early design efforts (for example pre-Phase A and Phase A at NASA) focus on proposing and determining the feasibility of a variety of design options for a given mission (Shishko 1995). In practice, however, consideration of a multitude of options requires significant time and money that is often not available. Instead, engineers typically set as baselines favourite or previously developed concepts and perform Analysis of Alternatives off of the baseline through small perturbations. Larger scale concept trades are sometimes done, but often at low fidelity (“back of the envelope”) or in small number (typically a handful of concepts). Confounding this preoccupation with premature reduction of the tradespace are customers who write solution dependent requirements, constraining the creative expertise of the designers.¹

The design process can be thought of as a space of decisions that designers constantly prune in order to reduce the set of alternatives before settling on a “solution” to the problem at hand. Focusing the design space, or tradespace, is useful for focusing development effort and necessary in order to produce a detailed specification. Premature focusing, however, can introduce artificial constraints on the design process and reduce the potential value created and delivered to the customers. Four classes of trades are introduced in Figure 1 to depict the spectrum of tradespace considerations. 1) Local point solutions, 2) Frontier subset solutions, 3) Frontier solution sets, and 4) full tradespace exploration.



Choosing a local point solution represents the least effort trade study approach. Incomplete knowledge of the bigger picture prevents knowledge of better value solutions. Finding the Pareto Frontier subset solutions begins to recognize the key value tradeoffs that exist in the tradespace. Several design options are considered in this approach, with no clear “best” solution clearly identified. Finding the complete Pareto Frontier identifies explicitly the key benefit-cost trade-off among design options. Given the Pareto Frontier, new design options can be immediately assessed in terms of their distance from the “optimal” trade-off curve. Complete tradespace exploration

¹ The discussion of what is actually done in industry is based both on discussions with former senior leaders in aerospace organizations, as well as on an industrial site visit research project. The research project includes interviews conducted at several space system development organizations including both Federally Funded Research and Development Centers and aerospace prime contractors. The research is ongoing and the results of these interviews will be published at a later date.

considers dominated solutions as well as the Pareto Front. Including dominated solutions in the analysis is an admission that uncaptured value metrics may exist (i.e., the requirements may be wrong) and allows for more detailed and dynamic analysis of the structure of the tradespace itself. This paper introduces the concept of full tradespace exploration and its benefits as a framework for communicating and quantifying concepts such as the impact of changing requirements, uncertainty, flexibility, and policy robustness

Multi-Attribute Tradespace Exploration (MATE)

MATE system description. The MATE system includes the context for the process developed, the inputs to the process, the outputs of the process, and the mappings between the inputs and outputs. The context could be described as “Engineering Systems Thinking.” The inputs could be described as “Value-centric Design.” The outputs could be described as “Tradespace Exploration.” And the mappings could be described as “Advanced modelling and simulation.”

Context. The development of the MATE process occurred over the course of five years, and is continually evolving. Various theories and methods have been experimentally included through application to seven aerospace system design projects.² Eight masters and three doctoral theses have been written about aspects of this process.³ Additionally, MIT has created a new Engineering Systems Division which espouses the importance of “holistic” thinking and continually provokes students to synergistically incorporate concepts from disparate fields.⁴

Process. The MATE process itself can be described as three layers: 1) Need identification, 2a) Architecture-level exploration and 2b) evaluation, and 3a) Design-level exploration and 3b) evaluation. Need identification is accomplished through formal preference elicitation from key system decision makers (Ross 2003b, Ross 2004). The key metrics are called attributes, which are decision-maker perceived metrics that reflect how well decision-maker defined objectives are met. A set of attributes should be complete, non-redundant, operational, decomposable, minimal, and perceived independent. In practice, cognitive limitations typically limit the set to fewer than seven attributes (Keeney and Raiffa 1993, Ross 2003b).

Value functions are functions that aggregate the attributes into a single metric that reflect the decision maker’s aggregate preferences. The value function is used to compare designs to determine “best” solutions. A spectrum of value functions exist and range from requirements (binary satisfaction: yes or no?), to continuous measures of functionality (e.g. how much commodity is provided?), to single attribute utility (e.g. how desirable is a given level of a given attribute?), to multi-attribute utility (e.g. what is the combined value of a given set of “independent” attributes?). These value functions are progressively more difficult to generate, but potentially more valuable by capturing more details of a decision maker’s key preferences, thereby opening up the assessment potential of a broad tradespace for system designers.

Utility function attributes have three key characteristics: decision-maker perceived definition, units, and range including “least acceptable” and “most acceptable” values. In the limit the range

² Four of these projects are discussed in (Ross 2003b), and one each in (Derleth 2003), (Spaulding 2003), and (McManus and Schuman 2003).

³ Masters theses include: (Derleth 2003), (Diller 2002), (Roberts 2003), (Ross 2003b), (Seshasai 2002), (Shah 2004), (Spaulding 2003), and (Stagney 2003). Doctoral theses include: (Jilla 2002), (Walton 2002), and (Weigel 2002).

⁴ See <http://esd.mit.edu> for more information about the Engineering Systems Division at MIT.

converges to a point, the utility function becomes a requirement.⁵

The MATE process has been compared to the NASA product development process through Phase A, as well as to that of an aerospace company, illustrating how MATE is “better” at streamlining communication of decision maker-articulated value (Ross 2003a, Ross 2003b).

Tradespace Representations

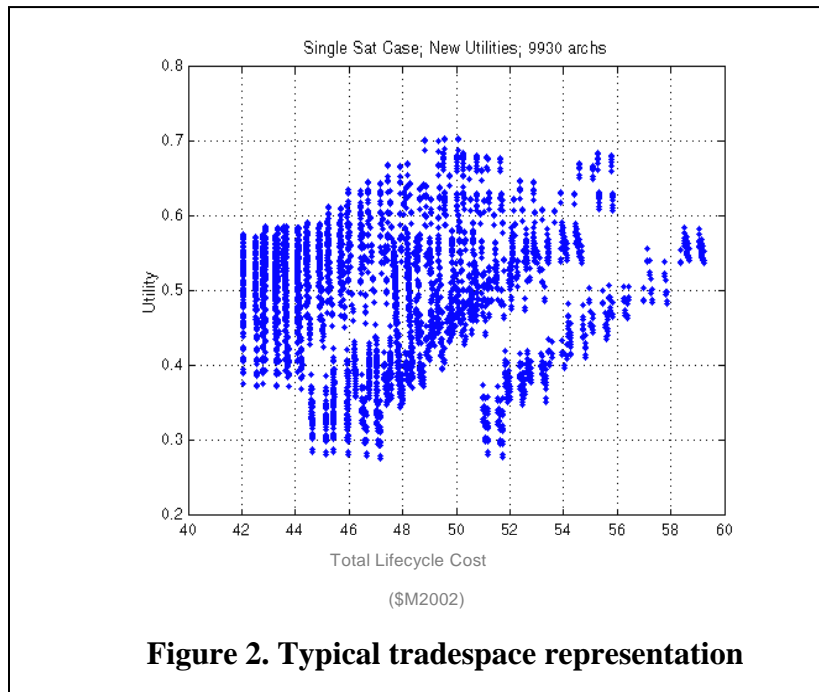


Figure 2. Typical tradespace representation

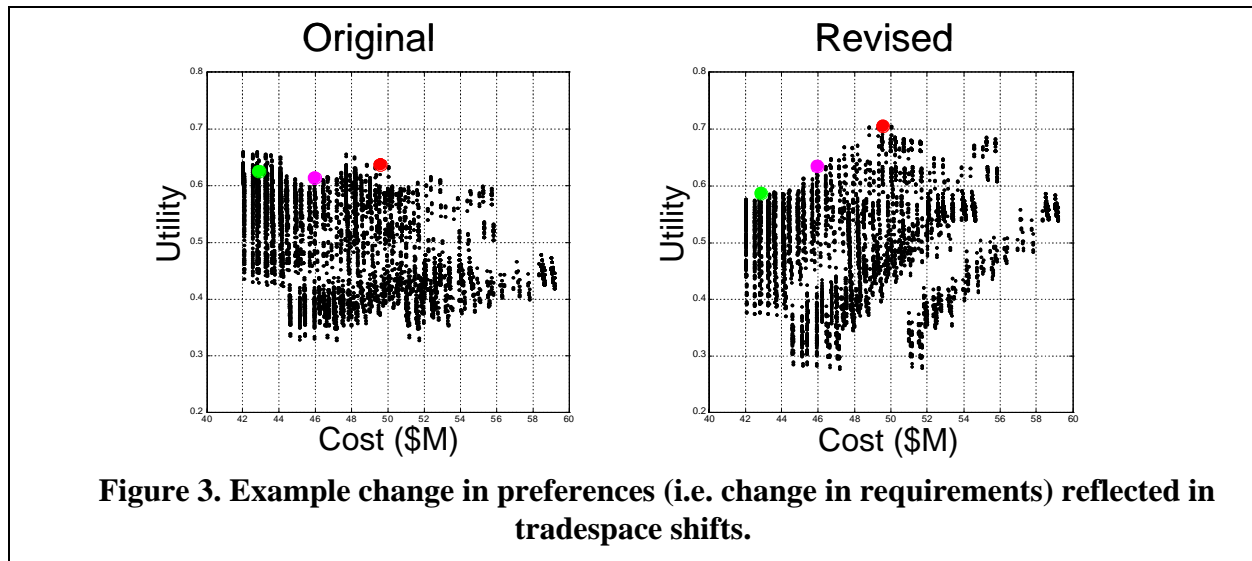
An architecture tradespace is typically represented by a plot of architecture and design options in terms of utility versus cost. Figure 2 shows a tradespace for a low altitude space science mission. Each point represents a unique design choice, which was evaluated through a set of models and simulations in terms of lifecycle cost and utility to a science user. Each point is a pointer to a database of information regarding that design option, including the values for the design variables, intermediate variables (such as mass, theoretical first unit cost, chosen launch vehicle, etc), as

well as the attribute values, single attribute utilities, and multi-attribute utility and cost. The tradespace Utility-Cost plot is a concise representation that highlights critical decision metrics.

The value-centric focus of the tradespace plot is that the key decision metric, utility, is defined by the decision maker who will ultimately decide between alternatives. As opposed to designer-specified metrics, such as mass or power, utility is a direct reflection of value, rather than an inferred one.

When the preferences of a decision maker change, akin to a change in requirements, the impact on the tradespace can be rapidly assessed. Figure 3 depicts the tradespace impact of a change in the utility function for a system after the decision maker saw the initially proposed design. Detailed analysis revealed that the points shifted *differentially* in the face of changing preferences, suggesting options which may be more insensitive to such changes. Not only does the plot depict designs and architectures that may be more robust to changes in requirements, but also it captures this change very rapidly (the new tradespace was recalculated in a matter of hours).

⁵ See (Ross 2003b) for a lengthy discussion on preference capture, value, and utility theory and its limitations, as well as examples of utility theory applications and validations. (Spaulding 2003) addresses the limitations of utility function elicitation and shortcuts in practice.



Another use for the tradespace plot is to depict how current point designs compare to one another in a macro-tradespace sense. Designs that are dominated (i.e. are inferior to the Pareto Front) are readily distinguished and immediately focus discussions on why that is the case. Figure 4 shows the tradespace for the Terrestrial Planet Finder (TPF) system and the red circles show the designs proposed by the large aerospace contractors. When shown to the companies, the fact that none of the proposed designs are on the Pareto Front resulted in significant discussions on why that might be the case, highlighting the need to understand if there are other metrics by which the designers “optimized” the system and whether that resulted in a more valuable system.

As a tradespace is being explored, various patterns begin to emerge. The “physics” of the Spacetug (Orbital Transfer Vehicle) system tradespace is illustrated in Figure 5. Note that the lines represent increasing mass fraction as the line moves from low to high utility. The lines appear to hit walls at specific utility levels, implying an increase in mass fraction beyond that point results in little added value, but much added cost. The electric propulsion-based space tug reaches this wall well to the left of the ideal utility level of 1, implying that no matter the mass fraction, these designs will never completely satisfy the decision maker. Some of the nuclear propulsion-based systems, however, do reach that ideal level. Both the rocket equation and the decision maker’s expressed preferences resulted in the existence of this wall

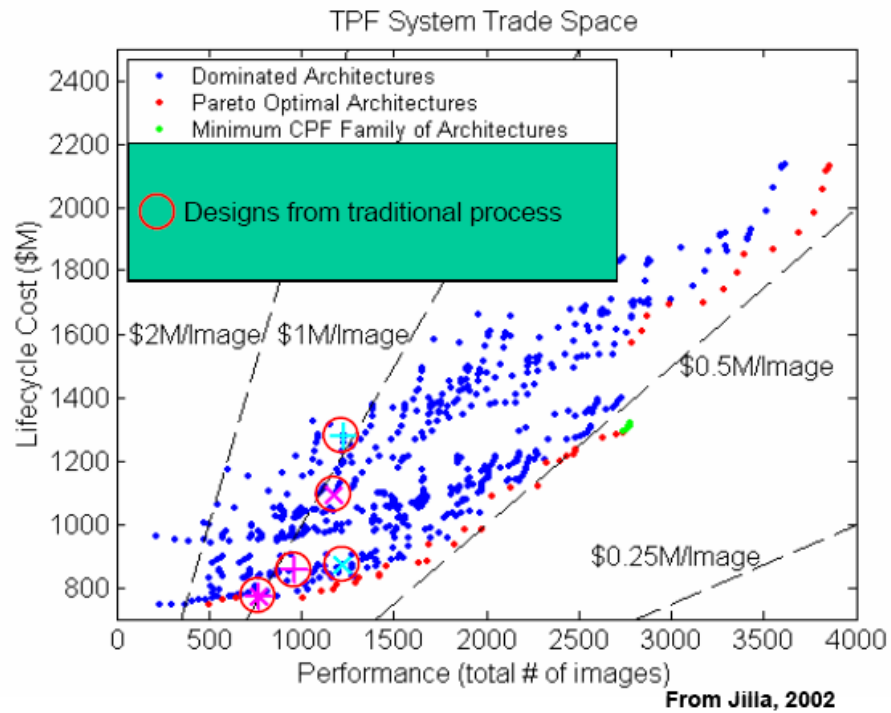


Figure 4. Example comparing point designs to larger tradespace.

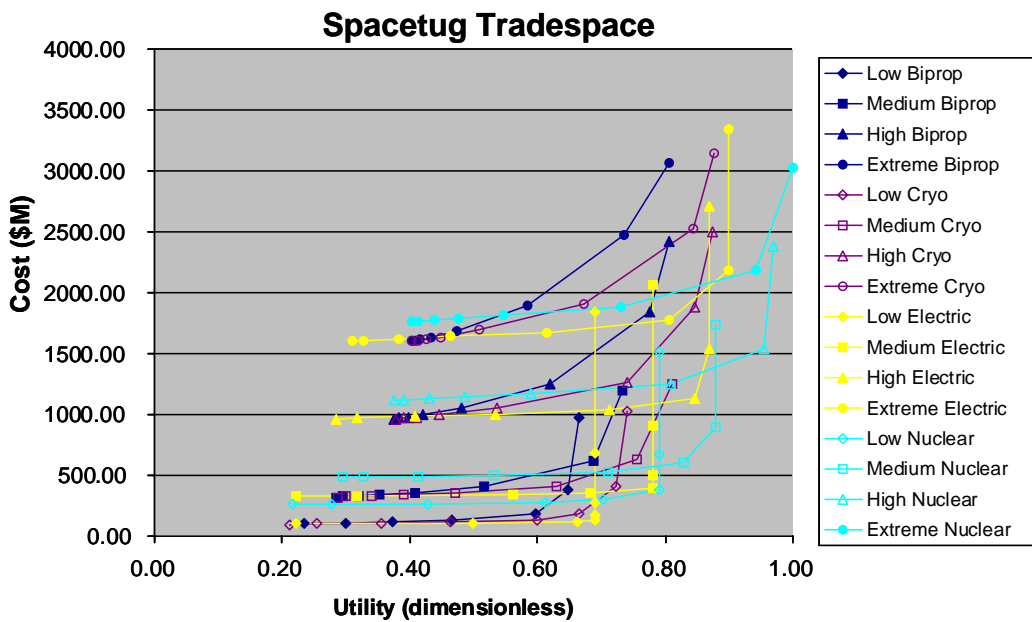
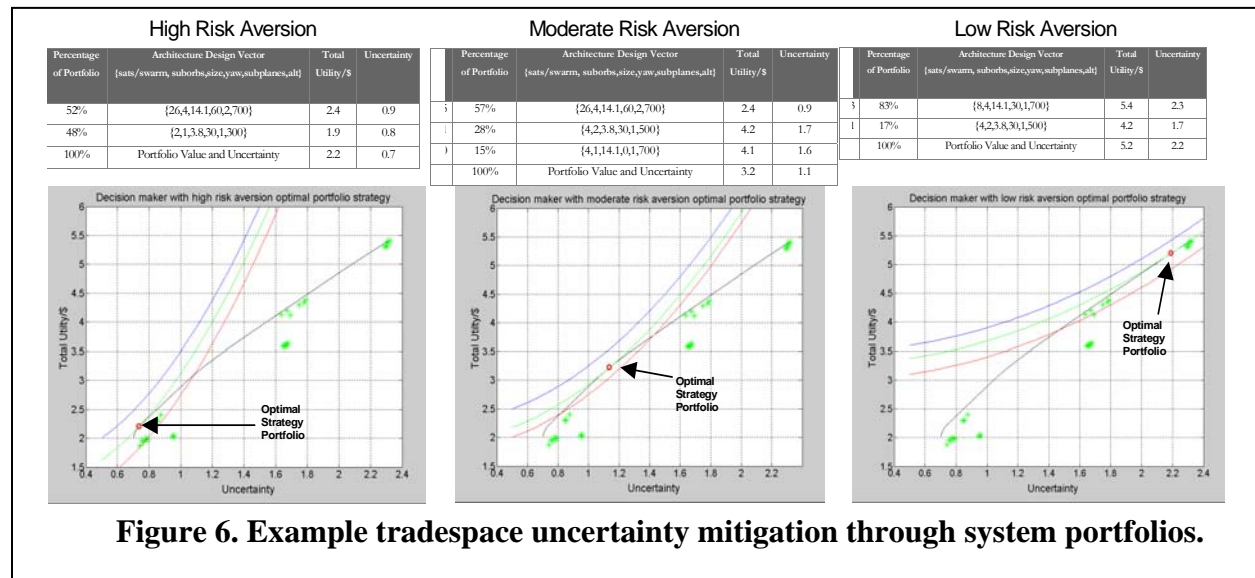


Figure 5. Example understanding “physics” of tradespace

Advanced Tradespace Concepts

Uncertainty. Oftentimes the uncertainty inherent in system development is treated synonymously with risk and as such carries negative connotations. (Hastings and McManus 2003), describes a more generalized framework for thinking about uncertainty, highlighting the fact that there is both upside as well as downside risk associated with uncertainty and that various mitigation strategies can be pursued to achieve desired outcomes.

In terms of tradespace representations, various approaches for including uncertainty have been pursued.⁶ (Walton 2002, Walton 2004) describes using Monte Carlo simulations to generate the probability distributions associated with each point in the tradespace. Once the uncertainty is quantified, a system designer can then use that information to take advantage of the downside of uncertainty as well as the upside (Walton 2001). *Portfolios* of system designs that combine options that have anti-correlated uncertainties will have lower uncertainty than individual designs alone (Walton 2002, Walton 2004). Figure 6 shows an example Uncertainty-Value space from which portfolios are constructed. Each point in the figure corresponds to a point in the tradespace. Like in financial portfolio theory, the efficient frontier of maximum value for a given level of uncertainty represents various combinations, or portfolios, of options. For stocks and bonds the uncertainty is typically called “risk” and the value is typically called “return.” Portfolios with the best balancing of risk and return are constructed based upon the risk tolerance of the portfolio holder. Likewise, Figure 6 depicts three types of decision makers: high, moderate, and low risk aversion. The optimal investment strategy is determined by the intersection of the iso-value contours of the decision maker with the efficient frontier. The analogy between partial ownership in financial commodities (i.e. stocks and bonds), to physical systems is partial investment in the development in those systems. As uncertainties are resolved through further development of the systems, the portfolio will be modified accordingly (Walton 2002).



⁶ (Walton 2002) explores using error ellipses, best-worst case lines, and color-coding to represent tradespace uncertainties, as well as the uncertainty-value plot.

One application of the uncertainty-focused interpretation of the tradespace is in understanding high leverage points for technology insertion or investment. Technology development that results in more anti-correlated design options may mitigate more uncertainty and helps the system developer to hedge against program failure due to correlated technology development. This application is an open area of research.

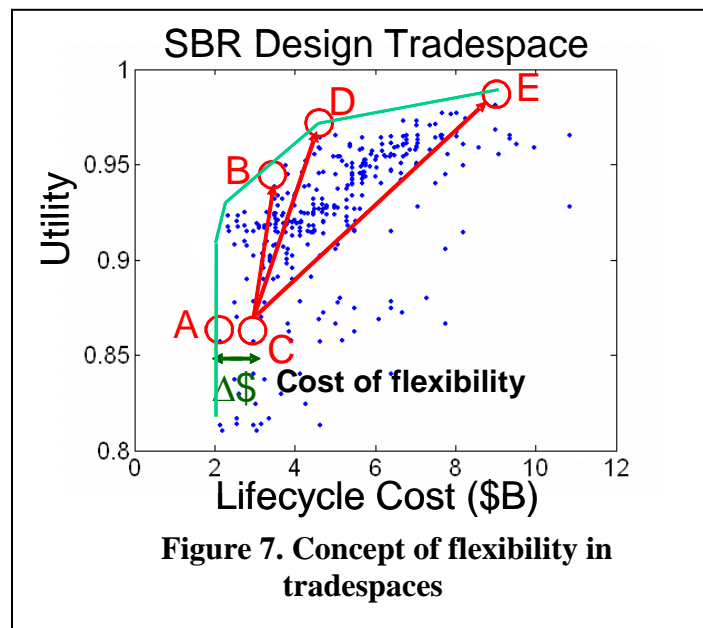
System Properties: “ilities”. In addition to the articulated need captured by the attribute set and utility functions of each decision maker, there may exist unarticulated sources of value. When offered to decision makers, system properties, cast in terms of “ilities” such as flexibility, sustainability, and scalability, are often desired. Flexibility is not easily defined, determined, or costed. Tradespace exploration techniques may provide an answer by giving the designer a larger

system view that includes the relationships between architectural and design choices.

The previously depicted Figure 3 shows a tradespace shifting as a result of changing preferences. Comparing the relative shifting of rank of designs along an iso-cost band gives insight into how particular designs may be robust to these changes (i.e. a point that moves from 3rd to 4th rank would be better than one that moves from 1st to 20th rank).

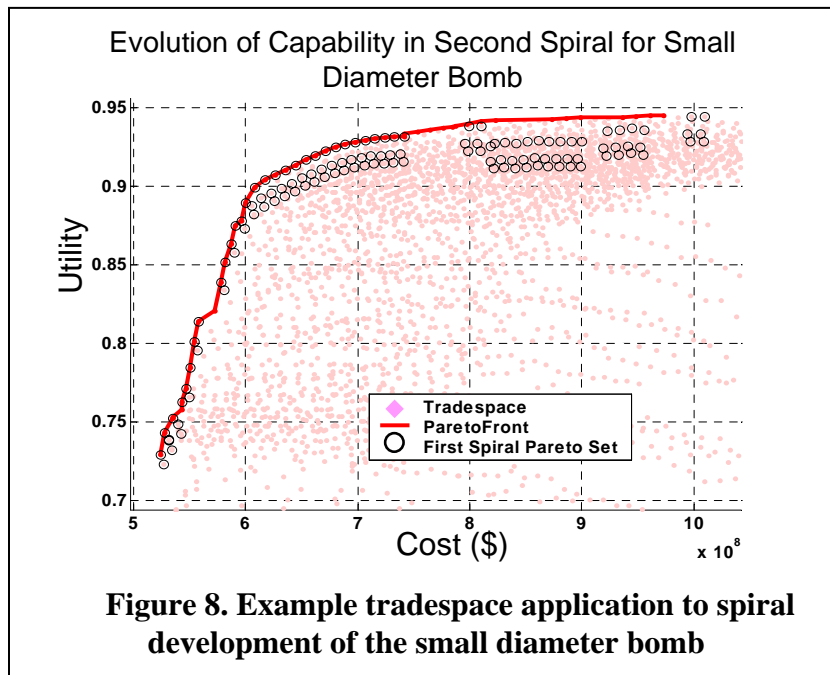
Figure 7 depicts the tradespace for a Space-Based Radar study done by (Spaulding 2003) and analyzed in (Roberts 2003 and Shah 2004). Typical analysis methods would suggest choosing among the designs A, B, D, or E as they lie on the Pareto Front,

however, when looking more closely at these design options, one sees that these points are somewhat “rigid.” If flexibility is valued, meaning, it is useful to have a system that can readily be transformed into a different, but related system at small cost, Pareto Front solutions may not be best suited. (Roberts 2003) and (Shah 2004) suggest that these points are in a sense optimized for best value at a point in time and do not account for changes in future use, a primary motivation for desiring flexibility. In Figure 6, option C has the same utility as option A, however at higher cost. The “dominated” point C, however, can be more easily “transitioned” to points B, D, or E, whereas option A cannot.⁷ The cost differential between option C and option A can be thought of as the cost of flexibility to move up the Pareto Front. Generalized quantifications of path dependence in transitioning between options in a tradespace is a current area of research and aims to help inform the costs and benefits of including system properties such as flexibility into an architecture or design



⁷ The determination of flexibility in this study derived from transition rules that defined what transitions were possible. Computer analysis of each design option revealed how many other options were accessible given the transition rules. “Rigid” designs could transition to far fewer designs than their more “flexible” counterparts.

Example MATE application areas

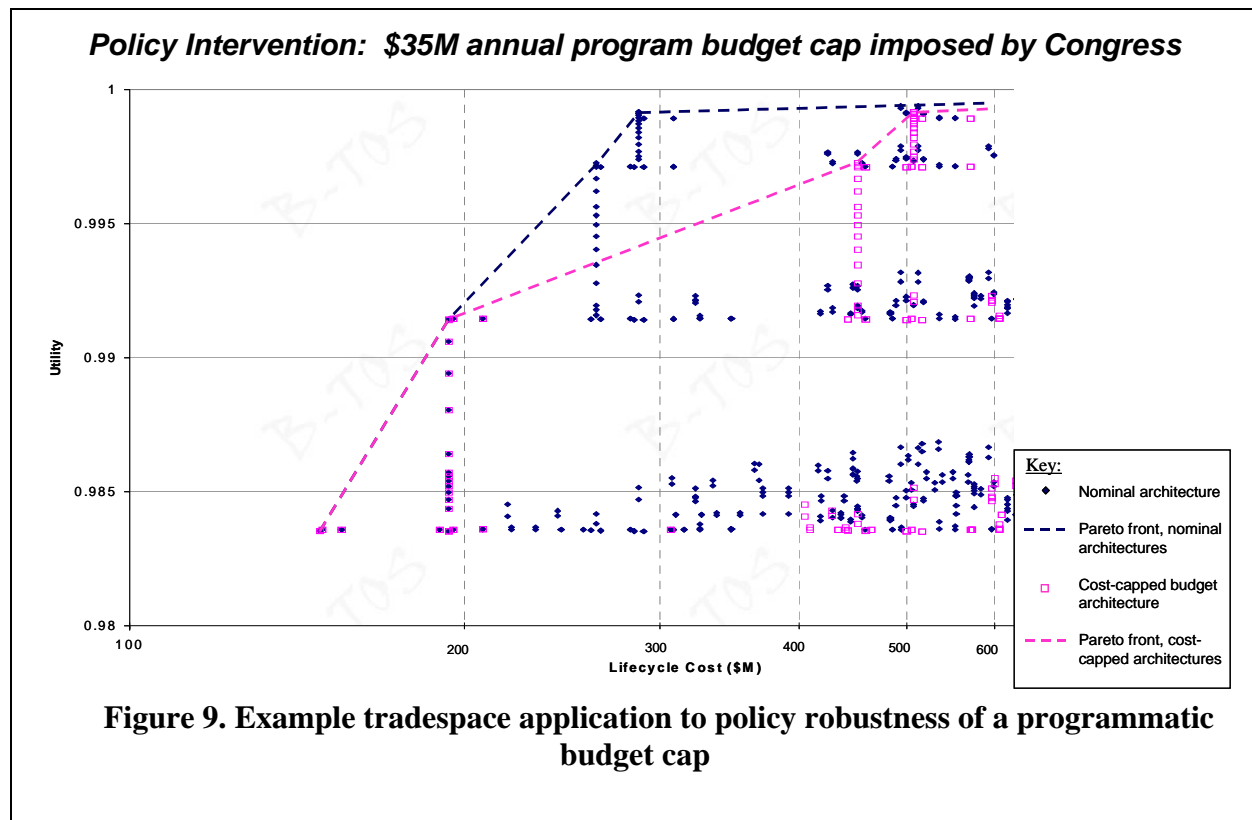


Spiral Development. It is often difficult to decide upon the best architecture or design of systems that are built through spiral development, where successive generations of designs are based upon rapid development and learning from usage in the field. One possible approach to better understanding “spiral-capable” designs is through utilizing tradespaces (Derleth 2003). Figure 8 depicts the tradespace of the second spiral of the small diameter bomb system. Overlaid on the plot are the options (open circles) that

were on the Pareto Front of the first spiral. Some designs remain best utility for a given cost, while others migrate to lower utility, suggesting that designs can be better chosen in the dynamic spiral context. Sensitivities to hypothesized learning from spiral to spiral can be investigated in the tradespace context and better architecture choices can be made.

Policy Robustness. Product development programs inevitably are affected by both nontechnical and system exogenous factors. Policies are often imposed as constraints to the system, however these constraints affect design choices differentially. (Weigel 2002, Weigel 2004b) utilizes the tradespace framework to quantify and identify the impacts of various downward program budget caps imposed by Congress. Figure 9 depicts an example \$35 million annual budget cap on a space system and the differential effect on the system options. The lower Pareto Front points are not affected as much as higher Pareto Front points. If a program manager were operating in an environment where such adverse policies might impact the system, design options along the lower Pareto Front would be less susceptible to expensive program delays due to insufficient funding.

In addition to budget caps, (Weigel 2002, Weigel 2004a) quantified the impact of the US launch policy on both a particular system and the entire historical manifest of US payloads launched. In particular, the US launch policy, which requires US government payloads to be launched on US vehicles, has resulted in higher costs, but at a higher probability of mission success as compared to a minimum cost decision maker. Policy makers can use this explicit quantification to decide both the costs and benefits of their policies on system development.



Conclusions

The power of the value-driven tradespace exploration paradigm has only been introduced in this paper. Value-driven tradespace exploration frees designers to utilize their expertise and creativity in order to develop superior concepts to deliver more value to the system stakeholders. Exploration, as opposed to optimization, better captures the fact that the system concept selection phase is dynamic and complex. An overall system objective function against which a system could be optimized is a poorly defined quantity. One might suggest the utility function is the objective function, however, utility functions are only well-defined for single decision makers and thus if there are many decision makers, there may be many utility functions.⁸ Additionally, the preferences of the decision makers, or utility functions, may change over time. Instead of optimizing, exploring the space to gain insight into the “physics” of the problem space reveals regions of the tradespace that provide value to multiple decision makers and explicitly highlights the tensions and trades that are important.

In addition to its power as a communication tool, the tradespace exploration framework provides designers and policy makers a frame to quantify previously “fuzzy” concepts, such as policy impacts and system properties, such as flexibility and relative robustness to changing requirements. The macro-view of the tradespace enables the creation of portfolios of options that mitigate some of the uncertainty that exists in conceptual design and highlights regions where technology development might provide a large benefit.

⁸ Aggregation of multiple decision maker utilities is a fundamental problem addressed by Political Science and has been proven to be impossible without a “dictator” defining the relative value of each decision maker (see Arrow’s Impossibility Theorem in (Hazelrigg 1996)).

Value-focused tradespace exploration continues to be a directed area of research and through its introduction into education curricula at MIT, may provide a natural mechanism for developing more holistic thinking system designers.

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Biography

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Daniel Hastings. Dr. Hastings holds a Bachelors degree in Mathematics from Oxford University, and both Masters (Aeronautics & Astronautics) and Doctoral (Plasma Physics) degrees from MIT. He currently serves as the Director of the Engineering Systems Division and holds a dual appointment as full professor in both the Department of Aeronautics and Astronautics and the Engineering Systems Division at MIT. His current research interests include space system architecting and space policy and technology policy.