MANAGING UNARTICULATED VALUE: CHANGEABILITY IN MULTI-ATTRIBUTE TRADESPACE EXPLORATION

by

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Submitted to the Engineering Systems Division
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Abstract

A framework for creating value robust systems in the face of changing value perceptions during the architecture and design of systems is proposed. Both unarticulated value, that which is not explicitly communicated to system designers, and dynamic value, that which changes over time, are used to motivate the dynamic Multi-Attribute Tradespace Exploration (MATE) process. Value can be represented as decision maker perceived attributes, which can be classified according to the ease by which the system can display them. The attribute class spectrum from least to most costly ranges from articulated, class 0 attributes, to inaccessible value, class 4 attributes. Supporting the value-adding approach, the system property concepts of flexibility, adaptability, rigidity, robustness, scalability, and modifiability are proposed to be different aspects of the same concept: changeability.

A quantification of changeability is shown to be the Filtered Outdegree of a design within a networked tradespace formed through explicit consideration of transition paths between design instantiations. A focus on designing not only for value, but for changeability as well, leads to the concept of path enabling variables, whose purpose is to increase change paths or decrease cost for change. Value robustness is shown to be achieved through either passive or active means. Passive value robustness can be quantified as the Pareto Trace number of a design, reflecting the number of contexts within which a particular design is determined to be best value at a given level of resource expenditure. Active value robustness is achieved through a strategy of pursuing designs with increased changeability and accessibility to likely high value regions of a tradespace. Supporting the process, the Design-Value Matrix and the Rule-Effects Matrix help system designers visualize the key factors for creating dynamic value-generating systems by capturing the important relationships between decision makers, design variables, attributes, path enablers, and resources.

The dynamic MATE process is applied to two real system cases including the Joint Direct Attack Munition (JDAM) and the Terrestrial Planet Finder (TPF). The framework is shown to be applicable at both quantitative and qualitative levels, giving insight into assessing and designing for changeability and value robustness for systems.

Thesis Supervisor: Daniel E. Hastings
Title: Professor of Aeronautics and Astronautics and Engineering Systems

To my family: Mom, Dad, and Brian, who provide my shelter in the face of an ever changing world…

Also to the dream…

Acknowledgements

As a general disclaimer, the author must admit that even if it appears as if he isn't paying attention to you, he is… The influences to his thinking come from everyone at all times, though the influence may not always be obvious. As such, acknowledging everyone who has contributed to the author's thinking, and therefore influenced the present work, cannot be done. Thank you to everyone who has touched my life. You should know who you are.

The academic adventure that is a PhD began in 2000, when I entered the MIT graduate program in Technology and Policy and Aeronautics and Astronautics, though I did not yet realize the PhD lay beyond the two Master of Science degrees. As part of an understanding with my advisor for a break, I took nine months off of school after finishing the Masters in June 2003. Solo-backpacking around New Zealand and Australia in the Fall of 2003 gave me fresh perspective, both on the world and in myself. I would like to thank the people and land of **New Zealand** who welcomed me at every turn and empowered me to discover my own ability to change and recognize exciting opportunities for personal growth.

Upon returning to MIT in January 2004 to begin the PhD in earnest, my advisor, **Professor Daniel Hastings,** thrust me back into the thick of things. Through his inspiring intellectual leadership, experience, and challenge, he reminded me why I returned from the intellectual freedom of wanderlust abroad for the intellectual gauntlet of MIT; tempered by the fires of academic inquiry, a mind grows sharper and can open doors unexpected. Thank you for your advice, stories, and support. I cannot imagine a better advisor or mentor for my temperament and interests. I only hope future graduate students will have the same positive experience as you begin your journey improving the lives of the MIT undergraduate community as the new Dean for Undergraduate Education.

While not interacting with these faculty members as often as my advisor, **Professors Olivier de Weck**, **Deborah Nightingale**, and **Thomas Allen** were incredibly influential guiding my intellectual growth. Each member was selected to be on my doctoral committee because of their perspectives joining aerospace with fields of my professional interest. Professor de Weck brought his experience with technical optimization techniques, especially multi-dimensional optimization and numerical exploration of space system design concepts. Professor Nightingale .brought her experience with the Lean Aerospace Initiative, including perspective and priorities of industry and government, which are often forgotten or neglected in academia, yet are keenly relevant for having impact. Professor Allen brought his experience with social interaction research and managerial psychology, representing the human side of the aerospace design problem. Thank you all for your guidance and perspectives; you have helped me to recognize the value of my work and how to view the world from new context perspectives.

Though not a member of my committee per se, **Dr. Donna Rhodes** provided invaluable feedback and support, both professional and personal throughout the doctoral effort. Thank you for your insights and friendship.

The members of the Hastings research group during my PhD time has changed over the years. When I returned from my "sabbatical," the goateed face of **Andrew Long** was waiting for me. A

new graduate student to MIT yourself, you provided a refreshing attitude that helped me in my transition back to school life. Recognizing the value of your direct and entrepreneurial style has inspired me to embrace those traits within myself. **Roshanak "Roshi" Nilchiani**, you succeeded in showing everyone the value of flexibility, both in your dissertation and in your PhD research style. Now I finally understand your absence from the lab during your final semester: the inspirational distractions brought on by the lab's collection of great minds are not conducive to finishing! Thank you for sharing your passion for space and humor for the space geeks surrounding you. **Nirav Shah** is the last of the pre-2003 gang involved in the development of my MATE Masters work. You are the keeper of the flame after I have left. I have great respect for your abilities, both intellectual and spiritual. Thank you for engaging conversations about the nature of systems, religion, and undergraduate life at MIT! I have known **Matt Richards** since his summer internship at the Jet Propulsion Lab in summer 2001, when I was working there as well. You have brought spice and enthusiasm to the lab, desperately needed in your absence. Thank you for taking me seriously when I need you to and not, when I don't. As the freshest of the PhD students, it is up to you to preserve the intellectual vitality and humor of the Hastings group. No pressure. **Captain (or is it Major?) Jason Bartolomei**, your enthusiasm and military experience have greatly enhanced my MIT experience. Thank you for showing me the value of charisma, charm, and deep questions; I look forward to continued intellectual sparring in the future. Your ability to juggle a PhD under a strict three-year time constraint, a family with four children, and an active military consulting docket, all while being an all-around great guy, is truly inspiring. **Spencer Lewis**, MIT prodigal son returned from a tour of duty in industry, has the amazing ability to ask questions ranging from the inane to the deeply profound, all of which inspire people present to pay attention lest they miss a key laugh or a key insight. Thank you for reminding me that there is no such thing as a dumb question; curiosity empowers us in the search for Truth.

Former members of the Hastings SSPARC group continue to influence me and must be explicitly acknowledged. **Dr. Myles Walton**'s work on tradespace uncertainties is still not formally included in ongoing research, but does remain an ever present reminder that uncertainty is not inherently bad, as it provides opportunities as well as risk. **Now-Professor Annalisa Weigel**, provided valuable advice as the senior graduate student in the group during my Masters work. During my PhD work, Annalisa was hired as a junior faculty member and continues to provide useful advice, though at a different level. Thank you for leading the way and showing me what success looks like after a PhD in space systems academia, as well as renewing hope that Wall Street will not lure away *all* of the young, smart space talent (hmmm Myles…). As the operating leader of the SSPARC project, **Dr. Hugh McManus** provided more senior mentoring and practical advice on a daily basis during my Masters work. While you have evolved to more of a consulting role these days, you are the world's second leading expert on MATE. Given your industry and academic experiences, your continued interest in MATE gives me great confidence that maybe it does provide some value. Thank you for sage advice, amusing stories, and setting an example for a comfortable work-life balance.

As co-inventor of the MATE-CON process, I must acknowledge **Lt. Nathan Diller**, even if he's off flying aircraft overseas. Applying MATE to picking presidents, you truly appreciated the generalizeable power of the MATE thinking. Too bad you owe the next decade or so to the military; your Harvard Kennedy School/MIT Engineering School education would serve you

well in future MATE consulting applications… I wish you the best. Thank you for forcing me to think about sticking around for a PhD, even if you called me Dr. Ross about four years too soon…

Two prior MATE researchers need to be mentioned as well: **Lt. Timothy Spaulding** and **Dave Stagney**. You gentlemen were taught the MATE method in your space system design course and actually believed it to be useful enough to incorporate into your own Masters research. Thank you for taking MATE and improving it! You have both provided motivation for considering MATE in a dynamic, real world context. Tim, thank you for your humor and holiday cards;, which for some reason make me want to get a dog and drive really fast. Special thanks are in order to my buddies from MIT Masters time: **Chris Roberts** and **Jason Derleth**. Even though neither of you stuck around for further MIT basting, you've continued to stay a part of my life, reminding me of what I gave up by continuing my RA stipend in place of a "real" job. Thank you for your friendship and open-invitation to visit DC and California. I hope to take you both up on those offers again soon!

No system exists in a vacuum, and neither does any graduate student, except maybe the experimental physicists, but I digress. I would like to acknowledge the **LAI** and **ESD** students and staff for providing a sense of community, irrespective of whether I decided to look up from my work. The opportunity for social outings for drinks, food, pool, whatever, reminded me that I was in fact at a school of people and not a factory of robots, as I was wont to become when buried in work.

During the course of some of the theoretical development of the PhD work, I enlisted the help of my theoretical physicist/mathematician friend **Alan Jamison**. I have known him since early high school, somehow ended up with him at the same university, and later under related employers. He keeps me connected to physics and the love of learning. Thank you for reminding me of the power of abstract thinking through formalized mathematics, getting me to take more advantage of Boston culture, and sharing the value of good barbeque and used books (the latter abundant in Boston, the former not so much).

The **Engineering Systems Division (ESD) faculty** has taught me the value of lateral thinking with depth. In order to be credible in academia, one must understand deeply. In spite of pressures to contribute within a well-defined field. ESD faculty have broken out of their "stove-piped" disciplinary departments and have tried to show that deepness also exists across their fields. It remains to be seen if junior faculty can succeed in such a dual expectation environment, but it is inspiring to be a part of the first generation of engineering systems PhDs who see the world in all of its multi-disciplinary-colored glory. Thank you for crafting such an excellent program and opportunity for intellectual growth. I cannot imagine any other PhD that I'd rather pursue.

Mom, **Dad**, and **Brian**, thank you for your unwavering support and enthusiasm for my academic adventures. I know it has been a long ride, but it is finally over (at least official, expensive, formal learning… you've taught me that learning is a life-long adventure and I don't plan to ever stop). Now you can call me the Doctor… or just Adam. Whichever.

Natasha Gordon, I cannot imagine what it is like to go through the PhD process without the benefit of grades or diploma. You have gone through all of my ups and downs, though tend to feel the downside more than the upside due to my tendency to complain more than praise. Thank you for your patience and support during this truly difficult experience. What doesn't kill us makes us stronger, right? Here's to a strong and happy life! Now to find those beautiful golden sunsets, lilting flutes floating on lazy summer clouds, and excited puppies…

The author gratefully acknowledges the financial support for this research from the Lean Aerospace Initiative (LAI), a consortium including MIT, government, and industrial members of the aerospace industry.

Biographical Note

Mr. Ross holds a joint Bachelors degree in Physics and Astronomy & Astrophysics from Harvard University and two Masters degrees (Aeronautics & Astronautics, and Technology & Policy) from the Massachusetts Institute of Technology (MIT). He is currently finishing (or maybe has already finished, depending on when you read this) his Doctoral degree in the Engineering Systems Division with a specialization in space system architecting and design. He serves as a Research Assistant with the Lean Aerospace Initiative at MIT.

Born in southern Connecticut in 1977, Adam Ross moved to Florida for high school where he came to over-appreciate the hot weather and constant flux of tourists. Anxious to return to the Northeast, and interested in learning about anything and everything, he headed to Harvard University in 1996 for an undergraduate liberal arts education. Since the quest for truth underscored much of his introspective musings, he decided to pursue an education in Physics and Astronomy and Astrophysics in an attempt to understand the workings of the very small to the very large. He also took enough courses in Economics to earn a minor, if only Harvard offered such a thing.

His work experiences include summer and term-time jobs at MIT (Lean Aerospace Initiative, Space System Policy and Architecture Research Center), JPL, NASA Goddard Spaceflight Center (during NASA Academy), Hughes Space and Communications (now Boeing Satellite Systems), Smithsonian Astrophysical Observatory, Harvard University (Jefferson Physical Laboratory), USDA, and Florida State University (Materials Research Department).

While at Harvard he started a student organization, the Society for the Exploration and Development of Space (SEDS), in an effort to educate and promote discourse in the larger Harvard community. Space was not just an object of scientific inquiry, but a place to be explored by all humankind.

While lobbying Congress with SEDS, he came to realize that many of the barriers to an expanding human presence in space stemmed from political, not technical, factors. Armed with this knowledge, and the realization that he probably wouldn’t become a world-renowned physicist, he decided to head off to the Massachusetts Institute of Technology in 2000 for graduate school, enrolling in both the Aeronautics and Astronautics department and the Technology and Policy Program (TPP). He knew little to nothing about engineering and figured that MIT would give him a good idea about how space systems were conceived and created. Additionally, the TPP education would help him better understand the non-technical barriers to space exploration.

His philosophy during his graduate education is one of eclectic synergy. He tries to learn a bit about many fields and recognize useful crossover applications. An example of such work is this thesis, which attempts to bridge individual and group psychology, economics, decision theory, and engineering design.

On the personal front, Adam strives to lead a balanced life. He can often be seen at the gym, reading a book, hiking in the wilderness, or staring at the stars. Landscape painting and music composition stand at the top of his “most-preferred to pursue, but not quite there yet” hobbies. He enjoys the company of his friends, family, and the occasional alien.

His goal in life is to visit Saturn someday. (Actually one of its moons since the surface of the planet itself is quite unsubstantial.) And after that, maybe head on a grand tour of the rest of the planets. Surely nothing is impossible.

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Preface

As most doctoral students probably feel, the author of this work feels that the following dissertation is much more than is written on the page. This work will attempt to formalize a method for thinking about decision-making and design in the context of change. Applications of the method and illustrations of the logic were chosen to balance understandability and usefulness to the reader against the expectations of an academic audience and the rigorous technical requirements of a doctoral work. In any case, the author hopes that the framework will help readers to better frame the problem that confronts all designers of complex systems: how to balance the creation of value with judicious expenditure of resources while keeping an eye on the ever changing context of both the developing and (hopefully) deployed system.

Many perspectives, both actual and theoretical, will be discussed. As a general convention, the reader should put himself in the shoes of the system designer. It is from this perspective that the following work is derived. Attempts to "get into the head" of other decision makers and stakeholders seek to clarify to the designer how both value and generalized costs may be viewed. Assuming that designers seek to balance utility and cost of system designs, this perspective is the right one to have, as long as the designer understands the biases introduced from this perspective. As the pivotal decision maker, the Designer must realize that his interpretation of value determines the ultimate shape of the system. During design, the "articulated" values of stakeholders only matter insofar as they affect the Designer's efforts.

In an effort to draw a relatively clear boundary around the scope of this work, the author has decided to apply the framework and methods in the context of aerospace systems. While it is a simple matter to extend the work to other areas, when the author refers to a "system," "aerospace system," or "space system," he is usually thinking in terms of expensive, complex systems with relatively few stakeholders/demanders/consumers. Keeping in mind the caveats presented during the course of the dissertation, it is probably safe for the reader to substitute the system of their choice for "system," though due to scoping considerations, the author makes no presumption of general applicability.

Additionally, the foundation for the doctoral research is the author's Masters of Science thesis: *Multi-Attribute Tradespace Exploration with Concurrent Design as a Value-centric Framework for Space System Architecture and Design*, 2003.[1] The reader of the current doctoral work would benefit greatly from an understanding of the concepts and examples presented in the prior work. Since the Masters thesis is referenced extensively in the current work, the reader is suggested to have access to the Masters work for easy reference. (Access is not required for a casual understanding of the current work, but is strongly recommended for a more complete and deeper understanding by any potential user of the proposed theory contained herein.)

Throughout the work, potential research topics generated by the text will be indicated in footnotes by a "🖇🕮." These avenues for further work are also gathered in the final chapter for easy reference.

[1] Ross, Adam M. (2003). Multi-Attribute Tradespace Exploration with Concurrent Design as a Value-centric Framework for Space System Architecture and Design. Dual-SM thesis in Aeronautics and Astronautics; Technology & Policy Program. Massachusetts Institute of Technology. Cambridge, MA: 258.

Chapter 1: Introduction

The limits of our creative potential are a function of our experiences. (Ross 2003) represents the culmination of three years of research into the nature of space system conceptual design, attempting to build up from first principles a "new" approach to developing systems of value. Unlike Science, which seeks to reveal some "Truth" hidden in Nature, Engineering seeks to manipulate Nature in order to fulfill some human purpose. Human need thus forms the core motivation for engineering design, and therefore the determinant of "value."

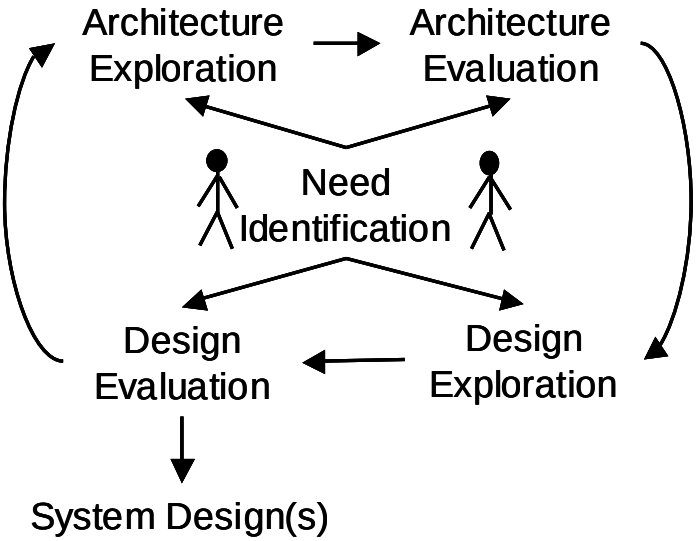

Figure 1 High-level MATE-CON activities[2]

The work done in (Ross 2003) marries decision theory, economics, and psychology to traditional engineering design in order to better capture the notion of "value." Multi-Attribute Tradespace Exploration with Concurrent Design (MATE-CON) is the proposed process in the previous research.[3] Figure 1 shows a high-level view of the MATE-CON process, which keeps the focus on delivering value throughout the conceptual design process. While (Ross 2003) shows that the process is "better" than traditional design processes, the work is incomplete, however, in fully capturing sources of value (Ross 2003; Ross, Hastings et al. 2003; Ross, Diller et al. 2004). Several researchers have applied MATE (the process without the Concurrent Design activity) to case studies involving aerospace systems and have gained insights into how the process can be used to illuminate other sources of value not captured by the attributes, explicit determiners of value in MATE. Additionally, interactions with "real world" practitioners of aerospace system conceptual design provide motivation for developing a more complete Conceptual Design

[2] Figure from (Ross 2003)

[3] The MATE-CON research was conducted as a part of the Space System Policy and Architecture Research Consortium (SSPARC). SSPARC's mission was to "develop new tools and processes to produce better, less expensive space systems more rapidly within technical and economic limits, while considering the impact of policy" (Ross 2003). The consortium, sponsored by the National Reconnaissance Office, included researchers at MIT, Caltech, Stanford, and the Naval Postgraduate School.

process that enables value-focused broad tradespace exploration, including consideration of multiple system properties, or "ilities."

1.1 Motivation

Conceptual design is a special point in the development process for products or systems. 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 (see Figure 2). The selection of the design concept and high level specifications are the outputs of this phase and inform the preliminary design phase to follow. Figure 3 below highlights the major activities conducted during Conceptual Design.

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. Tradespace exploration during conceptual design may empower designers to overcome these difficulties, as well as enable them to respond to dynamic changes to the system throughout the system development lifecycle.

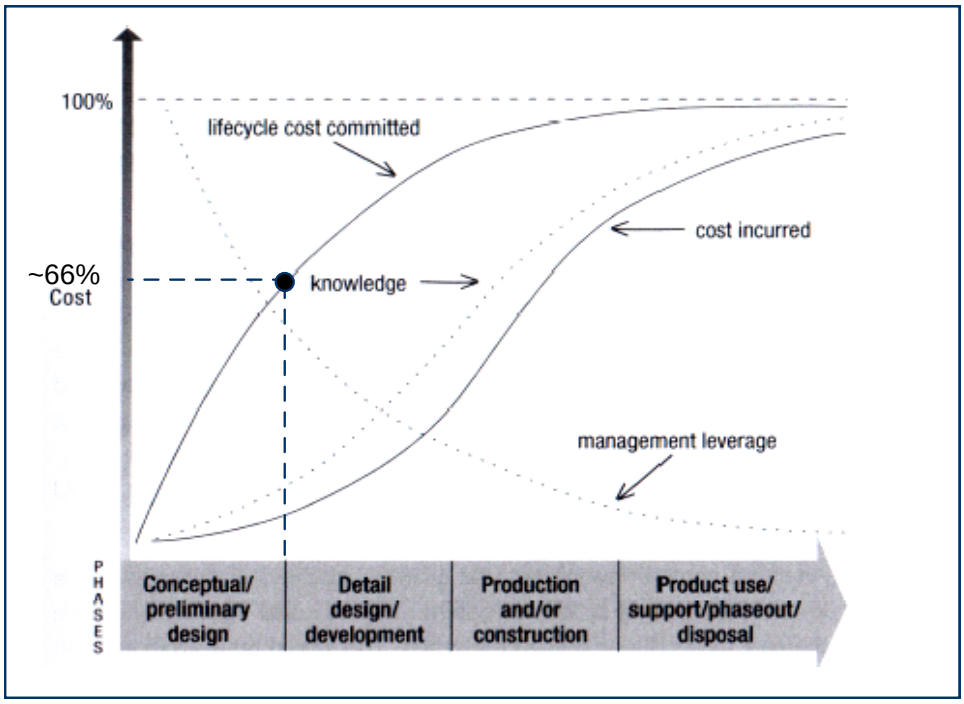

Figure 2 Cost committed versus cost incurred across product development phases show Conceptual/Preliminary Design as a high leverage part of process[4]

[4] Figure from Fabrycky, W.J. (1991). Life Cycle Cost and Economic Analysis. NJ, Prentice-Hall.

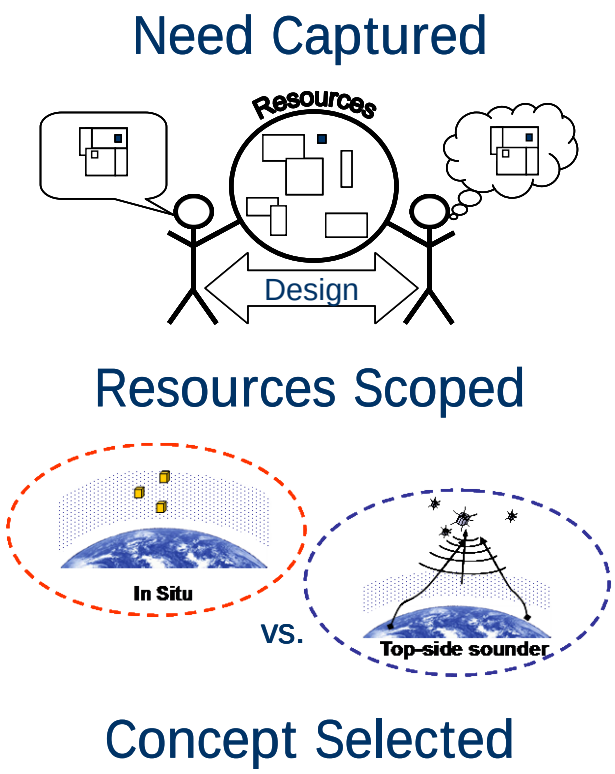

Figure 3 Principal activities during Conceptual Design include capturing need, scoping resources, and selecting concept

1.1.1 Previous MATE work

At the conclusion of (Ross 2003), several researchers were applying MATE to their research, finding useful techniques. The following questions were raised in these research studies: How can MATE be used as a guiding framework throughout an enterprise? (Stagney 2003). How can MATE be used to understand changes in preferences in a tradespace? (Spaulding 2003). How can MATE be used to generate "better" requirements? (Diller 2002). How can MATE be used to gain insight into a dynamic development process, such as spiral development? (Derleth 2003). How can MATE be used to quantify flexibility? (Roberts 2003) and (Shah 2004). How can MATE be used to design a space system? (16.89 2002), (Galabova, Bounova et al. 2003), and (McManus and Schuman 2003). How can MATE be used to quantify policy effects? (Weigel 2002). These questions were answered to varying degrees, with no definitive answers provided. They do, however, all provide insights into advanced analysis techniques that can be employed within the MATE framework, suggesting additional sources for providing "value" to system designers besides the directly assessed "utility."

1.1.2 External Interactions

Over the course of developing a research agenda, it is often useful to question its boundaries and motivations. Fresh insights from new sources can provide a welcome change to approaches and modes of thought. Three key interactions with interests outside of the researcher's typical research sphere have redirected the agenda: the Engineering Systems Division External Symposium, an Air Force/Industry Workshop, and an interactive study involving site visits to organizations in the aerospace industry.

1.1.2.1 Conferences (Internal/External ESD symposia)

In March 2004, the ESD External Symposium brought together people from both academia and industry to discuss the emerging field of Engineering Systems.[5] One of the recurrent themes of the symposium was the nature of system properties, or "ilities" What were these ilities and were they a fundamental aspect of systems? Does knowledge of these ilities allow for better system design?

1.1.2.2 Workshops (LAI/AF)

A Lean Aerospace Initiative/Air Force Workshop on System Engineering for Robustness in June 2004 challenged the aerospace community to develop a process that enables systems engineering for "Robustness". "Robustness" according to Dr. Marvin Sambur, Assistant Secretary of the Air Force for Acquisition at the time of the workshop, means:

- Capable of adapting to changes in mission and requirements;
- Expandable/scalable, and designed to accommodate growth in capability;
- Able to reliably function given changes in threats and environment;
- Effectively/affordably sustainable over their lifecycle;
- Developed using products designed for use in various platforms/systems; and
- Easily modified to leverage new technologies.

These goals are similar to the ESD defined ilities of adaptability, scalability, robustness, sustainability, and flexibility. Experts at the workshop admitted no such comprehensive approach existed and that further research was required in order to adequately address the Air Force need. One key problem that kept being raised involved the fact that the customer often wants to have ilities, but is not willing (or does not know how) to pay for them. A framework that allows for consideration of ilities during conceptual design, including quantification of value, would provide value to both the military and industry.

1.1.2.3 Industry Study

The MATE process was mostly developed within MIT, with additional input from SSPARC consortium members, including the Industrial Advisory Board. In order to further develop the process as useful, relevance to the real world needed to be established, including comparison to industry state-of-practice and needs. The researcher conducted a study, which included a series of surveys and interviews, in order to qualitatively assess and motivate further MATE development.

Traditionally, need is captured through requirements generation and management. According to the ESD Definitions Working Paper 2002-01, requirements are "the combined set of functions, ilities, and constraints (e.g., weight, volume, cost, physical laws) that an engineered system is supposed to achieve, deliver, or exhibit; functions can be said to be what a system 'does,' whereas the ilities and constraints are properties that a system 'has'." Thus far, the functions and ilities have been captured by MATE through the notion of attributes, which are decision-maker defined metrics. It is entirely possible that the attributes correspond only to functions, ilities, or

[5] See http://esd.mit.edu/symposium for access to the agenda, with links to presentations, and the ESD monograph (cited 3/18/06) See for example Moses, J. 2004, "Foundational Issues in Engineering Systems: A Framing Paper."

even form solutions. No limitations have been placed on the creation of an attribute, except insofar as it must be operationalized through a quantifiable metric in order to assess utility. (Note that quantifiable does not necessarily imply continuous or unbounded.)

In addition to delivering value through developing a system that "performs well in the attributes," the system architect or engineer can apply expertise to develop a system that may anticipate unarticulated attributes. System properties, whether desired by a decision maker or not, will exist and can be tracked by the system designer. The system properties, which can be classified into "ilities" and constraints according to (ESD_Symposium_Committee 2001), can give the designer information regarding the "goodness" of a design in addition to the explicitly defined attributes, or articulated value, to a decision maker.

For the industry study, a pre-interview survey sought to understand both how well and how important addressing the ESD ilities is during Conceptual Design. The ESD ilities, or system properties, may be one approach to addressing unarticulated need. In addition to the ilities listed in Table 1, Manufacturability, Operability, and Testability were also included in the survey. (Appendix A contains the pre-interview survey, including ESD definitions of these ilities.) Both senior and systems engineers were interviewed, with space system Conceptual Design experience ranging from 2 to over 20 years.

Table 1 ESD-defined Ilities

P1	Flexibility
P2	Agility
P3	Robustness
P4	Fail-safe
P5	Adaptability
P6	Scalability
P7	Modularity
P8	Safety
P9	Durability
P10	Sustainability
P11	Quality
P12	Reliability
P13	Reparability
P14	Maintainability

The results of the survey suggest that sustainability, flexibility, scalability, agility, and adaptability are poorly addressed, and yet very important to address in Conceptual Design, implying further research into these ilities to be of high value to industry. Figure 4 and Figure 5 show the primary survey results, sorted by industry type[6]. FFRDC (Federally-funded Research and Development Center) and Prime (Prime aerospace contractors) were the two industry types considered. Manufacturability, Operability, and Testability were all considered important research priorities, but are not considered for further research since they are "downstream" and

[6] Research priority = product of two survey question responses: (Q2-Q1)*Q2 (gap in how well it is addressed now weighted by how important it is to be addressed)

the researcher had chosen to exclude them from analysis. (It is interesting to note that they were indicated to be important, however).

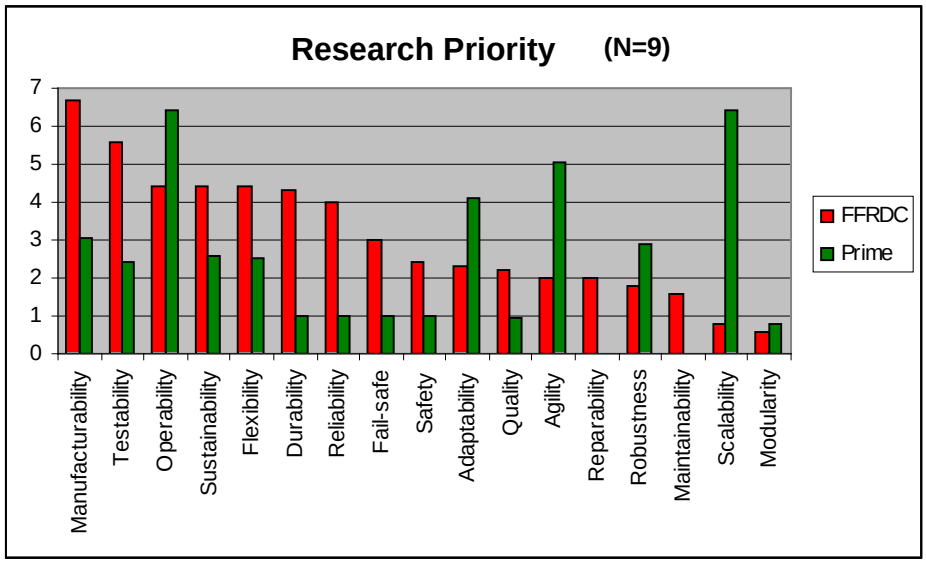

Figure 4 Ility Research Priority according to Pre-interview Survey (sorted by FFRDC)

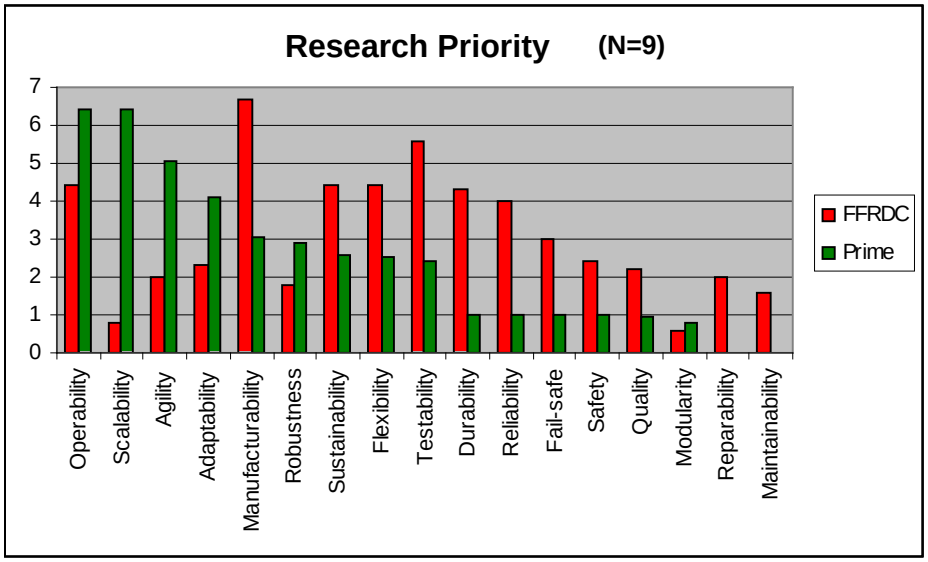

Figure 5 Ility Research Priority according to Pre-interview Survey (sorted by Prime)

Following the pre-interview survey, a series of on-site interviews were conducted. A copy of the semi-structured interview used is in Appendix B. (Note that whether and in which order the questions were asked varied across interviews based on participants' responses.) The interviews tried to assess three key issues faced during a space system conceptual design process:

1. How need is captured
2. How tradespaces are explored and evaluated
3. How the analyses fit into the larger organization and system development processes

Results from the interviews suggested that broad tradespace exploration is rare and often done in an ad hoc manner. Figure 6 shows some quotes from the interviews. Though not complete, the findings suggest that industry is unable to effectively explore tradespaces or account for ilities during Conceptual Design, motivating a real need for this research.[7]

> ***"True time-based analysis is difficult and may be inappropriate as details are shrouded by uncertainty in early design"***
>
> ***"Alternatives that are looked at are usually a synthesis of what senior people have had experience with… it's hard to argue with success, but no formal AoA is done…"***
>
> ***" 'ilities' are not part of the lexicon of even the most successful project managers"***
>
> ***"In order to deal with fidelity unknowns… we just re-use designs"***

Figure 6 Selection of quotes from interviews

1.2 Research Scope

The intent of this research is to expand upon the previous Masters work, (Ross 2003), to include consideration of four ilities and how they relate to not explicitly expressed, or unarticulated, value. The scope of the research is drawn both in order to bound the duration of research, as well as to increase the depth of knowledge within the domains previously studied. Fields considered include: Decision theory, Economics, Individual and Group Psychology, as well as Engineering Design and Optimization.

Recognizing that previous research questions were too broad, and that including consideration of all of the ESD ilities into the MATE framework is likewise too ambitious, new research questions were derived. These questions include the most important ilities, as revealed by the "real world" motivations discussed above.

1.2.1 Key Research Questions

Following the motivating interaction with the "real world" and ongoing research within ESD and the researcher's sponsor, the key research questions are:

1. What are the relationships between flexibility, adaptability, robustness, and scalability for aerospace systems and how do they relate to unarticulated value?

2. How can these ilities be quantified and/or used as decision metrics when exploring tradespaces during Conceptual Design?[8]

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[7] In fact, all participants expressed interest in a follow-up meeting to discuss deployment of this research.

[8] If ilities can be quantified, can they be used as attributes themselves, similar to "design flexibility" in Thurston, Deborah L. (1990). "Multiattribute Utility Analysis in Design Management." IEEE Transactions on Engineering Management **37**(4): 296-301.

1.2.2 Expected Research Contributions

The research contributions, motivated by the research questions, fall into the following six categories:

1. A unified definition of flexibility, adaptability, robustness, and scalability.
2. Quantification of flexibility, adaptability, robustness, and scalability.
3. A framework for capturing and representing unarticulated value.
4. A framework for discovering "best" solutions in multi-decision maker tradespaces.
5. A framework for considering "design for changeability."
6. Insight into real world aerospace system relevance through case applications.

1.3 Research Design—Methodology

In order to address the two research questions, the research design involves four main thrusts: knowledge capture and synthesis, theory development, experiments, and case applications. Knowledge capture and synthesis builds off of prior work in value-centric tradespace exploration. Theory development seeks to build new knowledge, informed by insights garnered through the other three thrusts. Experiments seek to isolate and understand complex relationships in a tradespace study, allowing for direct feedback between hypothesis generation and testing. Case applications seek to apply the research to more "realistic" and "messy" problems in order to better understand the limits, applicability, and deployability of the research.

1.3.1 Knowledge Capture and Synthesis

Tackling these questions is exploratory in nature, though the researcher is beginning with the MATE framework as a starting point. A number of theses and projects have used MATE since the publication of (Ross 2003), and have insights into how MATE may be used to assess such issues as policy robustness (Weigel and Hastings 2004), flexibility (Roberts 2003), and scalability (Spaulding 2003; Shah 2004). Figure 7 shows an example of how flexibility may be considered for the Space Based Radar system in a MATE framework (Roberts 2003). In the figure, various design options are plotted in terms of value (utility) and cost. The design option point A is on the Pareto Efficient Front of "best" value at cost. The design option point C, is at the same utility, but greater cost, so it typically would be considered to be an inferior solution. When considering change, however, option C can be transitioned to option B, D, or E, whereas option A cannot be transitioned. Roberts asks whether the difference in cost between option C and option A is the cost of the flexibility of option C, suggesting a mechanism for capturing flexibility in a tradespace framework. Figure 8 shows an example of how policy changes can affect a tradespace and reveal designs that are policy robust (Weigel 2002). The open box points represent design options affected by a policy change, whereas the closed points represent design options before the policy change. Design options are differentially affected by the policy and some points are shown to not be affected at all. Such unaffected points could be considered to be policy robust.

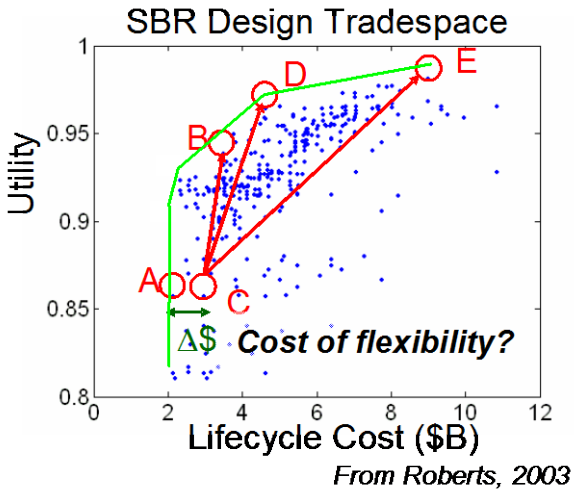

Figure 7 Example ility in MATE: Flexibility

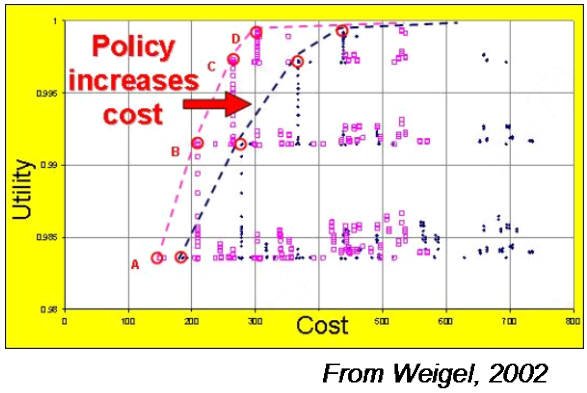

Figure 8 Example ility in MATE: Policy Robustness

1.3.1.1 Tool Development

One form of knowledge synthesis and capture is the formation of a standardized set of tools and approaches for conducting MATE studies. During the course of the research, the researcher created and compiled a set of Matlab functions into a MATE toolbox. Additionally, a standardized graphical user interface (GUI) was developed in order to facilitate future MATE analyses. Just as physicists have their laboratory, design engineers have their computer models and simulations.

Knowledge capture also involved recasting previous MATE studies, including the B-TOS, X-TOS, and SpaceTug studies, into a graphical model integration environment: Phoenix Integration's ModelCenter.[9] Figure 9 shows the X-TOS model in this graphical environment.

[9] The B-TOS and X-TOS studies were conducted as a part of a series of satellite mission designs called "Terrestrial Observer Satellite(s)". The series included A-TOS (in-situ ionospheric sampling satellite swarm), B-TOS (top-side sounding ionospheric observing satellite swarm), C-TOS (concurrent design effort applied to B-TOS), and X-TOS

The integration environment allows for easy reuse of modular code in order to facilitate new model development.

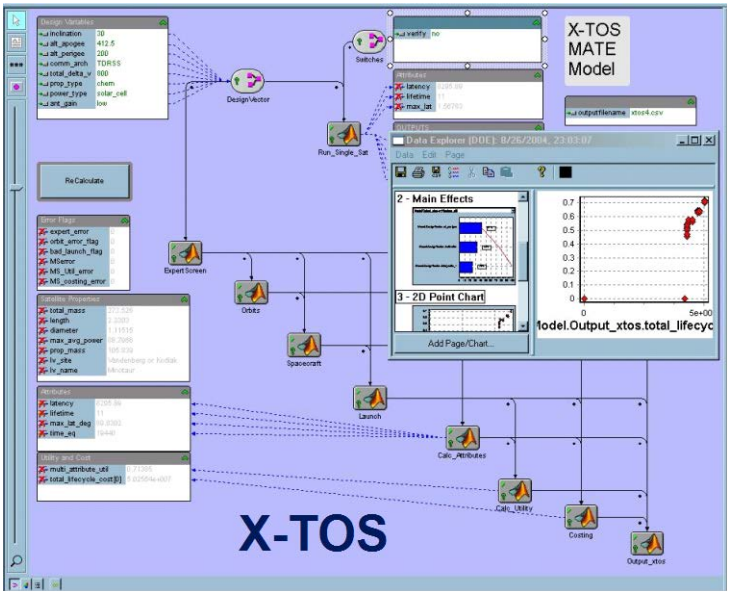

Figure 9 X-TOS MATE Model in ModelCenter

1.3.2 Theory Development

Theoretical work focuses on understanding the fundamental nature of the four ilities under consideration: flexibility, adaptability, robustness, and scalability. In particular, how these ilities can be quantified in a tradespace framework and how these ilities may interact with one another. Additionally, work was done investigating psychological phenomenon such as *experienced* versus *decisional* utility to get at the difference between articulated and unarticulated value.

1.3.3 Experiments

In order to isolate ility effects in tradespaces, a series of computer experiments were conducted. The outcomes of these experiments informed the theoretical and practical application developments for use in the case applications outlined below.

1.3.3.1 Dynamic context: temporal and conflicting preferences

In an effort to gain insight into robustness and flexibility in tradespaces, the following question is posed: How is a tradespace affected when articulated value changes? Two classes of value changes will be considered: 1) a single decision maker whose preferences change over time, and 2) the addition of new/different decision makers with their own preferences to the single decision maker preference set. These two classes represent a change in the "objective function" (value, or utility) for the system design effort. Insights are gained into how particular designs are "robust" to these changes in objective function, as well as how some might be "flexible" to meeting new objective functions. (Definitions for "robustness" and "flexibility" follow in later chapters.) It is anticipated that "optimized" designs, (i.e., those designs on the Pareto Front of best utility at a

(in-situ atmospheric sampling satellite) missions. The Space Tug study was a smaller summer study to analyze potential designs for a satellite whose mission is to move, or "tug" other satellites into new orbits.

given cost) may not perform well under new objective functions. As real world systems face changing preferences, "optimizing" designs according to a static objective function may be a poor strategy.

For these experiments, the X-TOS dataset was used.[10] The time consuming process of running the X-TOS models and simulations has already been accomplished, along with the necessary model validations. Figure 10 shows the X-TOS User attribute set, including name, range, units, direction of increasing utility, and definition. The experiments entailed changes to the attribute set and utility functions that were post-processed off of the X-TOS dataset. The "original" solution space (with a single, static decision maker) was used as the baseline for comparisons. Statistics were collected on each "perturbed" tradespace, including Spearman's Rho (see (Spaulding 2003) for an example on how Spearman's Rho can be used to compare tradespaces. Also see (Ha and Haddawy 1998) for a discussion of preference "closeness."), iso-cost design orderings, and the Pareto Set of designs. Since the perturbations only affect the utility values, iso-cost statistics can be employed.

Attribute	Range	Units	DIU	Def
Data Life Span	0.5-11	years	more	Elapsed time between the first and last data points
Sample Altitude	150-1000	km	less	Height of data sample
Diversity of Latitudes	0-180	degrees	more	The spread of latitudes in the data
Time spent at the Equator	0-24	Hours/day	less	Time spent per day near the equator
Latency	1-120	hours	less	Time from collection to transmission

Figure 10 The X-TOS User attribute set (DIU: Direction of increasing utility)[11]

1.3.3.1.1 Single Decision Maker

The single decision maker experiments are as follows:

Baseline: X-TOS dataset,

- 5 attributes: Data Life Span, Lat. Div., Equator Time, Latency, and Sample Alt. Do not manipulate Sample Alt due to lack of altitude attribute data for all points.

"Optimal" defined as Pareto Set

Exp1a "Major change" (Represents incomplete set or addition of new attributes)

- Reduce attributes X_i: Remove 1 or 2 or 3

[10] X-TOS is a satellite mission developed by the graduate students in MIT's graduate space system design course in Spring 2002. The mission involved a low altitude satellite conducting in-situ atmospheric density measurements.
[11] Figure from Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design.

- Add attributes X_i: (Add mass)

Exp1b "Moderate change" (Represents changes in attribute priorities)

- Changing attribute weights k_i: Compare "true" to rank ordered per Spaulding, X-TOS before and after

Exp1c "Subtle change" (Represents changes in attribute perception)

- Changing utility shape $U(X_i)$: Substitute linear prefs for 1, 2, or 3.

Exp1d "Evaluative change" (Represents changes in analyst valuation methods)

- Changing utility U(X) functional form: linear weighted sum, multiplicative, MAUF, modified MAUF (without K).

Independent variables

- $U(X_i)$, k_i, $X_j \varepsilon \{X_i\}$

Dependent variables

- Spearman's Rho: ρ_{sp}, Pareto Set

1.3.3.1.2 Two Decision Makers

The two decision makers experiment is as follows:

Baseline: X-TOS dataset,

- 5 USER attributes: Data Life Span, Lat. Div., Equator Time, Latency, and Sample Alt. Do not manipulate Sample Alt due to lack of altitude attribute data for all points.
- 4 CUSTOMER attributes: IOC Cost, Development Time, Satellite Lifespan, Satellite Mass

"Optimal" defined as Pareto Set

Exp2a "Static Pareto"

- Find Pareto Set for 2 static preference sets

Independent variables

1. $U(X_i)$, k_i, $X_j \varepsilon \{X_i\}$

Dependent variables

2. Spearman's Rho: ρ_{sp}, Pareto Set

These experiments provide insights into how robustness and flexibility to value perception changes can be viewed in a tradespace framework.

1.3.4 Case Applications

Two case applications are conducted, including application to an already designed system and a system currently in design. The already designed system is the Joint Direct Attack Munition (JDAM), developed by Boeing. The currently being designed system is the Terrestrial Planet Finder (TPF) space telescope, being developed by the Jet Propulsion Laboratory (JPL). Interviews, primary and secondary sources, and computer-based models and simulations are used to address dynamic issues that have heretofore not been considered, yet are fundamental to issues such as adaptability and robustness.

1.4 Structure of the Thesis

The structure of the dissertation is as follows: **Chapter 2** provides a brief overview of topics covered in the literature that had significant influence over the synthesis of ideas in the research. Not all literature referenced in the chapter will be explicitly addressed in the main body, nor is the listed literature exhaustive of the influencing body of knowledge that resulted in this work. **Chapter 3** provides a short overview of the static MATE value-centric design process, with extensive referencing to (Ross 2003) for more detailed discussions. MATE provides the foundation from which the current research builds. **Chapter 4** expands the restricted view of value presented in classical MATE analysis to include "unarticulated" value. **Chapter 5** introduces the concept of time, its relation to decision-making and design, and motivation for incorporating temporal analysis in order to deliver sustained value. **Chapter 6** defines the system properties, or "ilities," of interest in this research: flexibility, adaptability, scalability, modifiability, and robustness. **Chapter 7** applies numerical computer experiments to changing tradespaces in an effort to deduce quantitative methods for capturing system properties in practice. **Chapter 8** synthesizes the previous chapters and introduces dynamic MATE analysis. A running example applied to the X-TOS space system is provided to elucidate concepts and methods. **Chapter 9** and **Chapter 10** apply the dynamic MATE analysis at varying levels of fidelity to real world systems: the Joint Direct Attack Munition (JDAM) system and the Terrestrial Planet Finder (TPF) system. **Chapter 11** provides a discussion of the research, including limitations, implications, and potential application areas. **Chapter 12** summarizes the findings and suggests avenues for future work. **Chapter 13** lists references from the main text. **Chapter 14** is a notation glossary, which, though not exhaustive, attempts to highlight key variables used in the analysis. The remainder of the thesis contains various **Appendices** containing supporting data, templates, and references a reader may find of interest.

Chapter 2: Relevant Concepts Overview

This chapter will introduce various concepts that provide a foundation for much of the work that follows. It is by no means an exhaustive review, and additional concepts and sources will be introduced in later chapters. What follows does provide a basic introduction to motivating concepts for the thesis.

2.1 "Value"

> **Value**, n. 1: a fair return or equivalent in goods, services, or money for something exchanged; 3: relative worth, utility, or importance.[12] 6f: The quality of a thing considered in respect of its power and validity for a specified purpose or effect.[13]

The concept of value is at once abstract and yet pervasively accessible. It represents the essential raison d'être for human action: perceived benefit net of cost. The pursuit of value motivates exchange in markets, both formal and informal, as well as the discipline of design. Without creation of value, activities are an exercise in futility, promoting to the heat death of the universe without compensating benefit. Due to its inherently subjective nature, perceptions of value must be communicated between value-consuming and value-creating entities in order to ensure needs are met. The communication, or articulation, of value is a core concept in the design enterprise, often represented as "Needs Identification" in traditional development processes.[14]

The notion of articulated value is discussed in (Ross 2003), and for the purposes of this research will be assumed to include the explicitly communicated desires, or elicited attribute set, for each decision maker. The unexpressed, or unarticulated, values include those "somethings" that give value to the decision maker, but for one reason or another were not elicited in the attribute set. Reasons for decision makers having unarticulated values range from "could not" to "would not" to "should not" say. Chapter 4 will discuss the concept of unarticulated value in more depth and introduce a framework for capturing and anticipating their effects on value delivery through system design and realization.

(Keeney 1992) discusses the approach called "value-focused thinking" as opposed to "alternatives-focused thinking." The key differentiator between these approaches is to recognize that understanding the core value propositions of a decision maker can enable decision opportunities, especially to create new or additional value, as opposed to trying to seek criteria for already offered alternatives. Also discussed is the role of understanding and eliciting the objective hierarchy for a decision maker and identification of "fundamental objectives," which are those objectives that drive value perception, as opposed to the means for attaining value.

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[12] From Miriam-Webster Dictionary online, www.m-w.com/dictionary/value, cited 4/11/06
[13] From Oxford English Dictionary online, www.oed.com, cited 4/11/06
[14] See for example Chapter 4, "Identifying Customer Needs" of Ulrich, Karl T. and Steven D. Eppinger. (2000). Product Design and Development. Boston, Irwin McGraw-Hill..

Examining the psychological concept of value at the individual level, (Fischhoff 1991) discusses a continuum of value philosophies. The "philosophy of articulated values" proposes that people can answer any question put to them regarding their perception of value. The "philosophy of basic values" proposes that people can only answer questions relating to basic perceptions of value and must use inference to answer particular synthesized questions in context. Decision analysis, and multi-attribute utility theory in particular, tends to adhere to the latter philosophy, with utility functions corresponding to the basic values from which specific evaluation decisions can be made. Inappropriately assuming the articulated values philosophical approach can result in "misplaced precision, undue confidence in results, and missed opportunities to help."[15] Inappropriately assuming the basic values philosophical approach can result in "needless complication, neglect of basic methodology, and induced confusion."[16] Table 2 lists conditions that are favorable to using the Articulated Values philosophy, with its direct evaluation techniques. Engineering design efforts typically do not fall into these ranges of conditions and suggests usage of the Basic Values philosophy, with decision theoretic approaches to evaluation.

Table 2 Conditions Favorable to Articulated Values [Table from (Fischhoff 1991)]

Personally familiar (time to think)
Personally consequential (motivation to think)
Publicly discussed (opportunity to hear, share views)
Uncontroversial (stable tastes, no need to justify)
Few consequences (simplicity)
Similar consequences (commensurability)
Experienced consequences (meaningfulness)
Certain consequences (comprehensibility)
Single or compatible roles (absence of conflict)
Diverse appearances (multiple perspectives)
Direct relation to action (concreteness)
Unbundled topic (considered in isolation)
Familiar formulation

In the product design realm, (Roy 1990) explains the concept of the Taguchi loss function, which is equivalent to the negative value achieved by a system. A target value for a parameter is assumed to deliver maximum value to a consumer, while a deviation from that target gives decreasing value, or increasing loss. The goal of quality design is to minimize the loss function (deviation from the target value), or in other words, to maximize the value to the consumer.

Brining the concept of value to groups of individuals, (Cook 1997) and (Cook and Wu 2001) address the valuation of goods using revealed and econometric data, describing methods

[15] pp. 623. Kahneman, D. and A. Tversky, Eds. (2000). Choices, Values, and Frames. New York, Cambridge University Press. quoting Fischhoff, Baruch. (1991). "Value Elicitation: Is There Anything in There?" American Psychologist **46**(8): 835-47.
[16] pp. 623. Ibid.

frequently used in marketing and economic analysis. Statistical analysis on product demand and product attributes reveals those attributes most linked to revealed (demanded) value by the market. Most applicable to mass-produced goods, (Downen 2005) extends the approach to the small business jet market.

Brining the notion of value to a more encompassing level, the Lean Aerospace Initiative's (LAI) book *Lean Enterprise Value*, describes value as identifying, proposing, and delivering "needed capabilities of product or service" to end users and other stakeholders.[17] Originally deriving its roots from the Lean approach to reducing waste in manufacturing, the modern Lean philosophy has expanded beyond waste elimination and moved into the realm of continuous improvement driven by "doing the job right" as well as "doing the right job." The elimination of waste as well as the creation of value across an enterprise are the core themes in (Murman, Allen et al. 2002).

2.1.1 Utility Theory and Related "Value" Theories

Utility theory is a framework which attempts to capture and quantify the concept of value in order to use it as a criterion for decision making support. Commonly used in economic analyses as a metric for consumer choice, utility theory was formalized by a set of axioms in (von Neumann and Morgenstern 1947). (Ross 2003) introduces the application of utility theory in the context of space system design.

Expanding from a single attribute consideration to multiple ones, (Keeney and Raiffa 1993) derive the multi-attribute utility function and discuss approaches to garnering the attribute set of articulated values. Attributes not included in the set will not be included in the utility function and thus excluded from the decision metric for distinguishing between and among options. Alignment of costs and benefits within a multi-attribute utility function is not addressed and represents a tension that differentiates generic decision theory from engineering design. (Keeney 1992) discusses insights that can be gained from violation of utility axioms in practice, representing cognitive biases that prevent decision makers from following the rationality assumptions underlying the theory.

In practice, expected utility theory has been shown to be lacking as a descriptive theory of behavior. (Kahneman and Tversky 1979) introduced Prospect Theory as an alternative to Utility Theory. Merging understandings from Psychology and Economics, Prospect Theory incorporates empirically displayed cognitive biases, such as perceptions on differences instead of absolutes, loss aversion from a perceived baseline frame of reference, risk-seeking reversal from the loss to gain domain, and subjective interpretation of probabilities. The descriptive validity of Prospect Theory is superior to that of Utility Theory, however, its normative superiority is suspect. If decision makers seek adherence to the axioms of Utility Theory, they would be better off pursuing decisions supported by Utility Theory instead of Prospect Theory.[18]

Recognizing the subtleties of actual decision metrics, (Kahneman and Tversky 2000) discuss various types of utilities, including the difference between decision and experienced utility. "Experienced" utility is the hedonic perception of the present and rapidly changes into

[17] pp. 194. Murman, Earll, Thomas J. Allen, et al. (2002). Lean Enterprise Value. New York, Palgrave.
[18] The debate of prescriptive (or normative) versus descriptive theories (what *should be* versus what *is*) is addressed in (Ross 2003).

"remembered" utility in the mind of the individual. A rational, or at least learning, individual's "decision" utility will be informed by the "remembered" utility. In practice, losses and biases transform the utilities during migration from experience to decision. The temporal perception of value is described through theory and experiments, as well as the phenomena of how the framing of choices affects perception of value, including preference reversal.

(Dyer, Fishburn et al. 1992) discusses the difference between multi-criteria decision making and multi-attribute utility theory, including prospects for research advancement. Allowing for the assessment of decision alternatives in an ambiguous environment where the alternative set can change over time is a new area of application for these methods and relates directly to the research in this thesis.

2.2 System Properties: Ilities

In addition to the typical concerns of a system designer which typically include cost, schedule, risk, and performance, lifecycle issues should be considered for systems. The system properties, or "ilities," include concepts such as flexibility, adaptability, scalability, and robustness, which relate more to the lifecycle aspect of the traditional four system design concerns.

The motivation for changeability over a system lifecycle is categorized into three major drivers according to (Fricke and Schulz 2005): 1) dynamic marketplace, 2) technological evolution, and 3) variety of environments. These drivers result in two key aspects for system architecture to address: 1) they must be able to be changed easily and rapidly, and 2) they must be insensitive or adaptable towards changing environments. These concepts will be found to be synergistic with the work done in later chapters of this thesis.

2.2.1 Flexibility

The concepts of flexibility are varied, but a similar vein runs through: it has to do with how easily a system can be changed.

(Fricke and Schulz 2005) characterize flexibility as a "systems ability to be changed easily [by external agents, in order]… to cope with changing environments."[19]

In (Moses 2002), flexibility relates to the ability to "implement classes of changes in specifications with relative ease." Furthermore, the flexibility of a system can be quantified by "the number of paths in it, counting loops just once." The programmability of a system therefore relates to the flexibility, with more potential "paths" existing in a programmable system. So too does the ability to add nodes, "modify existing nodes, or create interconnections between nodes." Two types of flexibility are distinguished: 1) the ability to make numerous, small changes, and 2) the ability to make few, large changes. The author discusses three generic system organizations: the tree structured hierarchy, the network structure, and the layered hierarchy structure and how these organizations relate to both flexibility and complexity.

[19] pp. 347. Fricke, Ernst and Armin P. Schulz. (2005). "Design for Changeability (DfC): Principles to Enable Changes in Systems Throughout Their Entire Lifecycle." Systems Engineering **8**(4): 342-359.

The notion of flexibility is fairly well understood in the manufacturing realm, as discussed in (Shewchuk and Moodie 1998; Giachetti, Martinez et al. 2003). The former paper details the many existing, but conflicting definitions of flexibility in terms of two key aspects: the flexibility type and the flexibility measure. The type is the name of the aspect about which flexibility is desired. The measure is the proxy metric used to reflect how flexible a system actually is. In the latter paper the authors use formal measurement theory to propose aspects of system metrics and classify them into two types: structural or operational. Structural metrics are a property of the system itself, while operational metrics are a function of the operating conditions (i.e., temporal and context dependent). They then survey the manufacturing flexibility literature and assess proposed flexibility metrics in terms of their classification scheme.

(Chen and Yuan 1998) describes a probabilistic approach to achieving flexibility in design. By using probability distributions and probabilistic models, the proposed design approach allows for a range of solutions to satisfy a ranged set of requirements. While suggesting flexibility through finding solutions that can meet a range of requirements, this approach is similar to robust design in Axiomatic Design, where the goal is to find design parameters that maximize the probability of meeting functional requirements, (Suh 2001).

A number of recent research endeavors at MIT have attempted to capture aspects of flexibility for space systems. (Shaw 1999) defines flexibility as a type 2 adaptability metric, which can be defined "to be the proportional change in the CPF (Cost-per-Function) in response to a particular mission modification," quantified as:

$$F\big|_X = \frac{\Delta CPF}{CPF}\bigg|_X ,$$

where X is "just an identifier to specify the mission modification."[20]

(Saleh 2002) defines flexibility as "the property of a system that allows it to respond to changes in its initial objectives and requirements-both in terms of capabilities and attributes-occurring after the system had been fielded, i.e., is in operation, in a timely and cost-effective way." The important distinction here is that flexibility is a property that is measured after the system has been fielded. Two types of flexibility are discussed: capability, the ability for the system "to change its mode of operation," and attribute, the ability for the system to modify its performance. The author reveals that flexibility is very broad in scope and refines his approach to only consider the system lifetime, quantifying the value of flexibility in terms of lifetime extension.

(Nilchiani, Hastings et al. 2004) discusses flexibility in terms of on-orbit servicing of space assets. The author describes three classes of flexibility that make up "provider-side flexibility": mix flexibility, volume flexibility, and emergency service flexibility. Mix flexibility, akin to the capability flexibility mentioned above, reflects the strategic ability to "offer a variety of services with the given system architecture." Volume flexibility, on the other hand, similar to the attribute flexibility mentioned above, reflects the ability to "respond to drastic changes in demand."

[20] pp. 125. Shaw, Graeme B. (1999). The Generalized Information Network Analysis Methodology for Distributed Satellite Systems. Sc.D. thesis in Aeronautics and Astronautics. Massachusetts Institute of Technology. Cambridge: 290.

Emergency service flexibility reflects the "tactical ability of the system to provide emergency (non-scheduled) services to satellites in duress." The provider-side flexibility metric is described as the weighted sum of these three components. The author also describes a real options valuation method for flexibility though a case study example of the Hubble Space Telescope, summarizing the work in (Joppin 2004). (Nilchiani and Hastings 2004) adds the concept of software flexibility to address uncertainty faced by remote assets in space. The following metric is proposed to quantify flexibility:

$$F^{t_a - t_b} = \left(\frac{\sum_{i=1}^{n} R_i\left(p_i(t)\right)_{flex}}{\sum_{i=1}^{n} R_{i\,conv}} \right) \cdot \prod_{i=n+1}^{m} \left(\frac{U_i\left(p_i(t)\right)_{flex}}{U_{i\,conv}} \right) \cdot \frac{\int_{t_a}^{t_b} dC_{conv}}{\int_{t_a}^{t_b} dC_{flex}},$$

where

$F^{t_a - t_b}$: Flexibility of the space system over the time interval *ta - tb*

Ri: Discounted value of monetary benefits of function *i* of the system over its specified lifetime

i: system function *i* that is of importance to the stakeholders

Pi(t): Probability that a flexible change occurs to function *i* at time *t*

Ui: Utility of non-monetary system function *i* for stakeholders

C: System cost (total over the time interval of each system),

and *flex* "denotes a flexible system" and *conv* "denotes a conventional (non-flexible) version of the same space system.

The Change Mode and Effects Analysis (CMEA) method proposed by (Rajan, van Wie et al. 2005) defines a change potential number (CPN), which reflects a product's flexibility as:

$$CPN = \frac{1}{N} \sum_{i=1}^{N} \frac{\left[\left(R_i + F_i\right) - O_i + 8\right]}{27},$$

where R_i is the readiness, F_i is the design flexibility, O_i is the occurrence, and N corresponds to the maximum number of potential change modes, the number of potential effects of change, or the number of potential causes of change. R, F, and O are evaluated on a qualitative 10 level scale. According to the CPN equation, the higher the readiness for change—the ability to cause the change—and design flexibility—the ability of the product to be changed—the higher the product flexibility. On the other hand, the lower the occurrence for change—the likelihood of needing the change—the higher the product flexibility. The rationale for this last point is that a low cost for redesign is deemed synonymous with a high degree of flexibility, so it follows that for a system with a low likelihood of change, the expected cost for change is likewise low. An empirical study of mechanical products, such as a Braun Coffee Grinder, Stanley Screw Driver and Sanford Multi-purpose Pen, is performed and used to test the validity of the CPN as a measure of product flexibility.

A unified six-element framework for defining flexibility, formed through a fairly comprehensive review of the existing literature, is proposed in (Nilchiani 2005). The six necessary elements to

define a system's flexibility are the uncertainty, time window of change, system boundary, response to change, the system aspect to which flexibility is applied, and access to the system.

2.2.2 Adaptability

The concept of adaptability is similar to flexibility, except it adds the notion of "self-change."

According to (ESD_Symposium_Committee 2001), adaptability is defined as *"the ability of a system to change internally to fit changes in its environment,"* usually by self-modification to the system itself.

According to (Fricke and Schulz 2005), adaptability "characterizes a system's ability to adapt itself towards changing environments… [they] deliver their intended functionality under varying operating conditions through changing themselves."[21]

2.2.3 Robustness

The concept of robustness relates to a resistance to change; the system has an ability to continue to do or be something in spite of changes.

According to (ESD_Symposium_Committee 2001), robustness is defined as *"the demonstrated or promised ability of a system to perform under a variety of circumstances, including the ability to deliver desired functions in spite of changes in the environment, uses, or internal variations that are either built-in or emergent."*

In his pursuit of robustness, treated synonymously with delivering value, the Taguchi philosophy of quality is based on three ideas[22]:

1. Quality should be designed into the product and not inspected into it.
2. Quality is best achieved by minimizing the deviation from a target. The product should be so designed that it is immune to uncontrollable environmental factors
3. The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

Quality is a measure of closeness to target design for the system. Assuming a value-generating target design is specified, a quality system is one that will deliver more value than a low quality one. Robustness is in a sense, a minimization of loss of quality over time. In particular, Taguchi has a three phase approach to achieving robustness: 1) systems design, 2) parameter design, and 3) tolerance design. Robustness is achieved by minimizing the sensitivity of the system to "noise factors," or those factors outside of the designer's control that affect system performance.[23] Systems design is akin to concept design and is the phase where the "key emphasis… is on using the best available technology at the lowest cost to meet customer requirements obtained through

[21] pp 347. Fricke and Schulz. "Design for Changeability (DfC): Principles to Enable Changes in Systems Throughout Their Entire Lifecycle."
[22] pp 8. Roy, Ranjit. (1990). A Primer on the Taguchi Method. New York, Van Nostrand Reinhold.
[23] Adapted from pp 3. Park, Sung H. (1996). Robust Design and Analysis for Quality Engineering. New York, Chapman & Hall.

quality function deployment (QFD)."[24] The primary concept is selected in this phase. During parameter design, the levels of design variables, specified by the concept, are selected to minimize sensitivity to noise factors. During tolerance design, higher grade components are selected in order to reduce the range of variation of design variables at the level selected during parameter design. The cost of higher grade component selection is offset by lower lifecycle costs for the system due to higher quality.

In Axiomatic Design, as discussed in (Suh 1990; Suh 2001), the concepts of coupled, decoupled, and uncoupled designs are introduced through the Principle of Independence. The relationship between design parameters (DPs) and functional requirements (FRs) can be captured in a notional matrix; Independence is achieved if the DPs and FRs are related in a one-to-one manner. Reordering the matrix to make it lower triangular reveals the dependencies between design parameters and their resulting functional performance. Coupled designs cannot be made lower triangular and have a mostly full design matrix, representing a complex relationship between the DPs and FRs; a variation in one DP could have effects on multiple FRs. A decoupled design can be represented by a lower triangular DP-FR matrix; varying DPs in the proper order can allow a designer to isolate effects on FRs. An uncoupled design can be represented by a diagonal DP-FR matrix, meaning a change in one DP will result in a change in only one FR. Robustness can be achieved through the creation of designs pursuing minimum coupling, mitigating the effects of design variations on performance. Likewise robustness can be achieved by selecting design parameters with relatively "flat" performance curves so that if a variation does exist, the resulting variation in the performance is "flat" as well.

According to a synthesized definition by (Saleh 2002), robustness is "the property of a system which allows it to satisfy a fixed set of requirements, despite changes occurring after the system has entered service, in the environment or within the system itself, from the nominal or expected environment or the system design parameters." The author contrasts robustness with flexibility, stating the former relates to "satisfying a fixed set of requirements" while the latter relates to satisfying "changing requirements after the system has been fielded."

In a more narrow sense of robustness than Saleh, (Fricke and Schulz 2005) define robustness as that which "characterizes a systems ability to be insensitive towards changing environments." This perspective is an inside-out definition, defining the system in relation to its context, excluding variations in the system components. No changes to the system from external sources are necessary in order to achieve this type of robustness.

2.2.4 Scalability

The concept of scalability relates to the change in size or scope of a system at low "cost."

According to (ESD_Symposium_Committee 2001), scalability is *the ability of a system to maintain its performance and function, and retain all of its desired properties when its scale is increased greatly without having a corresponding increase in the system's complexity.*

[24] pp. 5. Park. Robust Design and Analysis for Quality Engineering.

(Fricke and Schulz 2005) describes scalability as an aspect of an architecture that has "units independent from scale or self-similar/fractals."[25] Two ways of approaching scalability are described: 1) the number of identical units in the architecture could be increased or decreased to effect a scalable functional change, or 2) a single unit could be increased or decreased in size to effect a scalable functional change.

(Roberts 2003) discusses "issues of scaling" in relation to an evolutionary acquisition strategy for the Space-Based Radar system. In particular, strategies are suggested using modular or staged approaches to increasing (or decreasing) capability, though with the caveat that one type of risk may be traded for another.[26]

2.3 Conceptual Design (Trade Studies)

Creating value and assessing system properties in system design requires the ability to analyze the mapping from value-space to design-space and the discovery of best solutions. Successful designers have the ability to find these "best" solutions through what some would consider to be magic. (Ross 2003) discusses an effort to bring the abilities held by a few expert designers into a more "natural" process for the general designer, making the "magic" accessible to a wider community. An implicit assumption in that work is that the discovery of successful solutions may rely too much upon intuition, circumstantial experience, and fortune. The complex relationship between dynamic preferences, technology, resource constraints, and the development and operating environments result in a design problem with many possible "bad" solutions. The goal of a good design process is to naturally guide a designer to the "good" solutions, relatively independent of the unique abilities of the particular designer.[27] Understanding the relationship between customer preferences and potential system designs is one of the key pieces of information that may distinguish between bad and good solutions. Conducting trade studies during and before Conceptual Design is one approach to exposing and understanding this relationship.

2.3.1 Product Development

Conceptual Design is the phase during development in which "the needs of the target market are identified, alternative product concepts are generated and evaluated, and one ore more concepts are selected for further development and testing."[28] Since the purpose of development is to deliver value, identifying that value is critically important. Likewise, the delivery of value is in terms of the concept selected. The concept generation and evaluation step is critical to ensure proper matching of value delivery to expectation. (Ulrich and Eppinger 2000) describes product design and development from a consumer good perspective. Of particular interest are chapters 6 and 7: "Concept Generation" and "Concept Selection," which describe techniques for proposing

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[25] pp. 253. Fricke and Schulz. "Design for Changeability (DfC): Principles to Enable Changes in Systems Throughout Their Entire Lifecycle."

[26] Staged deployment may mitigate market risk, by better matching capacity with actual demand. Delaying "full operational capability," however, may increase the risk of technological obsolescence. pp. 63, Roberts, Christopher J. (2003). Architecting Strategies Using Spiral Development for Space Based Radar. SM thesis in Technology and Policy Program. Massachusetts Institute of Technology. Cambridge, MA: 86.

[27] Of course the abilities of the designer determine the extent to which designs are "good." The point is that traditional processes may inhibit ready discovery of good designs due to inefficient communication of key information including, but not limited to, the relationship between customer preferences and design options.

[28] pp. 17 Ulrich and Eppinger. Product Design and Development..

and evaluating concepts. (Unger 2003) explicitly considers the design and development of the product development process as a risk management framework within dynamic and uncertain contexts. Feedback within development process structures, such as the case with spiral development, enables improvement to the concept or system in response to changes in the environment. (Browning 1998) specifically addresses consideration of schedule design and customer valuation through development process design. Using Design Structure Matrices (DSMs), Browning uses stochastic schedule and cost models to integrate cost, schedule, and performance analyses to inform management options and controls to improve product development planning.

2.3.2 Tradespace Exploration

Moving beyond the traditional trade study process that may consider up to a couple dozen concepts for evaluation, tradespace exploration seeks to compare hundreds to thousands of designs in order to better understand the underlying relationship between preference structure and potential designs.

Proposing the Generalized Information Network Analysis (GINA) approach to conceptual trade studies, (Shaw 1999) introduces the concept of exploring a large set of space system design options in terms of generic metrics that allow for "apples-to-apples" comparison across disparate concepts. (Jilla 2002) takes the GINA approach a step further by adding multi-disciplinary optimization techniques to more efficiently assess and compare the space of design options. Proposing the Multi-Attribute Tradespace Exploration (MATE) approach, (Ross 2003) replaces the information-centric metrics of GINA with value-centric metrics from utility theory. (Ross and Hastings 2005) summarize the work of several space system tradespace research theses through their contribution to tradespace exploration insights, especially in terms of understanding "higher order" effects on designs, including differential responses to uncertainty, policy and budget constraints, and changing preferences.

(de Weck, de Neufville et al. 2004) discuss the staged deployment of a satellite constellation using tradespace paths instead of "optimal" points. The dynamic deployment of the design seeks to reduce exposure to market risk by tuning capacity over time. (Chaize 2003) more fully elaborates on the nature of tradespace paths and their relation to platforming strategies for space system design. Another dynamic use of tradespaces is discussed in (Roberts 2003), which uses tradespace exploration to provide insight into acquisition strategies, including spiral development of capabilities. Strategies incorporating transition paths of designs for the Space-Based Radar (SBR) system are proposed, with the potential for incorporation of new technologies and system capacity tuning over time.

2.3.3 Design of Experiments

When exploring tradespaces, the problem of determining which designs to study is a real one. Limited computational resources must constrain the design space since the number of design options that can be considered grows at a geometric rate. As an example, a system that can be characterized by three variables, with two levels of each variable is of size $n=L^V=2^3=8$. 5 variables with 3 levels each would have $n=3^5=243$. In general,

$$n = \prod_{i=1}^{DVN} L_i$$

where DVN is the number of variables, and L_i is the number of levels of variable i. A typical design problem has DVN~7-9, and L_i~5-10, putting n in the range 78,125 to 1,000,000,000. If the assessment of each design takes finite time, then performing a full factorial (complete enumeration) assessment may take a very long time. Design of Experiments (DOE) is a process by which an analyst can sample a smaller fraction of the possible space and still draw meaningful conclusions about the structure of the space. (Antony 2003) provides an introduction to engineers and scientists on the use of DOE for improving processes, in particular with full and fractional factorial experiments. (Box 1999; Box and Liu 1999) use DOE with Response Surface Methods (RSM) as a method for discovering best designs for a paper helicopter, without needing to consider the full enumeration of design options.

Other techniques for tradespace sampling include latin hypercube, fractional factorial, and orthogonal arrays.[29] Any advanced DOE text will provide more information on these techniques, among others.

2.3.4 Pareto Visualization

In a multi-dimensional optimization problem, the concept of optimality must be expanded beyond the simple scalar solution available in a single dimensional problem. The Pareto Set of design options includes those that satisfy the Pareto optimality conditions, which include those designs whose objective function values cannot be increased without decreasing one of the other objective function values. (Jilla 2002) discusses the role of Pareto optimality and the representation of the Pareto Set as a "Pareto Front" of designs in a tradespace framework.

Discovery of the Pareto Front can be accomplished using DOE or optimization techniques. (Yukish and Simpson 2004) describes discovery of Pareto points in multi-dimensional data sets. After discovery of the Pareto points, visualization should be done in order to communicate choices for effective decision making. (Stump, Yukish et al. 2004) have developed the Trade Space Visualizer (ATSV) to represent multi-dimensional data created during engineering design. In particular this technique has been used to visualize design uncertainty. (Lotov, Bushenkov et al. 2004) discuss a Pareto visualization method at length as a useful decision-making aid for multi-dimensional problems. The technique of Interactive Decision Maps includes usage of color, contour lines, and interactive sliders to help the decision maker discover the Pareto surface.

2.4 System Analysis Methods

Various methods typically used in systems analysis can be applied to the problem of dynamic tradespace exploration. While not all of these methods will be used, their formulation and applications have informed the development of later theory. Additional methods are referenced in the text as appropriate.

[29] Taguchi methods (discussed previously under robustness) include usage of DOE techniques to readily discover robust design options. Orthogonal arrays are used to reduce the number of design combinations for consideration. (Jilla 2002) compares Taguchi orthogonal arrays to other heuristic optimization techniques in terms of computational efficiency for finding families of "best" design options.

2.4.1 Valuation Methods: Discrete Choice Analysis

Discrete choice casts the consumer choice problem into one of discrete events, such as "buy" or "not buy." The probability of "buy" can be described by functional models whose form is the basis for discrete choice analysis. In general a "buy" decision is made if the utility to a decision maker exceeds some threshold. Since both the threshold and the true functional form for the decision maker utility function is unknown, the choice is probabilistic.

$$U=V+\varepsilon,$$

where V is the observed value function, and ε is the unobserved component of value. Different assumptions on the distribution of ε result in different models. The logit model is used when ε is assumed to be independent of each other, whereas the probit model is used when ε is jointly normally distributed. (Train 2003) provides a good overview of the different discrete choice models and their derivation through simulation.

Discrete choice analysis can be a functional fit-based approach to determining revealed value in a marketplace based on product attributes. Data, either empirical or simulation-based, reflecting consumer choices must be available in order to derive the quantitative parameters in these types of discrete choice models. (Cramer 2003) describe the logit model functional form for discrete choice analysis. A logistic equation is used to express the probability of discrete choice. (Wassanaar, Chen et al. 2005) extend discrete choice analysis from the realm of market research to that of engineering design. A hierarchy of attributes is mapped to engineering parameters and used within a decision-based design process to motivate potential designs and the customer demands for those designs. In all of these models, consumer preferences are aggregated and their complete value functions are assumed to be non-deterministic. The use of such models in markets with few consumers may not be appropriate due to small sample size and the potential for explicit attribute valuation discussions.

2.4.2 Optimization Methods (dynamic programming, etc)

In order to find the "best" value for a system, mathematical techniques known as optimization can be employed. Optimization seeks to maximize or minimize the value of an objective function given constraints on factors to be altered. (Hillier and Lieberman 1995) gives a good introduction to optimization techniques used in operations research, such as linear programming, integer programming, and dynamic programming. (Cook and Russel 1993) discusses optimization techniques in the context of management science, and in particular as a tool for assisting decision making.

2.4.3 Decision Theory

In general, decision theory is the field dedicated to helping people to make better decisions. Usually it involves a formalization of the structure of the definition of a problem, generation of alternatives, assessment of the alternatives, and selection criteria for choosing the best alternative to solve the problem. (Buchanan and Andrew 2006) gives a good overview and history of the development of decision theory from reading entrails to the marriage of Psychology with Economics in modeling actual human decision processes. Utility theory, mentioned earlier, is a type of decision theory, where the criteria for evaluating outcomes is the utility function and the alternatives are assessed in terms of their performance in attributes of the utility function. Many

decision theoretic approaches exist. A popular alternative to utility theory is the Analytic Hierarchy Process (AHP). AHP uses pairwise comparison of alternatives to derive the best solution to a problem. (Bhushan and Rai 2004) describes using AHP in strategic decision making.

2.4.4 Real Options Analysis

A concept borrowed from the financial markets, a real option gives the right, but not the obligation, to exercise a change on a system for a specified price at a specified time. Real options provide a mechanism to "calculate the value of flexibility," a previously difficult task for engineering analysis.[30] (Wang and de Neufville 2006) provide two case examples of screening for real options "in" engineering systems, specifically for the placing of a hydro power system, and the deployment of a satellite constellation. A screening model followed by a simulation model is used to identify high potential real options for further consideration and valuation.

Various applications of real options to technical considerations have been conducted. (Shishko, Ebbeler et al. 2004) describe using real options to value technology development choices for NASA missions. (Rouse and Boff 2004) provide a framework for using real options to value a firm's R&D as a way to create options for meeting "contingent needs" and mitigating uncertainty.

In sum, real options provide a useful framework for valuing options for change, but do not necessarily provide insight into what should be changed. (Wang and de Neufville 2006) and other real option "in" system papers attempt to consider system element changes, as opposed to system management changes, however further work needs to be done to identify key elements that can be valued using real options. (Real options valuation techniques are useful after the options have been identified.)

2.4.5 Network Analysis

A network is a graph of nodes, or vertices, connected by arcs, or edges, as shown in Figure 11. A growing subfield within the sciences, both physical and social, seeks to apply this mathematical model to real systems in order to explain various structural forms and resulting behavior phenomena. (Newman 2003) summarizes network theory applied to complex systems, addressing concepts from basic graph theory to models of network growth and processes. (Ahuja, Magnanti et al. 1993) describes network model formulations for problems and optimization techniques to solve minimum cost, maximum flows across them.

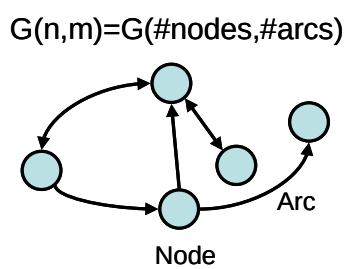

Figure 11 Network representation with nodes and arcs

[30] pp. 9, de Neufville, Richard. (2004). Uncertainty Management for Engineering Systems Planning and Design. Engineering Systems Symposium 2004, Cambridge, MA, MIT.

Chapter 3: MATE: Static Value-centric Design

This chapter introduces the important concepts from (Ross 2003), in particular laying out the foundational principles for Multi-Attribute Tradespace Exploration (MATE), a static, value-centric design process and philosophy.

3.1 The Goal of Design

Let us suppose that the following statement captures the goal of design:

Create a system that fulfills some need while efficiently utilizing resources within some context

Traditional design approaches either begin with a need or a pre-conceived system and attempts to fill in the remaining goal elements.[31]

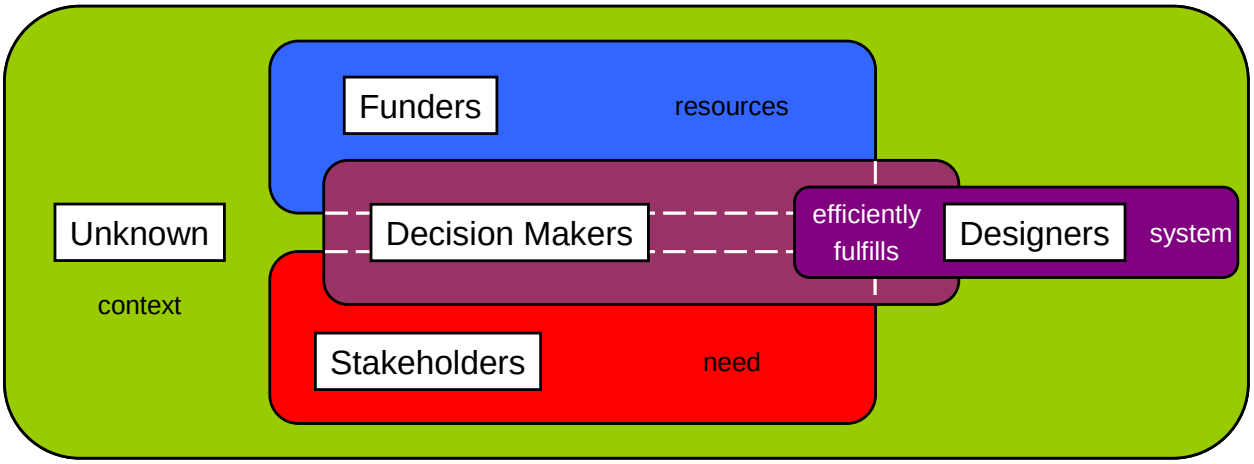

Figure 12 The goal of design

A first approach parsing of the goal of design statement results in the following key terms:

"system"—the concept, process or object, that is the product of the creative design process though which a need will be fulfilled.

"need"—the driving value statement that led to the desire for a "system" in the first (or other) place. Some needs drive the design process, others follow from it. (Driving needs versus derived needs will be discussed later.)

"efficient"—the design of a "system" inefficiently requires less expertise than one devised elegantly and "efficiently". In a world of limited "resources," expenditure of time, money, labor, information, energy, and matter must be done with an eye to avoiding waste in order to improve the chances the "system" will be realized.

[31] Examples of these two approaches are "market pull" and "technology push."

"resources"—the fundamental inputs and mediating supplies that are used to realize a "system." Resources typically include currency flows such as money, energy, information, matter, and perhaps time and labor as well.

"context"—the constraints and environment that exists at and beyond the "system" boundary. Often the context is imposed or out of the control of the designer and must be treated as an exogenous variable in the design endeavor.

Figure 12 shows a graphical depiction of the goal and the key terms. The context surrounds the entire endeavor, including the roles of participants and their domain of influence.[32] The Stakeholder role includes influence over the definition and evaluation of the needs. The Funder role includes influence over and allocation of the resources. The Decision Maker role acts as the gatekeeper of needs and resources, determining whether to pursue a system development effort.[33] The Designer role includes influence over the definition of the system, while efficiently utilizing resources and fulfilling needs, as determined by the Decision Maker.[34]

(Diller 2002; Ross 2003) describe traditional design approaches, incorporating the above concepts, while developing the Multi-Attribute Tradespace Exploration with Concurrent Design (MATE-CON) process as an alternate approach to the design endeavor. Specifically, MATE-CON focuses on Decision Maker derived need as a driving force for the design activity. Decoupling the design from the need through tradespace exploration, MATE-CON is both a solution-generating, as well as decision-making framework. At a high level, the MATE-CON process has the three following layers: Need Identification, Architecture-level Evaluation and Exploration, and Design-level Evaluation and Exploration.[35] MATE (without the –CON) refers to the first two layers, without the more detailed concurrent design-level analysis.

[32] In order to distinguish roles from the people who fill them, names will be capitalized when referring to the *role*.

[33] The existence of multiple decision makers, or any other role, adds to the complexity of the design problem space. Multiple decision makers may jointly, or separately, have the power described here, working cooperatively or competitively to achieve their aims. Ideally the design endeavor is cooperative, but reality may not provide such a rosy scenario. Strategic behavior can occur among stakeholders or stakeholders and funders in order to make themselves better off, sometimes at the expense of others. Such behavior can obfuscate the real value propositions for people, or reduce the options space, preventing the discovery of designs that could make everyone better off.

[34] Murman, Allen, et al. Lean Enterprise Value. on page 169 discusses various interpretations of the concept of "stakeholder," including a three category definition described by Kochan and Rubenstein to determine the "saliency of potential stakeholders." Paraphrasing, the three categories are: 1) extent to which they contribute resources, 2) extent to which they are affected by the resource usage, and 3) extent of the power they have over the system. Category 1 corresponds to the role of Funder. Category 2 corresponds to the role of Stakeholder. Category 3 corresponds to the role of Decision Maker.

[35] (Ross 2003) describes the steps of MATE-CON in detail.

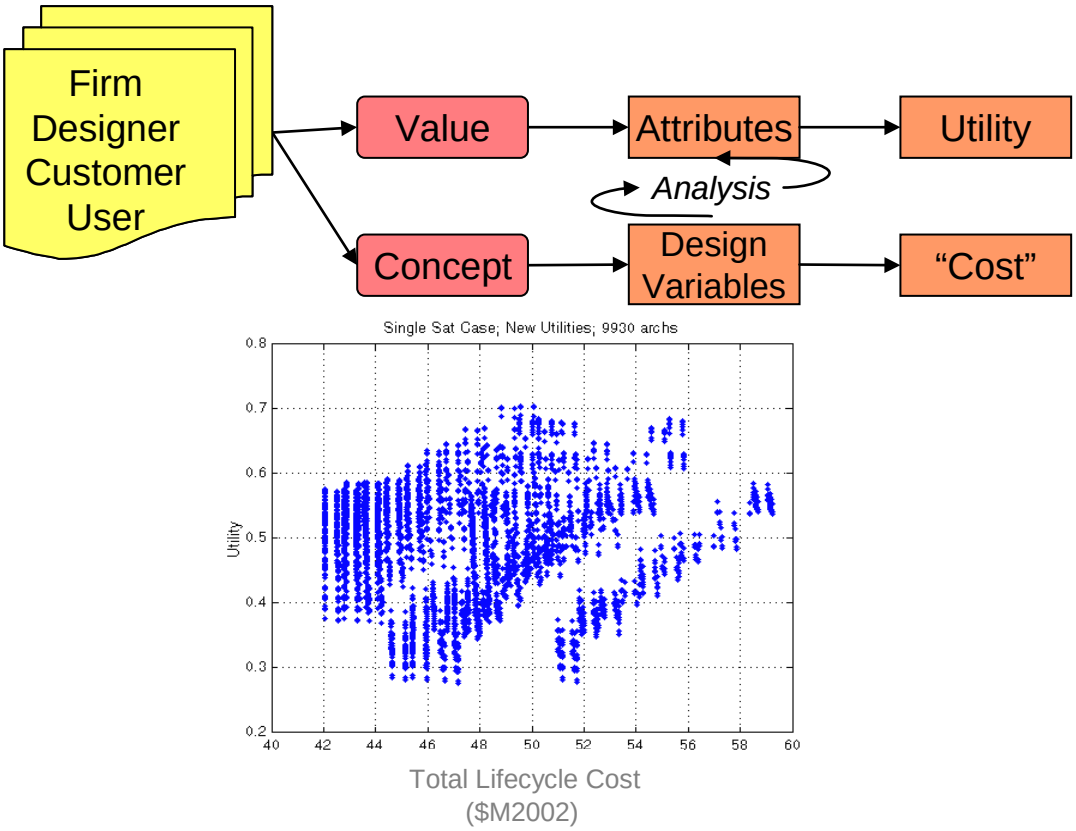

Figure 13 MATE process flow from stakeholders to tradespaces

Figure 13 shows the high level activities in the MATE process.[36] Stakeholders, or decision makers, including such roles as Firm, Customer, and User, express their value propositions in terms of quantifiable metrics, the attributes. The aggregate value of the attributes for a particular decision maker is captured in terms of an elicited utility function. Generated by the designers, concepts are parameterized in terms of design variables, which are varied and assessed through analysis in terms of their attributes. The cost of creating the designs, and the utility generated from their realization are plotted in a utility-cost tradespace for exploration of benefit-cost tradeoffs.

3.2 Value Metrics: Attributes

The Stakeholder role, as defined above, represents those individuals, groups, entities, etc, which derive value from association with the system. Stakeholders in general, however, may have little direct influence over the creation of the system itself. If the goal of the Designer were to maximize value delivered to the entire stakeholder set, some method for capturing each stakeholder's value proposition would be necessary in order to have a direct effect. Even if such an under-taking were possible, the picture would still be incomplete.

[36] MATE includes elicitation of value in terms of attributes from stakeholders, and focuses the generation of concepts in terms of alternative designs. A multitude of designs are assessed in terms of benefit perceived and resources required (utility and cost respectively) and are explored in a tradespace framework.

In addition to need, a system requires resources. Resources are the raw and mediating materials, processes, and expertise, both tangible and intangible, which are used to create the system. The gatekeepers for both the need and resources are the Decision Makers, who have significant influence over either the driving need or resource allocation that affects system creation. Since the Decision Maker wields the power over whether a system is created, the Designer should focus on maximizing value to the Decision Maker.[37] (Decision Makers can be a subset of the Stakeholder plus Funder roles).

Each decision maker has a set of objectives about which decisions are made. Attribute-based value is an effort to operationalize the concept of objective driven decision-making. The following is a question to pose to decision makers when eliciting attributes: "when making a decision about a particular option, what are the characteristics that you would look at?" Those characteristics are the attributes.

> An ***attribute*** is a decision maker-perceived metric that measures how well a decision maker-defined objective is met.

The characteristics of an attribute include its definition, units, and range from least to most acceptable values. The definition should be developed in concert with the decision maker in order to ensure the decision maker actually has value perception over it. The range reflects the fact that value is perceived for multiple attribute levels, and in the limit the range converges to a point, the attribute becomes a requirement.

Of course a decision maker could have multiple objectives and therefore a set of attributes. According to (Keeney and Raiffa 1993), an attribute set must be complete, operational, decomposable, non-redundant, minimal, and perceived independent. Operational means that the decision maker actually has preferences over the attributes. Decomposable means that they can be quantified. Non-redundant means none are double-counted. Minimal and complete are in tension, since a designer seeks to capture as many of the predominant decision metrics as possible, while keeping in mind human cognitive limitations in. (In practice a set is typically limited by the human cognitive capacity for parallel thought, roughly 7+/-2 (Miller 1956; Simon 1996).[38] The perceived-independent property is important for the utility independence axiom, described below, to hold. (The attributes need only be "perceived" independent; they do not need to actually be independent!) In practice, no set can be simply guaranteed to have all of these properties. The problem of completeness applies just as easily in the requirement generation process in standard engineering practice. Designers must do the best they can.

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[37] A rational, value-maximizing decision maker would seek to make stakeholder values a subset of his own value, thereby passing through to the Designer the needs of the stakeholder set. In practice, the pass-through is tempered by incomplete information, politics, and ignorance. A role of the Designer is to facilitate the conversation around value-creation with the Decision Maker. A point to keep in mind is the potential for Stakeholders to become Decision Makers when given authority or power. In this case the Designer would be better off paying attention to Stakeholder preferences in addition to Decision Makers.

[38] In practice, human cognitive limitations prevent consideration of more than about 7+/-2 simultaneous concepts. Decision Theory seeks to transcend cognitive limitations in order to make *better* decisions. The cognitive limitations only affect the attribute-driven analysis if a human decision maker must provide information reflecting simultaneous consideration of an attribute set. If simultaneity is not needed, the limitation may not apply. In this way the decision theoretic approach can be a superior decision-making method to unassisted human deliberations.

An example set of attributes from the X-TOS design project is in Table 3. Each attribute has a most acceptable (best) and least acceptable (worst) values, as well as units.

Table 3 X-TOS User attributes[39]

Attribute	Best	Worst	Units
Data Life Span	132	0	months
Sample Altitude	150	1000	kilometers
Diversity of Latitudes	180	0	degrees
Time Spent at Equator	24	0	hours
Data Latency	1	120	hours

After the attributes have been determined, the utility function, which captures the perceived value under uncertainty for each attribute, can be elicited.[40] The single attribute utility functions are a proxy representation of value to a decision maker for differing levels of an attribute. Typically von Neumann-Morgenstern utility functions are used, which are defined over the range of 0 to 1. A utility value of zero corresponds to an attribute at its least acceptable level; a utility value of one corresponds to an attribute at its best level, beyond which no additional value is perceived. If an attribute is worse than its worst level, the utility function is undefined, while if the attribute is better than its best level, the utility function remains at a value of one.

In the case of multiple attributes, a multi-attribute utility function can be formed, aggregating the single attribute utility values into a single decision metric. The multi-attribute utility value represents the satisfaction of a decision maker. The multi-attribute utility function varies from 0 to 1 in a similar fashion to the single attribute utility function. (It takes on a value of 0 when all of the attributes are at their worst level, and a value of 1 when all of the attributes are at their best level.)[41] Proper usage of Utility Theory requires adherence to the axioms and limitations of the theory, and any MATE analyst should be sure to understand its applicability, especially when considering descriptive and prescriptive decision-making support methods.[42] A key point to remember is the difference between a descriptive theory (what people actually do) and a prescriptive theory (what people should do) when eliciting the system attributes. Analysts cognizant of human cognitive biases will be in a better position to tease out the proper rational

[39] p. 94. Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design.

[40] See (Ross 2003) for a detailed discussion with examples and references to single attribute utility elicitation methods.

[41] (Ross 2003) discusses the theory, applicability, and limitation of Multi-Attribute Utility Theory, as well as Single Attribute Utility Theory.

[42] Utility theory is often depicted as a prescriptive theory since its axioms are appealingly rational. In practice, the literature has shown that it fails as a descriptive theory of how people *actually* make decisions. Prospect Theory is an attempt to merge Psychology with Economics to develop a more accurate descriptive theory of choice. When deciding which theory of choice to apply to MATE, it was determined that the method that should be used is the one that will make the decision maker better off. The MATE process does not seek to describe how people *actually* make design decisions, but rather seeks to prescribe how people *should* make design decisions. See (Ross 2003) p. 56 for discussion of Prospect Theory and its relation to MATE.

decision metrics that will make a decision maker better off than one dependent upon short-sighted heuristics.[43]

3.3 Concept Design: Design variables

In order to meet the needs of the decision makers, a designer must leverage his expertise to create a system. System concepts embody the essential elements, or nature, of the system itself. An example of a concept is a "car." The "car" is a mechanism for human-operated transportation of people and goods using a self-propelled container with wheels. It has windows to allow for viewing the surroundings, doors to allow for entrance and exit of passengers, and access to the machinery for maintenance and refueling. The concept of car can be instantiated in many specific designs, such as a Ford Taurus or Honda Accord. For MATE analysis, the key quantitative tool for the designer to capture concepts is the *design variable*.

> A *design variable* is a designer-controlled quantitative parameter that reflects an aspect of a concept, which taken together as a set uniquely define a system design or architecture.

Imagine design variables as the design "knobs" on some hypothetical system design console. As the designer turns the "knobs," which can be a continuous or discrete motion, the system changes, as do the resulting effects on the attributes. An Etch-a-sketch™ has two knobs that can be turned, thereby moving the point on the display. The lines drawn are the attributes, while the happiness one derives from the resulting picture is the utility. If the user desires to sketch in 3D, the designer must add another knob!

An example set of design variables from the X-TOS design project is in Table 4.

Table 4 X-TOS Design variables[44]

X-TOS DESIGN VARIABLES	Range
Mission Scenarios	
Single satellite, single launch	
Two satellites, sequential launch	
Two satellites, parallel	
Orbital Parameters	
Apogee altitude (km)	200-2000

[43] Three types of cognitive biases are: Availability, Representativeness, and Anchoring. *"Availability"* is the tendency of people to weight the probability of an event by the ease with which some relevant information comes to mind; other information, although relevant, is ignored simply because it does not come to mind so quickly. *"Representativeness"* is the tendency to ignore good probabilistic information on the basis of information that is irrelevant in fact, but that is believed by the decision maker to be representative of relevant information. *"Anchoring"* is the tendency of many people, even after learning that they have based probability estimates on worthless information, to continue to be influenced by the earlier assessments (See Kahneman, D., P. Slovic, et al., Eds. (1982). Judgment Under Uncertainty: Heuristics and Biases. New York, Cambridge University Press. for more information.)

[44] p. 96. Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design.

X-TOS DESIGN VARIABLES	Range
Perigee altitude (km)	150-350
Orbit inclination	0, 30, 60, 90
Physical Spacecraft Parameters	
Antenna gain	high/low
Communication architecture	tdrss/afscn
Power type	Fuel / solar
Propulsion type	electric/chem.
Delta_v (m/s)	200-1000

Total # of Explored Designs = 50,488

The set of design variables is sometimes called the design vector. Each unique concept can be specified by a different design vector. Referring back to the car example, the Honda Accord or the Ford Taurus can be codified as particular values in a design vector (having the same values for some variables, but differing in others, such as body styling). The span of all design vectors under consideration forms the design-space. The process of developing the design variables is described in (Ross 2003). In short, the attributes are used as seeds for creative brainstorming. Inspecting each attribute individually, or in combination, the designer asks himself "what real-world object or process can result in the "display" of that attribute, and in the proper range?" The object or process can be quantified as a design variable (with natural or designer-defined units). A Quality Functional Deployment (QFD)-like matrix is used to keep track of potential design variables and their effect on the attributes. Various combinations of design variables can then be grouped into concepts for further consideration.

Figure 14 below shows an example QFD used in deriving the X-TOS design variables. Attributes elicited from decision makers form the columns. Proposed design variables are placed in the rows. Qualitative effects are captured through allocating a 1, 3, or 9 to each row representing the amount of impact that design variable is expected to make on each attribute. In this way, the designer can be assured that each attribute has at least one driver, and can help determine which design variables to focus on creating more value.

After the design variables are determined, a system model is created in order to assess how various combinations of design variables perform in terms of the attributes. Both the cost of the design and the utility of the attributes are calculated and used as the decision metrics for exploring a tradespace of a multitude of design options.

QFD X-TOS

DESIGN-ATTRIBUTE

	VARIABLES	Units	CONSTRAINTS	Weighting	1 Distribution of Altitudes	2 Number of Altitude Bands	3 Distribution of Latitudes	4 Number of Latitudes	5 Distribution of Time/Cycles	6 Total Data Points	7 Sample Resolution	8 Sample Accuracy	9 Data Completeness/Mission Success%	TOTAL (USER)	10 Lifecycle Cost $ (2002)	Total (CUSTOMER)	11 Ease of Modeling	Total (DESIGNER)
1	Orbital parameters	6 param			9	9	9	9	9	9	9	1	3	67		0		0
2	Number of different orbits	integer			9	9	9	9	9	9	1	0	9	64		0		0
3	Number of s/c in each orbit	integer			0	0	0	0	3	9	9	0	9	30		0		0
4	Satellite lifetime	months			0	0	0	0	9	9	0	0	9	27		0		0
5	Mission Scenario	-												0		0		0
6	Shape	-			0	0	0	0	0	3	0	1	9	13		0		0
7	Communication scenario	-			0	0	0	0	0	0	0	0	0	0	9	9		0
8	Launch (vehicle, date)	-			0	0	0	0	0	0	0	0	0	0	9	9		0
9	Redundancy/Functionality	-			0	0	0	0	0	9	0	0	9	18	9	9		0
10	Time/Position determination	-			0	0	0	0	0	0	9	9	0	18		0		0
11	Heritage	-			0	0	0	0	0	0	9	9	9	27	9	9		0
12	Sequencing	-												0		0		0
13	Number of mission cycles	integer												0		0		0
14	Number of s/c in each cycle	integer												0		0		0
	TOTAL				18	18	18	18	30	48	37	20	57		36		0	

Qual. Effect

- Good
- Fair
- Poor

Figure 14 X-TOS Design-Attribute QFD[45]

3.4 Tradespaces

The notion of tradespace is fundamental to the MATE process. The tradespace includes both the space of design and the space of attribute trades. Technically speaking, the tradespace is the span of the design variable set and attribute set, along with their mappings to cost and utility. Cost is a scalar measure of resources necessary to realize a particular design. Utility is a scalar measure of fulfilled need for a particular design.

Tradespace: {Design,Attributes}←→{Cost,Utility}

(Ross 2003) differentiates between the {Design,Attribute} space and the {Cost,Utility} space, calling the former the Tradespace, and the latter the Solution Space. In those terms, the tradespace is literally the space of actual trades, while the Solution Space is a compacted space facilitating finding the best "solutions." More generally, however, both are tradespaces since they both reflect the fundamental trades occurring between designs and attributes, or resources and needs.

[45] Figure from Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design.

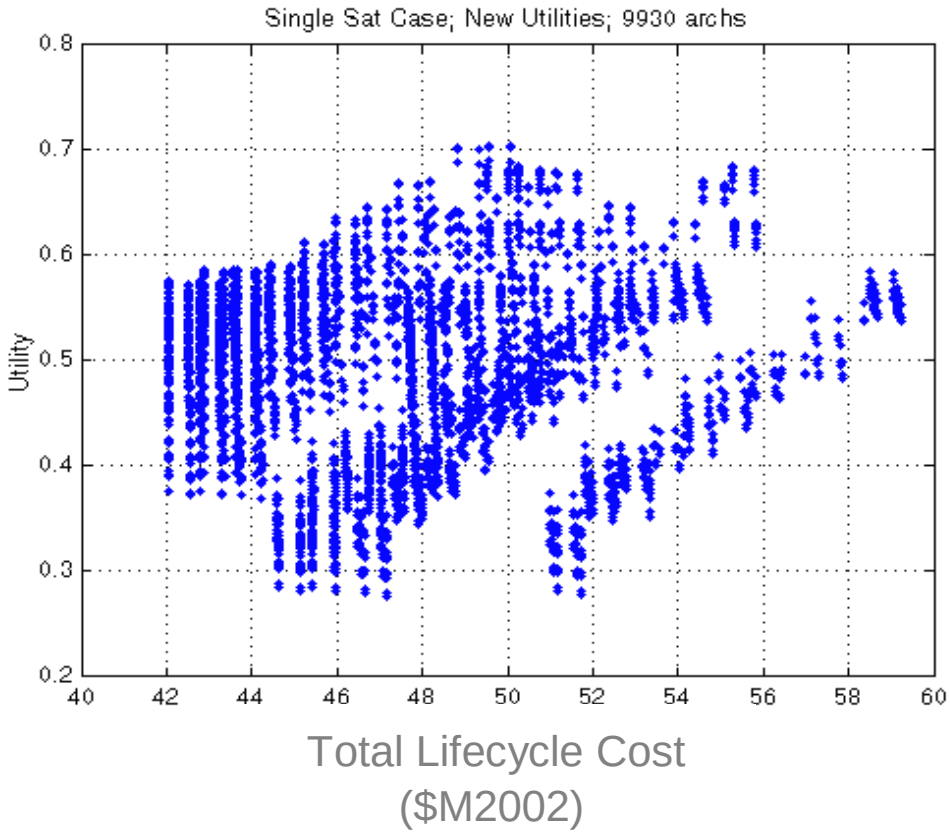

Figure 15 X-TOS Utility-Cost Tradespace[46]

A typical tradespace plot used in MATE analysis is the utility-cost space, since it has fewer dimensions and highlights the key trade between resource and need for a decision maker. Figure 15 shows an example from the X-TOS project. The goal for design option selection is to find options at highest utility at a given cost level, which forms the Pareto Frontier of solutions. The decision maker must decide the appropriate trade of resource expenditure versus need fulfillment in order to find the "best" option for further design and development.

3.5 Tradespace Exploration Paradigm

When viewing traditional design efforts in terms of the tradespace approach, one can see that the usual design efforts entail the definition of a design point a priori[47]. Local point solution trades begin with a design baseline and use that baseline as an anchor to consider alternatives, typically only varying design parameters a small amount. Some designers recognize the value of seeking diverse design options and seek to "optimize" their objective function, typically a proxy for utility or cost. Finding the frontier subset solutions includes various "best" or "optimized" designs. Moving beyond the subset solutions, designers could seek to discover the shape of the frontier itself, defining explicitly the inherent trades between cost and utility, or any other

[46] Figure from Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design.
[47] See Keeney, Ralph L. (1992). Value-Focused Thinking: A Path to Creative Decisionmaking. Cambridge, MA, Harvard University Press. for a discussion of "alternative-focused" thinking instead of "value-focused" thinking.

objective functions. Multi-disciplinary optimization often seeks this type of information. Previous applications of MATE, however, have sought to understand the structure of the tradespace itself. Instead of optimizing, or seeking the Pareto Frontier, full tradespace optimization looks for patterns and structures emerging within the dominated region of the tradespace[48].

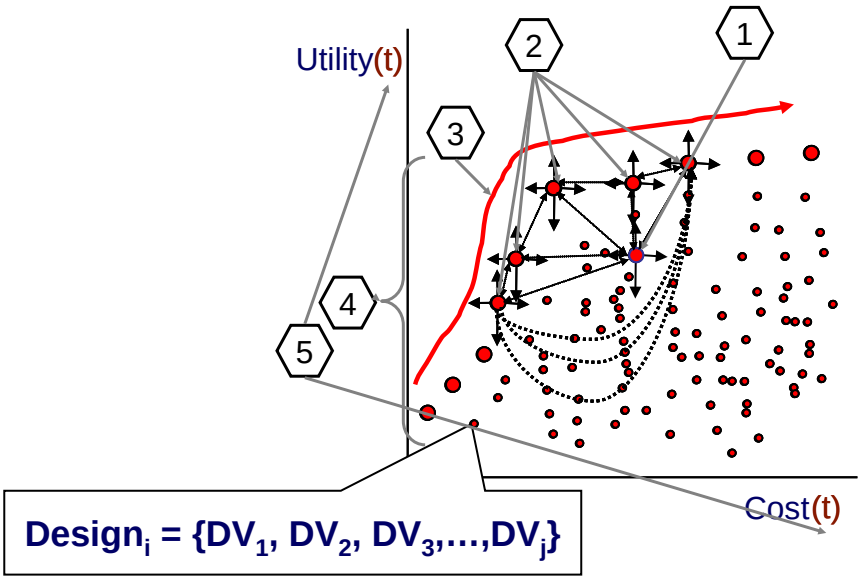

Figure 16 Tradespace depicting different trade types

Moving beyond the classical MATE approach, one can envision a tradespace dynamic in nature, where the utilities and costs may change with time, either because the systems themselves are changing, or the utility or cost mappings are changing. The dynamic perspective is the one that will be developed and discussed in this dissertation. Figure 16 places the various types of trades into perspective (1: Point solution, 2: Pareto subset, 3. Pareto Frontier, 4. Full tradespace, 5. Dynamic tradespace).

The tradespace exploration paradigm enables big picture understanding of how resources can be used to meet need, through designs and articulated attributes. (Ross and Hastings 2005) describe the tradespace exploration paradigm and its ability to elucidate differential context effects, such as changes in policies, budgets, and requirements, on designs.

3.6 Follow-on Research (theses)

Eight Masters theses were written either developing or extending the MATE process, including (Diller 2002; Seshasai 2002; Derleth 2003; Roberts 2003; Ross 2003; Spaulding 2003; Stagney 2003; Shah 2004). Additionally, three Doctoral dissertations were written incorporating and

[48] The Pareto Frontier is defined as the curve (or multi-dimensional surface) along which an objective value must be traded for another and no mutually improving movement is possible. See Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design. for more information, or any multidisciplinary optimization or advanced operations research text.

contributing key tradespace exploration techniques and insights, including (Jilla 2002; Walton 2002; Weigel 2002)

The following are brief summaries of the contributions of each work.

In (Diller 2002), the basic motivations for the development of MATE are laid out, including the restrictive nature of the traditional requirements-driven design process. MATE is introduced as a possible solution to the "premature reduction" of the tradespace.

In (Seshasai 2002), the development of the Multi-attribute Interview Software Tool (MIST) is discussed, in the context of need capture and efficient communication of information during a system development process. The tool leveraged the prior experience of MATE practitioners and facilitated further MATE studies by reducing the utility interview burden on decision makers.

In (Ross 2003), the development and theory of MATE is shown through applications to the Terrestrial Observer Swarm (TOS) projects A, B, C, and X. MATE as a process is also shown to be a "better" process through formal Dependency Structure Matrix (DSM) analysis when MATE is compared with NASA and an aerospace company's typical design processes.

In (Derleth 2003), a MATE study was conducted on the Small Diameter Bomb (SDB) system in the context of spiral development. Three spirals were considered, with new attributes and design variables entering spirals 2 and 3. In comparing the tradespaces qualitatively across spirals, Derleth noticed that designs were differentially affected in terms of both value-perception and cost incurred.

In (Spaulding 2003), a MATE study was conducted on the Space-based Radar system (SBR). In addition to performing tradespace exploration analysis, Spaulding experimented with utility elicitation methods, comparing formal utility interviewing to subjective utility function sketching. The study introduced the usage of Proportional Utility Loss and Spearman's Rho statistics for quantitatively comparing tradespaces derived from the formal and informal utility methods.

In (Stagney 2003), MATE with Concurrent Design is compared to several other design processes and determined to perform better in several key metrics. The concept of applying MATE across a business enterprise and system lifecycle would enable more efficient communication of needs and resources, thereby delivering more value to all stakeholders involved in a real development project. Stagney brought the MATE process to a real aerospace company and attempted to test its applicability in a working business environment. While deployment was not possible due to time and cultural constraints, a simplified version was shown to increase the time available to design teams, enabling them to consider more design options than previously possible.

In (Roberts 2003), MATE is applied to the spiral development process for the Space-based Radar system. Temporal concepts including "transition architectures" and the time value of utility are discussed, as is the stated need for understanding how to find "scalable" or "flexible" designs. Transition rules for the SBR are proposed, and an "acquisition tradespace" representation depicts utility versus time and cost versus time for transitioning designs.

In (Shah 2004), modularity is proposed as a mechanism for promoting flexibility in the Space-based Radar system. A modular design is said to "scale" better in an evolutionary acquisition environment, enabling lower cost design changes and promoting better value over time. Transitions in the MATE SBR study were cast in terms of the application of modular operators on the system.

In (Jilla 2002), the problem of finding the Pareto Front of complex multi-dimensional tradespaces is addressed and a new methodology: Muliobjective, Multidisciplinary Design Optimization using Simulated Annealing (MMDOSA) is proposed. Application of heuristic search techniques, especially simulated annealing, are shown to quickly and efficiently find the Pareto Front of designs with limited knowledge of the complete tradespace.

In (Walton 2002), the tradespace perspective is shown to be useful for representing and characterizing various types of uncertainty. The creation of portfolios of possible design options enable designers to mitigate uncertainty early in the design process by taking advantage of anti-correlated uncertainties between system options.

In (Weigel 2002), the tradespace perspective is shown to be useful for representing the differential effects of policy changes on various system options. Policy robustness for tradespace exploration is proposed as a feasible goal, and the total costs of proposed policies are shown to be quantifiable. Weigel proposes the application of real options to remove negative effects from policy changes, thereby reducing the exposed risks that some programs may face for being in a "policy-sensitive" region of a tradespace.

Chapter 4: Expanded Value: Including the "Unarticulated"

One of the motivations in extending the classical MATE approach was to incorporate the findings of follow-on theses, as well as revisit some of the underlying assumptions of the approach. It turns out that these two motivations coincide when considering an expanded definition of value. Instead of assuming that the decision maker has explicitly stated all of the attributes that go into his value function, what if the designer anticipates that the utility function may not capture all of the potential value for the system? The "unarticulated" value includes any aspect of the system that may be value-perceived, but has not been explicitly communicated through attributes.

The transition from a static, well-defined value proposition to a dynamic, poorly defined value proposition requires an expanded notion of value and how it might be assessed by the designer.

4.1 Thinking and Deciding

The first step in understanding value-perceptions is to glean some insight into the thought process itself. "Getting into the head" of the decision maker is a desirable goal for any designer who wishes to deliver value. (Baron 2000) is a representative textbook from the field of psychology and cognitive sciences. Baron, an expert in the field, outlines a basic model of thinking called the "Search-Inference Framework," capturing the essence of most accepted models. In this framework, a person has a question he wishes to have answered. The question could be a problem or any other type of motivation desiring resolution. In order to tackle the question, the person develops goals, which are proxies for the question solution. Given the goals, the person searches for possibilities that may meet the goals. Evidence is gathered and inferences are made with the evidence for each possibility to determine to what extent each possibility achieves the goals. As long as the question remains unsolved, the person will continue to search for goals, possibilities, and evidence in an effort to answer the question. The bottom line is that people will change their minds.

Applying this model to the MATE process reveals some interesting insights.

Search-Inference	Definition	MATE
Question	Dilemma to be solved	System Objective
Goals	Criteria used to evaluate possibilities	Attributes
Possibilities	Possible answers to the question	System Designs
Evidence	Belief or potential belief that helps to determine extent to which a possibility achieves some goal	System Analysis

Thus if the question or dilemma is to create maximal value to a decision maker, the search-inference framework exactly describes the process the system designer and decision maker go through jointly in order to solve the dilemma. Since the definition of "value" to a decision maker may change over time, so too will the attributes, and by implication, the system designs.

The other side to unarticulated value, besides dynamically altered value functions, is the possibility of unexpressed needs. A spectrum of perceived value is proposed in Figure 17 in order to remind the designer of possible types to consider, including the dynamic values.

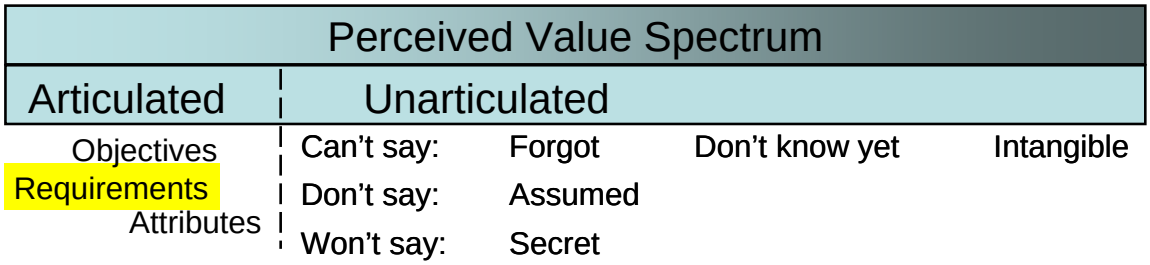

Figure 17 Perceived value spectrum

Elucidators, or mechanisms, to move the values from the unarticulated to the articulated perceived-value categories include the following:

- Personal reflection (time)
- Conversations with mediators (facilitation)
- Experience with the system (learning by doing)
- Interactions with system context (competition, test-driving)
- Change in context (change of the "rules")

A key question confronting the designer at this point is how to deliver value in the face of various value-perceptions.

4.2 Revealed Preferences

One process, utilized extensively in economic market analyses is that of revealed preferences. Revealed preferences are preferences captured through the behavior of decision makers, based on statistical analysis of their choices. Presumably decision makers choose systems that deliver value and thus reveal information about their preference structure, or tastes. In the case of aerospace systems, such data is often unavailable due to the limited and or specialized nature of the system products, as well as the limited number of purchase or acquisition decisions. The unique context of each system need may entail a specialized set of preferences that cannot be garnered from past behavior. Instead of relying on statistical analysis of past behavior, revealed preferences could be captured through conversations with decision makers about hypothetical system choices in the current context. Utility theory as applied in MATE applies this type of method to revealing preferences.

Unfortunately the process of preference elicitation typically does not give a complete picture to the system designer. Additionally, conflicting preferences of decision makers may be revealed that do not point the designer to an obvious aggregate preference set for maximizing delivered value. (See 4.6 for a discussion of group aggregate preference structures.)

Suppose a designer needs to create a box that fulfills the needs of five decision makers. The decision makers all agree that they care about the color of the box (articulated value: color attribute). Through formal value elicitation process the color is determined to deliver value if

either red or blue. Four of the decision makers desire a red box and one desires a blue box. Should the box be red or blue? In this case the designer may choose to make the box red since a clear majority of decision makers desire a red box. Excepting the possibility that the "blue" decision maker has veto power or extreme importance in the final design, this solution may seem adequate. Figure 18 shows this system value dilemma.

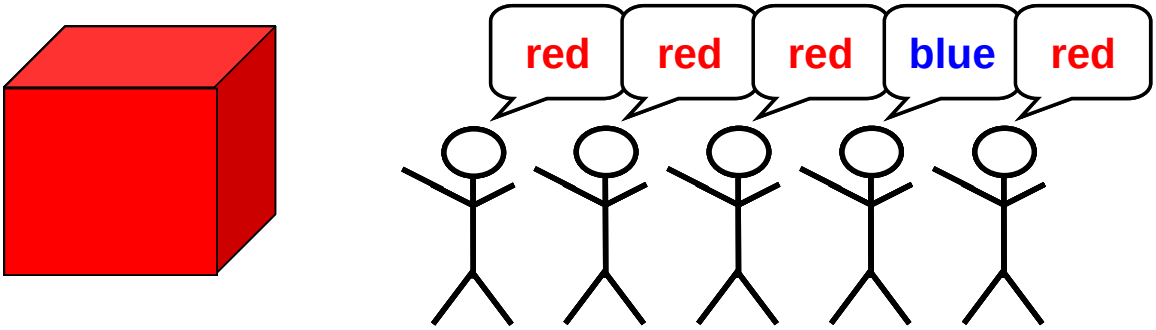

Figure 18 Articulated need for a red box

Suppose a short time later two of the decision makers change their minds and decide that they now prefer blue. Now three decision makers prefer blue and two prefer red. The designer now is in a tough place. Cleverly he creates a third design alternative: a two colored box that is both red and blue. Assuming the decision makers do not receive negative value from having the other color on their box, they may all be better off with this option. The designer has managed to deliver value again. Figure 19 shows this new system value dilemma.

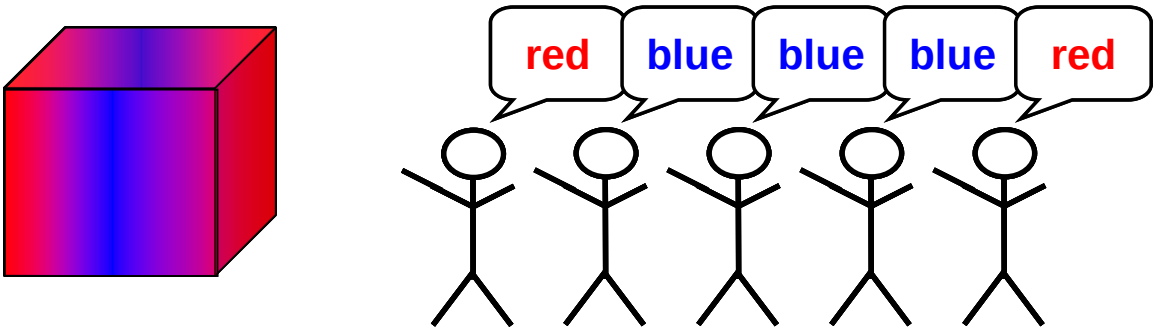

Figure 19 Articulated need for a blue-red box

Suppose that the second case above happened a little differently. Suppose that when the designer asked each decision maker what color they wanted the box to be the first and fifth decision maker said red and the third and fourth said blue. But the second decision maker didn't seem to understand the question and said "loud" instead of a color. A little confused, the designer repeats the question and again gets the answer "loud." "Okay" thinks the designer, the second decision maker doesn't care about color and instead is now articulating a new attribute: sound level. Since the other decision makers didn't mention sound level, they must not care about it. The designer then proposes a loud, half red, half blue box. Unfortunately for him, all of the decision makers are unhappy with this option. Figure 20 shows this new system value dilemma.

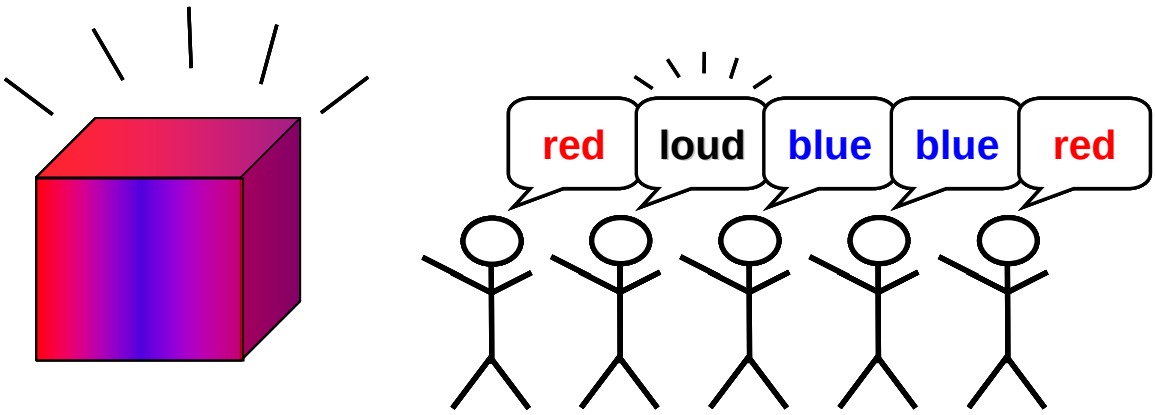

Figure 20 Articulated need for a red-blue loud box

It turns out that all of the decision makers care about both the color and sound level. For those that did not articulate the value of sound level, it was because they assumed that the designer knew that not mentioning it meant a quiet box. Additionally, the second decision maker who expressed a desire for a "loud" box actually had a communication impediment preventing him from expressing his desire for a red box. If the designer had both the articulated and unarticulated value known, he would have found that three decision makers desire red, two desire blue and four decision makers desire quiet and only one desires loud. A mostly red, quiet box would have delivered more value to the decision makers than a loud half and half red/blue box. Figure 21 shows the previous case with the unarticulated value highlighted as well.

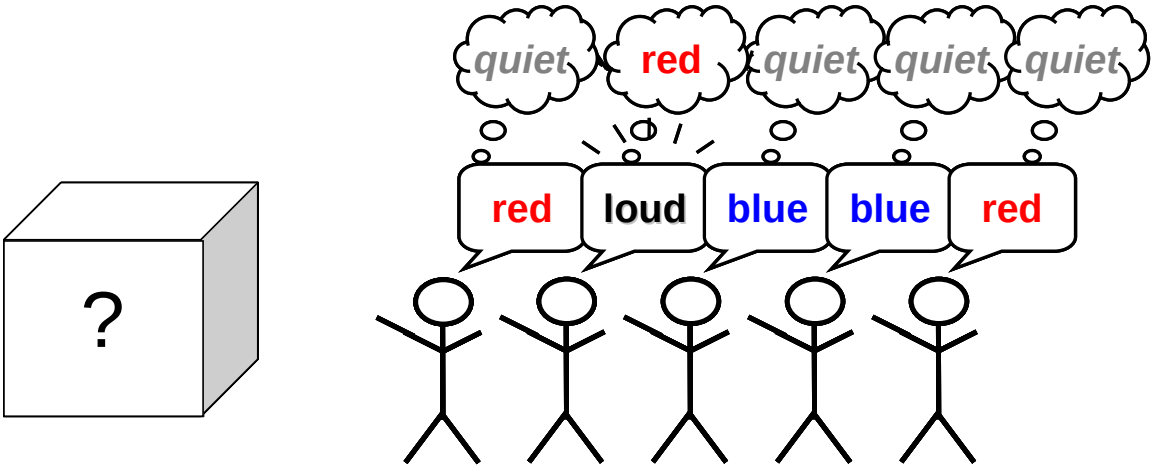

Figure 21 Articulated and unarticulated needs for a box

Clearly if the system designer seeks to deliver value he must be aware of both articulated and unarticulated need.[49] The current preference set of decision makers include both current articulated and unarticulated needs. The current preferences are a snapshot in a dynamic stream.

[49] Econometrics is a statistical technique used in economics to estimate relationships from market revealed data. The systems under consideration in this thesis do not have such data available. For other types of system, for which such data is available, numerical techniques exist to mitigate against the risk of missing attributes in modeled value functions. Two approaches to capturing unarticulated value as a perturbation to an explicit value model is described in Petrin, Amil and Kenneth E. Train (2003). "Omitted Product Attributes in Discrete Choice Models." NBER Working Paper Series. Working Paper 9452. Cambridge, National Bureau of Economic Research**:** 28.

The causes of apparent dynamic preferences of the decision maker to the designer include 1) personal drift of the decision maker's thinking, 2) changing context affecting the dilemma being considered by the decision maker, and 3) movement of needs from unarticulated to articulated. In any case, in order to maximize delivery of value, the designer must match the dynamic current preferences to the best extent possible. Since personal drift is the most difficult to ascertain, paying attention to the context as well as to the articulation of needs should be the main focus of a designer. The problem of capturing these two forces can be viewed in terms of access to information.

4.3 Accessing Information

It is well known in the economics literature that access to information is necessary to have an efficient market. The existence of knowledgeable suppliers and demanders means that no one gets taken advantage of and everyone knows what everyone is looking for. Once asymmetry in information exists, "market inefficiencies" begin cropping up. Examples of inefficiencies due to information asymmetry include used goods markets, auctions, product safety, and new entrants into a market.

In a used goods market, the buyer does not have complete information on the history of the good. Fear of "buying a lemon" often keeps buyers away from used car markets, especially since the seller has incentive to withhold negative information. In auctions, it is in the bidder's best interest to bid as low as possible, while still high enough to make a profit. Since the auctioneer desires to take the highest bid, often the winner of the auction is left with the "winner's curse" and ended up bidding too much, meaning he would have been better off not winning the auction. Product safety is an important area where manufacturers are incentivized to make their products appear as attractive to consumers as possible, perhaps even hiding negative side-effects or quality issues. Consumers desire a good product, but may be unwilling to pay the extra cost required to make a robust and truly safe good. Lastly, new entrants into a market suffer from lack of recognition, even if providing a superior product. Access to consumers and providing believable information about their products is difficult in an era of "buyer beware" and consumers who, by and large, prefer to stick with reliable knowns rather than venture into uncertain territory.

Knowing the unarticulated values of a decision maker and the context within which that decision maker make decisions is a similar case of asymmetric information. The decision maker himself has the most knowledge of his context and preferences, however, it may not be in his best interest to divulge all of this information since it could negatively effect his utility. An example would be giving up any sort of competitive advantage that may exist due to the information asymmetry (including knowledge of future needs, potential new technologies, new uses for the system that the user does not want the designer to know about, etc). The dilemma then confronting the designer is how to elicit enough information to deliver value. Information intentionally withheld may actually result in more value to the decision maker and perhaps should not be revealed. Other information may be unintentionally withheld, for whatever reason, and the role of a good designer should be to help elicit those unarticulated values.[50,51]

[50] The requirements generation process for engineering design is the typical stage when preference elicitation occurs. The systems engineer works with customers and users to determine the "true" needs motivating system value. The role of the system designer/engineer is to "facilitate" the discovery of the need, or purpose, for the system.

In the marketplace, government or corporate policies and regulations are often needed to repair market inefficiencies. Examples include consumer labeling laws, the freedom of information act, product lifetime warranties, and transparent transaction laws. In the design world, standard processes often serve the role of guide to eliciting common value propositions. Additionally, innovative and dynamic product development processes attempt to gain interactive feedback with the user or customer in order to more closely integrate driving needs with design.[52,53]

4.4 Updating Information: Learning

Since information is constantly being created, it is necessary for the designer and decision maker to be aware of the need to continually update the balance of information. Interaction with the system and feedback from the users, as done in spiral development models, provide one mechanism for learning from the system.[54,55] Civil space systems are often developed as unique systems, with only one being developed, since development is too costly and time consuming, or the timing of the need is unique in nature. In such cases, feedback from spirals is impossible and the designer-user team must create an alternative arrangement for learning from the system and each other. Military space systems, on the other hand, are sometimes developed in blocks in order to enable learning to occur. The GPS and Milstar systems, for example, have been deployed in a series of generations, with each successive generation benefiting from the "experienced value" of prior ones. In all of the learning efforts, the key facts that must be communicated between the decision maker and system designer are the available resources, constraints, and value propositions.

4.5 Sources of Value: Attribute Classes

The elicitation of attributes, both articulated and unarticulated, can be done through a facilitation process mediated by system designers. The literature on requirements generation can inform the elicitation process. Section 3.2, "Preference Capture," of (Ross 2003) describes the general

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[51] Unarticulated values are sometimes referred to "latent needs" in the product development literature. A method for eliciting latent needs not accessible through marketing research using "co-creation" of products with customers is proposed in Durgee, Jeffrey F. (2001). Qualitative Methods for Identifying Latent Needs for New Consumer Technologies. IEMC'01 Proceedings Change Management and the New Industrial Revolution, Albany, NY.

[52] As an example, consider the Evolutionary Acquisition strategy of Spiral Development. Spiral development entails rapid fielding of a system with basic capabilities in order to elicit feedback from the user for further system development and refinement. A key point is that the system is not deployed at full capability; rather "full capability" is an elusive moving target toward which each spiral attempts to bring the system. For application of spiral development in a MATE framework see Roberts. Architecting Strategies Using Spiral Development for Space Based Radar. .

[53] For a more general discussion of product development processes and their ability to respond to changes in the market, see Unger, Darian W. (2003). Product Development Process Design: Improving Development Response to Market, Technical, and Regulatory Risks. PhD thesis in Engineering Systems Division. Massachusetts Institute of Technology. Cambridge: 205. .

[54] See Ulrich and Eppinger. Product Design and Development. or almost any other product development book for information on how to get feedback on products from users or customers. Software developers have more experience due to the short cycle times involved with their product.

[55] For a discussion on the use of team decision making as a collaborative argumentation and reflection process for learning during project definition see Whelton, Michael and Glenn Ballard. (2002). Wicked Problems in Project Definition. International Group for Lean Construction 10th Annual Conference, Brazil. (Application area: lean construction projects.)

concept of attribute elicitation for use within Multi-Attribute Utility Analysis and Prospect Theory, two decision-analytic theories that can be used to improve engineering design decision-making.[56,57] Putting attributes into a temporal discovery context, (Whelton and Ballard 2003) provides a framework for thinking about the evolution of articulated needs from fuzzy wants through attribute definition down to concrete requirements. Formal interviews, group discussions, learning by doing ("playing" or "test driving" the system), and introspection are just a few of the methods that can be used to elicit value propositions from decision makers.

Throughout elicitation, it is important for the analyst to keep in mind the concept of "framing." Framing represents the cognitive context from which a decision maker considers a problem. For example the same outcome could be cast in terms of a "cost" or in terms of an "uncompensated loss" and will be perceived differently by the decision maker.[58] Consistency and care in the framing of attribute elicitation is essential to ensure reliable and repeatable value perceptions.[59]

In terms of capturing value propositions, the previously developed concept of attributes can be used as a metric measuring how well objectives deliver value. Spanning the range from known articulated value to unknown unarticulated value, attribute classes can be defined.

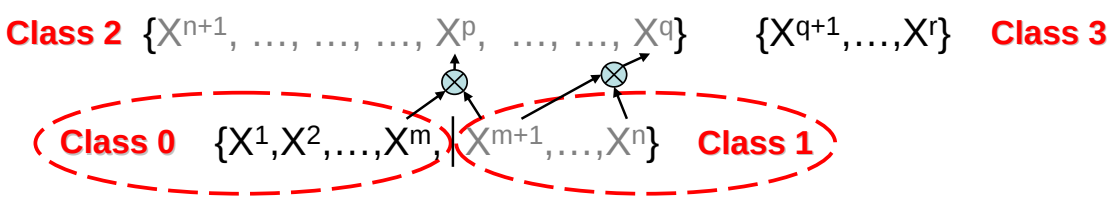

Figure 22 Attribute classes 0 to 3

Table 5 Attribute classification (0 to 4)

Class	Name	Property of Class	Cost to Display
0	Articulated Value	Exist and assessed	0
1	Free Latent Value	Exist, not assessed	0
2	Cheap Latent Value	Can exist by recombining class 0/1	Small
3	Accessible Value	Can be added through changing {DV} (scale or modify)	Small→large
4	Inaccessible Value	Cannot be added through changing {DV} (system too rigid)	Large→infinite

[56] de Neufville, Richard. (1990). Applied Systems Analysis: Engineering Planning and Technology Management. New York, McGraw-Hill Co. provides a good introduction to the application of attributes within multi-attribute utility analysis to engineering problems.

[57] Keeney. Value-Focused Thinking: A Path to Creative Decisionmaking. discusses the elicitation of stakeholder objectives hierarchies and quantifiable attributes for use in analytical decision-making support.

[58] Cognitive bias as a result of framing is a well documented phenomenon in the psychology literature. See Kahneman and Tversky, Eds. Choices, Values, and Frames. for a collection of several dozen such papers, including descriptions of Prospect Theory, a theory of value combining insights of cognitive biases from Psychology into an Economic model of choice.

[59] It is important for the analyst to be able to distinguish changes in value perception due to a real underlying value perception change versus errors in measurement due to cognitive biases or inconsistencies in framing for attribute elicitation.

In order to deliver value, an attribute must be perceived by a decision maker and be "displayed" by the system. The "existence" of an attribute of the system means that the system has either the form or function specified by the attribute and is thus "displayed." "Articulation" refers to explicit communication by a decision maker that a particular attribute or set of attributes is value-perceived. "Potential" attributes are those that could be "displayed" by the system if the system were changed in some way. For the following attribute class definitions, a state 1 system is the "original" or "as-designed" system, while a state 2 system is the "changed" system. Figure 22 depicts the relationships between attribute classes 0 to 3 (ultimately system accessible value). Table 5 shows the attribute classification scheme with class properties and cost to display (movement from current class to class 0).

4.5.1 Class 0 Attributes: Articulated Value

The first of the classes of attributes to consider are those that are typically included in a MATE analysis: the articulated attribute set. Class 0 attributes are those that are "displayed" by the system and are explicitly communicated by a decision maker. The "cost" to add class 0 attributes to a state 2 system is zero since the attributes already exist.

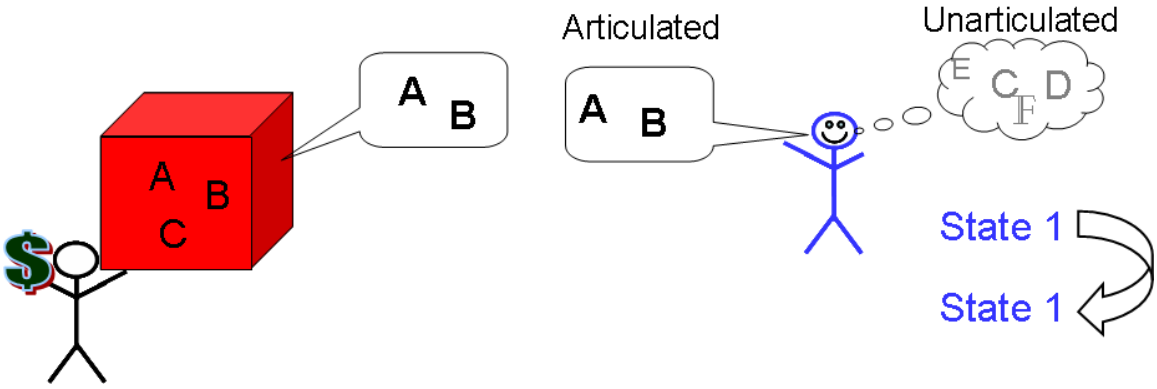

Figure 23 Class 0 Attributes: Articulated Value

As an example, class 0 attributes are equivalent to the requirements currently met by the system. A cell phone that provides, and was designed to provide, good sound quality, few dropped calls, and durable design meets the articulated values of the consumer who explicitly demands such attributes.

4.5.2 Class 1 Attributes: Free Latent Value

In addition to displayed attributes that are value-perceived, a system can display a number of other attributes, which are not value-perceived. Class 1 attributes represent a type of latent value. If a decision maker adds such an attribute to his value-perceived set, no "cost" is incurred to change the system since it is already displayed. These attributes represent "free latent value."

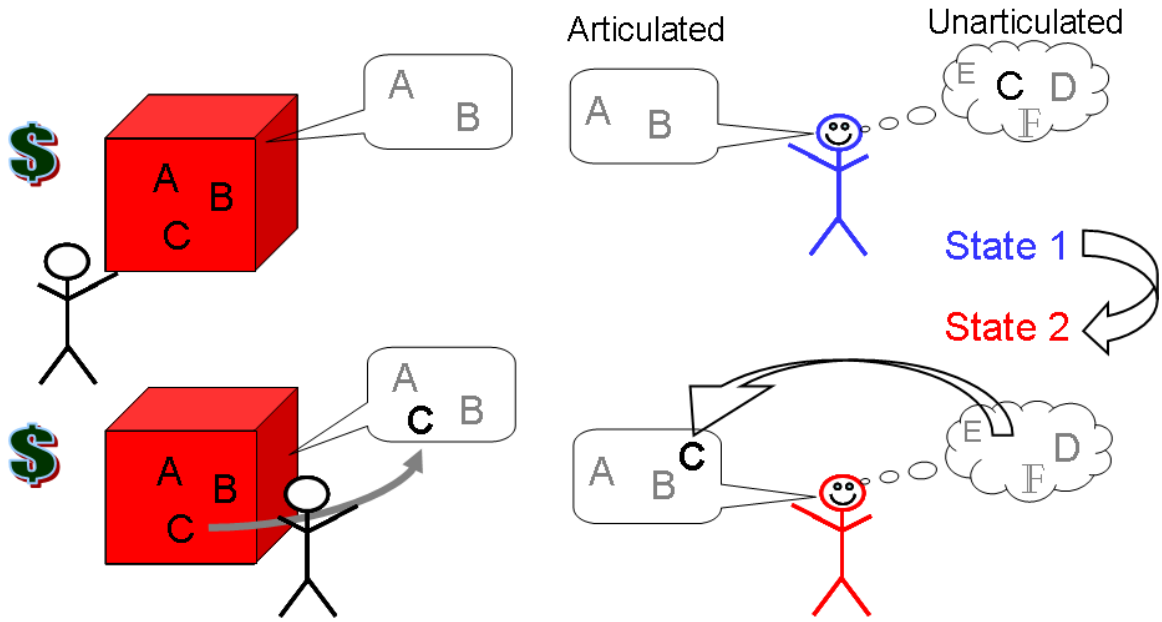

Figure 24 Class 1 Attributes: Free Latent Value

As an example, consider a customer seeking to purchase a new car. Going into the showroom, the customer may consider body styling and gas efficiency as his decision criteria: articulated attributes. Upon test driving a few cars, he comes to realize that comfort also generates value and was a previously unarticulated value. The cars being considered already "display" the comfort attribute and thus do not require modification to delivery comfort value to the customer. In this example comfort is a free latent value for the already existing car.

4.5.3 Class 2 Attributes: Cheap Latent Value

The next class of attributes captures the other type of latent value in a system: those that can be introduced into the system through small cost by recombining existing attributes. The system itself does not require a change, rather the interpretation of the existing attributes may require minor change. The cost of such recombination is much less than that which would be required to change the initial system itself, thus these class 2 attributes are "cheap latent value."

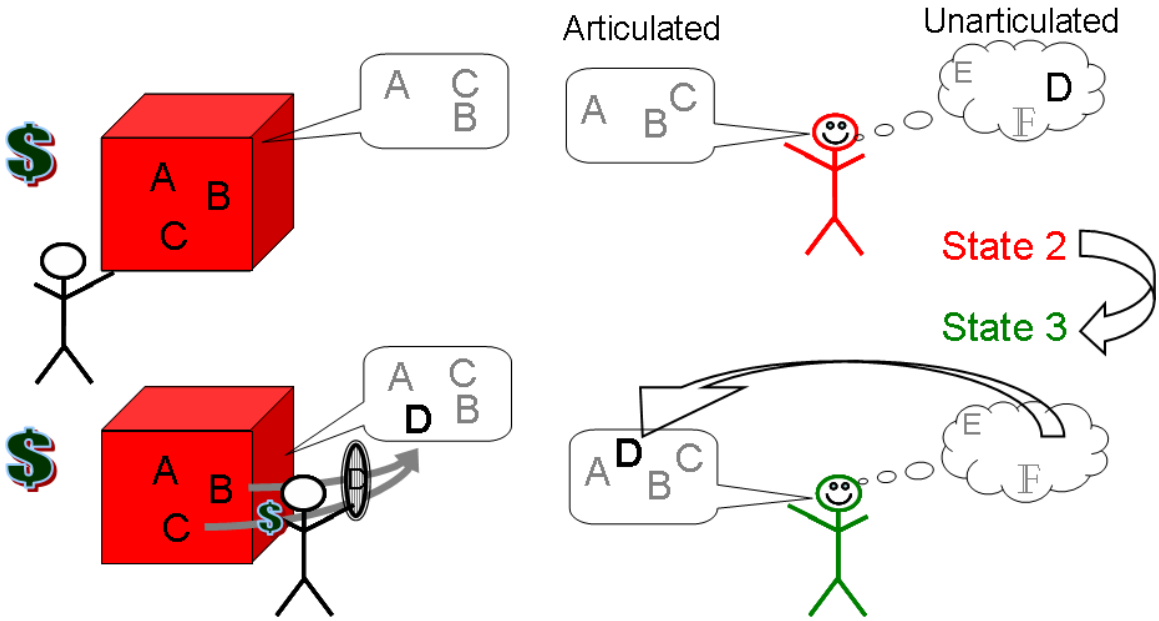

Figure 25 Class 2 Attributes: Cheap Latent Value

As an example, consider the GPS system, with its two attributes: ability to provide time and position data. Initially, the decision maker cares about these two capabilities, which are his attributes. Later the decision maker realizes that he also cares about his velocity. The system designer wants the system to continue to deliver value. Luckily the new attribute, velocity, can be derived from a recombination of existing capabilities. The system itself requires no change, rather a hand held device or other such interpretive system, can be used to derive the new attribute. Another example of cheap latent value for GPS is interactive navigation systems in car, providing real time driving directions to destinations of interest. Compared to changing the GPS system, such new capability is very "cheap."

4.5.4 Class 3 Attributes: Accessible Value

When the system itself must be changed in order to "display" a new attribute, such an attribute belongs to class 3, if the cost is not unreasonable. The cost of such a change can vary from small to large, and each decision maker subjectively defines the reasonability of that cost. Even though the system must be changed, the attributes created in this way are "accessible value."

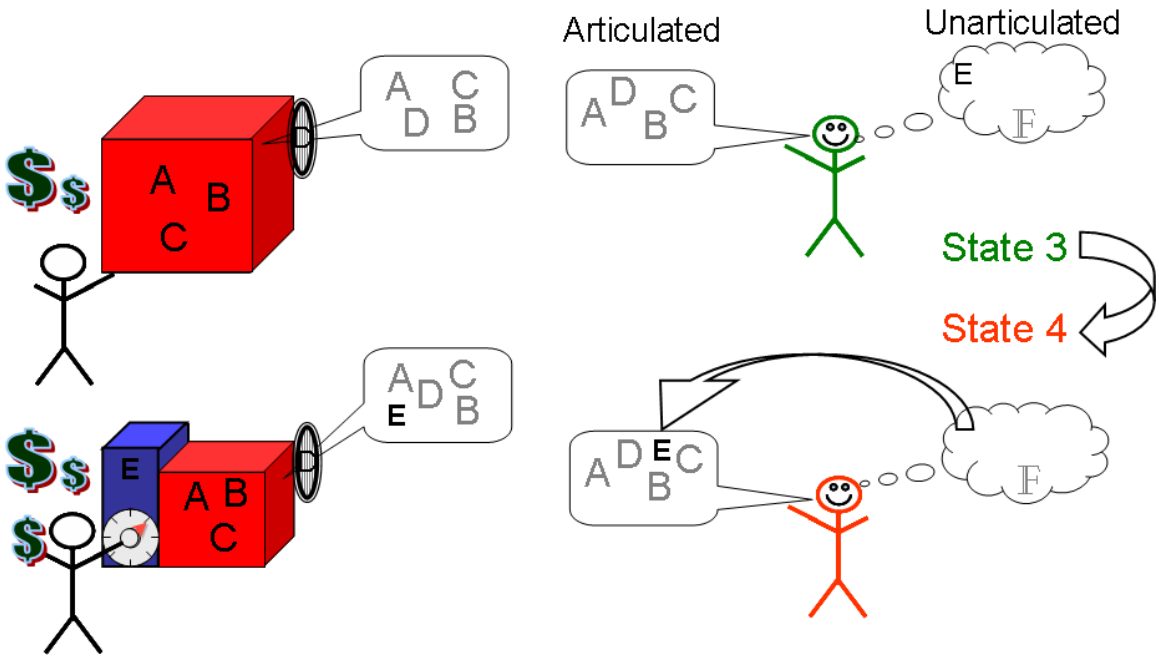

Figure 26 Class 3 Attributes: Accessible Value

As an example, consider an audiophile consumer with an adequate stereo system. Suppose the consumer wishes to add to the system the ability to play MP3 format audio files. In order to add this capability, the system itself requires modification. Options include replacing the CD player with an MP3-compatible player, or perhaps modification of the current system software to enhance audio decoding. In any case, the system must be changed to display MP3-playing capability.

4.5.5 Class 4 Attributes: Inaccessible Value

When the system cannot be changed or the cost incurred too extreme to enable the system to display a new attribute, such an attribute belongs to class 4. These attributes do not flow from the particular system concept being considered, or perhaps represent an unreasonable burden to include, and are "inaccessible value" to the system under consideration.

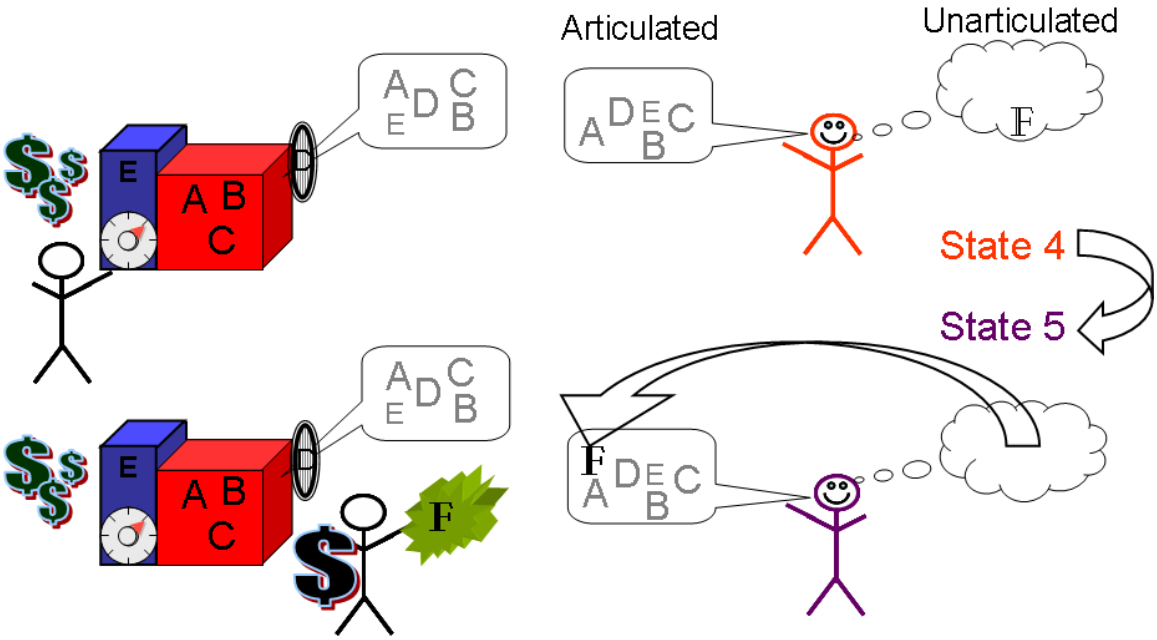

Figure 27 Class 4 Attributes: Inaccessible Value

As an example, consider the desire to include a food preparation capability into a passenger car. While having that capability might add value to a particular decision maker, the cost of doing so is either prohibitive, or would require the concept of car to be revisited. (A camper, however, often does include a kitchen and could readily accommodate such a new attribute, but the transition from passenger car to camper is not cheap and requires discontinuity in concept.)

4.6 Determining Total Value: Individual vs. Group

Of course in the real world, one often is confronted by problems with more than one decision maker vying for value from a system. In fact, in the limit that there are many decision makers and many options, classical economics gives valuable insights into how value flows between suppliers and demanders. In the regime considered here, however, systems are generally unique and value-driven by a relatively small group. The system designer is confronted with the dilemma of deciding how to prioritize among decision makers, including tradeoffs between conflicting objectives and allocation of costs and benefits.

A key contribution in the field of preference aggregation is the work of Kenneth Arrow. His General Theorem of Possibilities, also known as the Impossibility Theorem, proposes five

reasonable conditions of an aggregate preference function, or social welfare function[60]. He goes on to prove mathematically that one of the conditions must be violated. The interpretation is that no "satisfactory" way exists to aggregate preferences without dictatorial or imposed orderings (Arrow 1963). Here "satisfactorily" means that "the social welfare function does not reflect individuals' desires negatively"… and has "the usual properties of rationality ascribed to individual orderings."[61]

In spite of this finding, aggregation does occur, either explicitly or implicitly, in many decision problems. The following sections describe some of these methods of aggregation, how they violate the five conditions, and how "satisfactory" the results can be to the decision makers.

4.6.1 Voting vs. Market

Political science seeks to aggregate preferences through a set of well-defined voting systems. A simple majority rule is one such example, where if more than half of a group prefers an option, that option is deemed the best option for the group. Voting systems consist of two parts: the ballot, and the vote tallying method.[62]

Types of Ballots
Binary: an option is voted for or not
Ranked: all options are ranked from least to most desired
Rated: each option is scored independently on a desirability scale

Tallying methods for binary ballots
Plurality: voters may only choose one option per ballot, option with most votes wins
Approval: voters may choose as many options as like, option with most votes wins
Runoff: multiple plurality votes occur until one option has majority votes, sometimes eliminating least voted options between rounds

Tallying methods for ranked ballots
Instant Runoff Voting (IRV): voters' ranked lists are used to simulate multiple election rounds, with options having the fewest first choice votes eliminated between rounds, option with majority wins
Borda count: options receive points based on rank, option with highest score wins
Condorcet methods: compare every option pairwise with every other option, one at a time, with the higher voted option defeating the other option; if no option is undefeated, secondary criteria are applied (include **Minimax**, **Ranked Pairs**, and **Schulze methods**)

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[60] Condition 1: Existence of Social Ordering for each Individual Consistent with Individual Ordering, Condition 2: Positive Association between Individual and Group Preferences, Condition 3: Independence of Irrelevant Alternatives, Condition 4: Non-imposed Preferences (Sovereignty), Condition 5: Non-dictatorship. p.23-31 Arrow, Kenneth J. (1963). Social Choice and Individual Values. New Haven, Yale University Press.
[61] p.59. Arrow. Social Choice and Individual Values. In fact, the interpretation is that one of the five criteria must be violated. They are also known by: unrestricted domain, non-imposition, non-dictatorship, monotonicity, and independence of irrelevant alternatives. The unanimity, or Pareto efficiency, criterion can be used by replacing the monotonicity and non-imposition criteria.
[62] Most of this section is from the Wikipedia entry on voting systems: http://en.wikipedia.org/wiki/Voting_system, as viewed on 3/5/06. More information on voting systems can be found on: http://wiki.electorama.com/wiki/Main_Page

Tallying methods for rated ballots

Range voting: voters give ratings to each option, option with highest total score wins (includes **approval voting** when range is from 0 to 1)

Criteria which voting theorists typically consider desirable for voting systems include the following (nonexhaustive):[63]

- Majority criterion - If there exists a majority preferring a single option, does it always win if that majority votes sincerely?
- Monotonicity criterion - Is it impossible to cause a winning option to lose by ranking it higher, or to cause a losing option to win by ranking it lower?
- Consistency criterion - If the electorate is divided in two and a choice wins in both parts, does it always win overall?
- Participation criterion - Is it always better to vote honestly than to not vote?
- Condorcet criterion - If an option beats every other option in pairwise comparison, does that option always win?
- Condorcet loser criterion - If an option loses to every other option in pairwise comparison, does that option always lose?
- Independence of irrelevant alternatives - Is the outcome the same after adding or removing non-winning options?
- Independence of clone options - Is the outcome the same if options identical to existing options are added?

The vote tallying methods described above are compared against these criteria in Table 6. Two of Arrow's criteria: Monotonicity, and Independence of Irrelevant Alternatives (IA independence) are explicitly shown in the table. The IA independence criterion is violated by most of the methods, except for the Approval and Range voting methods. These two methods, however, fails the majority criterion, implying that if most people desire an option in that method, it may not be chosen by the vote. The satisfaction of voters can be gauged indirectly by meeting the criteria listed above.

Table 6 Example Vote Tallying Methods and Desirable Criteria[64]

	Majority	Monotonic	Consistent	Participation	Condorcet	Condorcet loser	IA independence	Clone independence
Plurality	**Yes**	**Yes**	**Yes**	**Yes**	No	No	No	No (vote-splitting)
Runoff voting	**Yes**	No	No	No	No	**Yes**	No	No (vote-splitting)
IRV	**Yes**	No	No	No	No	**Yes**	No	**Yes**
Approval	No	**Yes**	**Yes**	**Yes**	No	No	**Yes**	Ambiguous

[63] Ibid. Criteria paraphrasing listing in "Voting System" entry on Wikipedia.
[64] Table adapted from Wikipedia entry on "Voting System."

	Majority	Monotonic	Consistent	Participation	Condorcet	Condorcet loser	IA independence	Clone independence
Range voting	No	**Yes**	**Yes**	**Yes**	No	No	**Yes**	Ambiguous
Borda	No	**Yes**	**Yes**	**Yes**	No	**Yes**	No	No (teaming)
Minimax	**Yes**	**Yes**	No	No	**Yes**	No	No	No (vote-splitting)
Schulze	**Yes**	**Yes**	No	No	**Yes**	**Yes**	No	**Yes**
Ranked Pairs	**Yes**	**Yes**	No	No	**Yes**	**Yes**	No	**Yes**

In the political voting systems, coalitions may form in order to manipulate voting outcomes. Examples of a coalition include voluntary ones, such as voting blocks, and involuntary ones, such as bribed or coerced voters. Additionally, any voting system that violates IA independence is one that can encourage manipulation, i.e., people may intentionally misrepresent their individual preferences in order to get a preferred aggregate outcome.

Economics, in contrast to political science, seeks to allocate options based on market mechanisms. "Aggregate" preferences for a market result from a macro-view of many individual choices. The theory predicts that individuals will match their expenditure with their "willingness to pay" for a good. The willingness is the utility equivalence principal: rational decision makers will expend resources efficiently, that is until their marginal cost of choosing the good equals its marginal benefit, subject to a budget constraint. In a free market, with perfect competition, the free flow of information will enable suppliers and demanders to determine the optimal price level and product mix in order to maximize value for both parties. The aggregate preferences can be considered to be the quantity supplied, quantity demanded, price, and product mix offered in the market. In practice, the market-driven allocation of resources, while efficient, suffers from issues of inequality and justice. Individuals with greater resources have greater power and can impose their preferences on others, thus violating the non-imposition criterion. Likewise, the market mechanism clearly violates the IA independence criterion, as the addition of new products can trigger dramatic preference variations due to the limited resources of the market players.[65]

4.6.2 Social Choice

In some cultures or organizations, group norms can specify aggregate preferences. By definition these methods violate the non-imposition or non-dictatorial criteria. Satisfaction, however, may be met if the members of the group value group membership over the cost of having their individual preferences suppressed. Businesses and military organizations are examples where norm-based aggregation is used to make decisions. Typically members of these organizations do not mind having their preferences excluded since the benefit of membership outweighs their preference exclusion.

[65] The voting system most like the market system is the one employed at corporations, with one share=one vote. In markets dollars=votes, and the distribution of wealth and access to information can determine market winners. Unlike political systems, fairness is often not considered a central criterion for determining aggregate preferences.

4.6.3 Engineering Requirements

In the engineering process, user or customer preferences are usually imposed through explicit requirements. Likewise, management may impose strategic preferences regarding system development and capability generation. Similar to the norm-based aggregation above, these technocratic organizations violate the non-imposition or non-dictatorial criteria. (Scott and Antonosson 2000) explicitly discuss the applicability of Arrow's theorem to decision making in engineering endeavors, arguing that the case is not one of social choice, but rather imposed preferences. In fact, (Hazelrigg 1996) argues for the use of imposed utility functions in order to ensure alignment of objectives across engineering individuals and activities.

In Multidisciplinary Optimization (MDO) approaches, the aggregate value function takes the form of a set of objective functions, which represent the goals for the system. The aggregate best set of options lie in the Pareto Set of options, which are those options where none of the objective function values can be increased without decreasing some of the remaining objective function values. This approach avoids the Arrow problem since members of the Pareto Set are not ordered, and strictly speaking are not part of an aggregate value function. Determining which member of the Pareto Set to use will, however, require some sore of aggregate value function. MDO does not explicitly determine which method should be used.

In Multi-Attribute Utility Theory, (Keeney and Raiffa 1993) suggests a possible aggregation mechanism of the "supra-decision maker." In this case, a single decision maker has a multi-attribute utility function whose single attribute utility functions are actually the multi-attribute utility functions of other decision makers. Implicit in this formulation is interpersonal comparison of utility through the supra-decision maker's k_i values. In military organizations, or other hierarchical organizations, the existence of a supra-decision maker may be possible, however applicability may be limited.

In Operations Research/Management Science, decision problems are often cast in terms of objective functions, which are often mathematically aggregated. Goals such as weighted minimum cost, or minimum risk, summed across decision makers can make for a tractable numeric problem. Goal programming is one technique to address multiple criteria (or decision maker preferences), which seeks to satisfy the most important criteria, while "satisficing" the remaining criteria (getting "as close as possible" to satisfying).[66]

4.6.4 Multi-stakeholder Negotiations

One method for aggregating preferences is to put the decision makers of interest together and have them figure out their group preferences together. Social processes will lead to compromise and preference alignment, resulting in a group preference set. Violation of the non-imposition criterion is most likely. Satisfaction, however, is possible if agreement is made amicably. (Fisher, Ury et al. 1991) discusses a structured process for negotiation, including the four following recommendations:

1. Separate the people from the problem

[66] See Cook, Thomas M. and Robert A. Russel. (1993). Introduction to Management Science. Englewood Cliffs, NJ, Prentice Hall. for discussion on goal programming.

2. Focus on interests, not positions
3. Invent options for mutual gain
4. Insist on using objective criteria

Following these recommendations increases the likelihood of finding a mutually beneficial option for the decision makers, as well a compromise that will last. Before going into the negotiation, each decision maker determines his Best Alternative to a Negotiated Agreement (BATNA) as a fall-back option, thereby reducing the downside uncertainty of a failed agreement.

As an alternative negotiation strategy, (Hazelrigg 1996) suggests negotiating decision makers be allowed to make side payments in order to compensate those made worse off by giving in to a particular proposed solution. The issue of fairness for side payments may prevent such a strategy from being practical, especially when such side payments can be considered as illegal bribes.[67]

4.6.5 Using MATE

In general, no optimum solution exists when multiple stakeholders have conflicting needs. Instead, the set of non-dominated solutions can be found in a tradespace framework, with each dimension represented by a decision maker's multi-attribute utility. Multiple decision makers using the MATE method couples the MDO approach of narrowing the option space to the most efficient solutions, with the multi-stakeholder negotiation approach to select the best compromise solutions.

[67] Contract competition in particular would view side payments as unethical, as would an engineering organization viewing side payments between its staff and management.

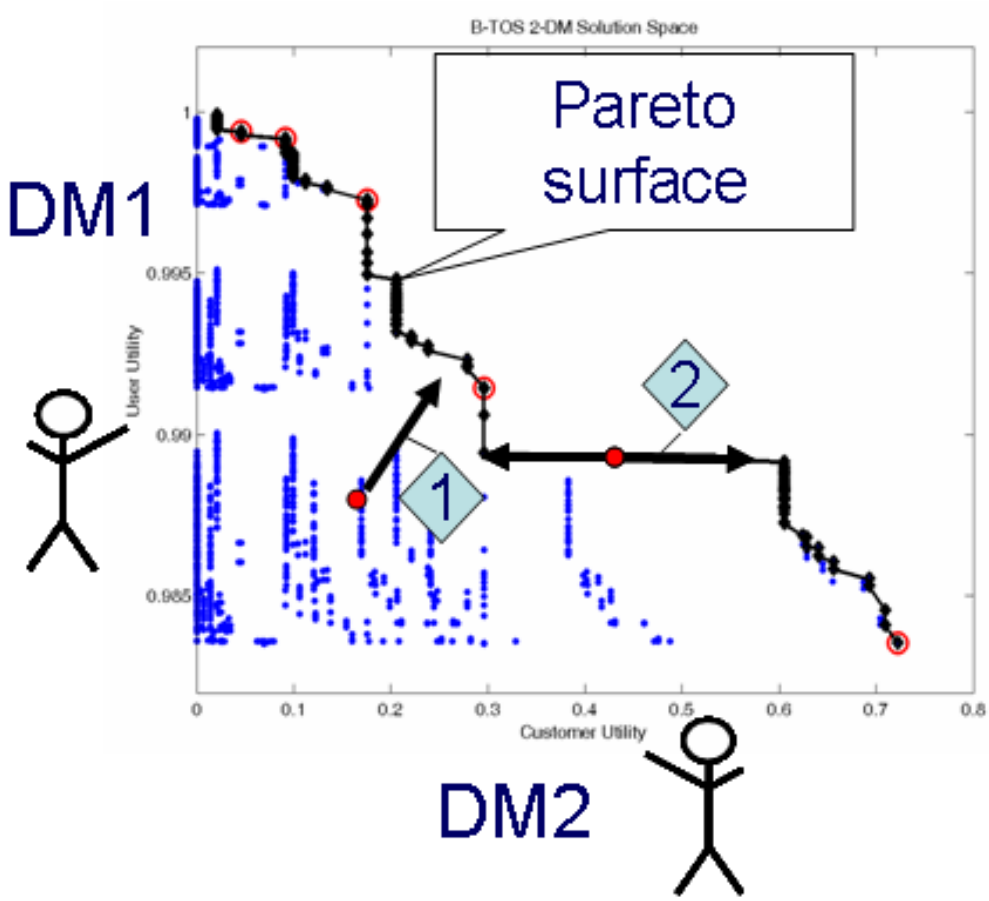


Figure 28 Two decision maker tradespace can be used for negotiation support

The tradespace will highlight two types of strategies: 1) finding the win-win systems (moving toward the Pareto surface), and 2) finding the real trades (along the Pareto surface). (See Figure 28.) Identification of the attributes for the decision makers is the same as step (2) and (4) under the multi-stakeholder negotiation approach. The tradespace exploration approach, and the multi-dimensional Pareto surface in particular, contains the systems where trades between decision makers must be made. The win-win solutions (non-dominated) are options which provide mutual gain over the dominated ones, matching step (3) above. Negotiation allows the decision makers to determine amongst themselves how to properly trade off conflicting values. A clear negotiation advantage exists for those parties who understand the tradespace. The tradespace exploration approach, when coupled with structured multi-stakeholder negotiation makes explicit the best options for negotiated compromise.

Chapter 5: Dynamicism: Matching Change with Change

This chapter provides the motivation for incorporating time into MATE analysis. The context of changing value propositions is an extension of the concept of unarticulated value discussed in the previous chapter. Change and time are inextricably intertwined: change cannot occur without time providing the dimension over which it can occur, while time would be left unnoticed without change providing a basis for comparison from one time to the next. Even though the world is dynamic, traditional static design seems to work well enough. Considering the relative success of past systems, a fair question to ask at this point is "why should systems change?"

5.1 The Nature of Change

> *Dynamicism*: noun. 1: The practice or process of shaping an underlying cause of change.[68]

Change only exists in a dynamic context. It is the path from an initial state to a final, different state. In a world without time, change has no meaning. Standing in the present, looking toward the future, two dynamic change cases exist: an uncertain future or a certain future.

The first case for change is an uncertain future. The existence of an unknown value proposition, or variations in future contexts, can change the perceived value of a system. Since future decision makers may value different attributes, it makes sense that the system should be able to change in order to meet that new value proposition. An example of this case is market uncertainty for a product. The first generation Nintendo® Gamecube included several unused ports. The designers wanted to make future changes, through the additional of components, to the system relatively cheaply. (After a year of sales, uncertainty was reduced and the designers realized that the change would be unnecessary, resulting in a second generation system not having the ports.) The uncertain future case is the typical motivation for desiring flexibility in a system and can be valued using real options analysis.

The second case for change is a certain future. The motivation for the certain case is the existence of high carrying costs for an unused attribute. An example is the ability to refuel a car. Suppose a car were designed to carry all of its lifetime fuel onboard. Clearly such an amount of fuel would make the car an infeasible mode of transportation; however, by creating the ability to change the amount of fuel onboard allows the car to perform its function[69].

5.2 Time

Hot food cools, young people age, seasons change… all at Time's mercy. Time is an inherent part of the physical world, and provides the coordinate frame from which change can be viewed.

[68] Definition based on "dynamic" and "-ism" from Miriam-Webster Online, www.m-w.com

[69] The total amount of fuel needed by a car over its lifetime is an uncertain quantity, but the fact that it requires fuel is not uncertain. For most cases of car usage, the minimum amount of fuel needed over its lifetime is still too much to carry even allowing for a range of lifetime fuel needs.

In physics, in general relativity specifically, Einstein treats time as one of the interrelated dimensions that define the fabric of the universe: the space-time coordinate system. Events in the physical universe have a four-dimensional location in space-time. Events that have occurred, or will occur, have a position in this hyperspatial view of reality. Unlike over the three spatial dimensions, physical reality, as far as we know, does not have control over its position in the fourth dimension. "Time's arrow" refers to the direction that the universe is forced to travel: forward in time. It is this asymmetry of time relative to space that results in what is known as the second law of thermodynamics.[70]

The second law of thermodynamics states that all forms of energy tend to move from areas of high to low concentration, and therefore dissipate. In the universe, entropy, or disorder, tends to increase through natural processes. Time is the coordinate along which these processes occur. Reversible reactions in chemistry and physics are those that are independent of time; irreversible reactions (including nonconservative, or path-dependent forces) only occur in one direction of time.

In engineering, Static analysis is devoted to creating structures that do not change with time. Explicit balancing of dynamic forces must occur until time no long has its detrimental effects. In the end, time wins out, as no human-created structure has withstood the test of time in the long run. Time is also the definitive dimension in analysis of signals, time-varying impulses conveying information, which can be transformed into symbols for communication. Without time, communication has no meaning.

In economics, time is poorly captured in classical theory. Static equilibrium analysis explicitly assumes that time effects are temporary and quickly dissipate. In fact, "long run" analysis was developed to generate insights independent of temporal considerations. The addition of system dynamic analysis to economics has revealed insights into such phenomena as network effects, market inefficiencies, and market bubbles.

In psychology, it is well known that people tend to regard themselves as a static "self." People have the tendency to seek mechanisms to preserve the self in the face of external change forces. A fundamental discomfort with change and the threat to the self has motivated countless coping behaviors, including denial, short-sightedness/narrow-mindedness, and habit formation. Part of the reason may stem from human cognitive limitations, which prevent full consideration of a dynamic environment.[71] Temporal limitations of short term memory result in a constantly cleared recent experience memory buffer.[72] Additionally, often people use heuristics to make decisions since full consideration of a dynamic context is beyond the processing and

[70] Some philosophers argue the other direction: it is the second law of thermodynamics that give us a sense of time. In any case, the concept of time and the second law of thermodynamics are intimately connected.

[71] For discussion of bounded rationality and decision making in economics, see Gabaix, Xavier and David Laibson. (2001). "A New Challenge for Economics: "The Frame Problem"". Collected Essays in Psychology and Economics. I. Broca and J. Carillo. London, UK, Oxford University Press.

[72] For discussion of computational theory of mind see Simon, Herbert A. (1996). The Sciences of the Artificial. Cambridge, MA, The MIT Press. and Simon, Herbert A. (1990). "Invariants of Human Behavior." Annual Review of Psychology **41**: 1-19.

understanding of a single human mind. Yet in spite of these limitations, humans still manage to cope with the effects of time, albeit inefficiently.[73]

5.3 "____ over time"

To first order, time can be incorporated into dynamic perspectives by considering the world to be a movie made up of a series of static frames run in quick succession. The snapshot interpretation allows for a simple extension of static analysis techniques and perspective. Figure 29 shows the relationship between the static and dynamic perspectives. Continuity of states across the boundary of the frames ensures coherent stringing of the static snapshots. In the limit each frame duration approaches zero, the analysis becomes continuously dynamic.

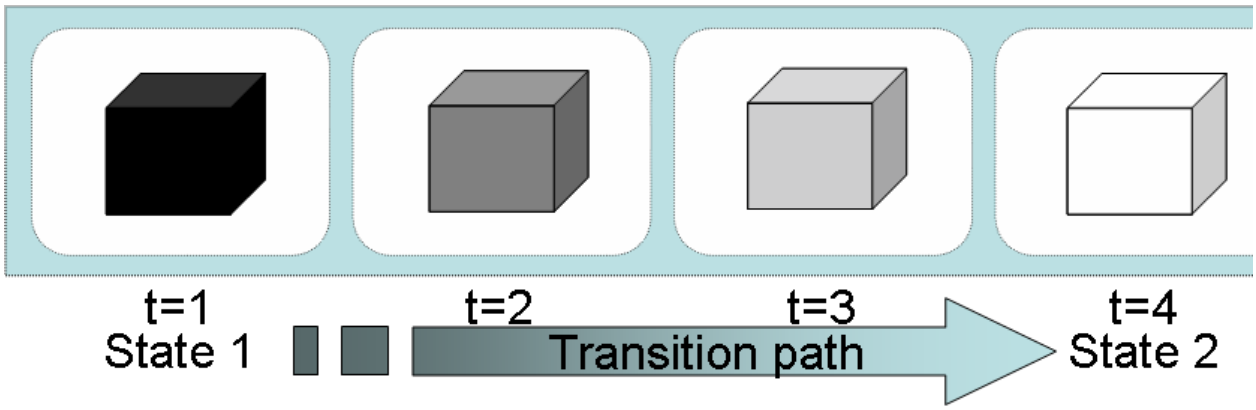


Figure 29 Time as a series of static snapshots

Wrapping time into the perspective of system development depicts the forces of value over time. When confronted with a decision, a decision maker perceives his options through a "decisional" value lens. Once the decision maker interacts with the system in use, the decision maker perceives his choice through an "experienced" value lens. These two lenses are not the same. An example of these two perspectives confronts restaurant patrons on a daily basis. The patron reading the menu selects from the options using "decisional" value, which is an expectation of the experience with the ultimate choice. Upon eating the meal, the patron might realize that his eyes were too big and his "experienced" value was less than anticipated. If the patron learns from the experience, the "experienced" value will inform his "decisional" value and the next time the decision may be different.[74] In systems where learning cannot occur, convergence between these two lenses cannot be expected.

[73] See Saleh, Joseph H. (2002). Weaving Time into System Architecture: New Perspectives on Flexibility, Spacecraft Design Lifetime, and On-orbit Servicing. PhD thesis in Aeronautics and Astronautics. Massachusetts Institute of Technology. Cambridge: 224. for a discussion of the parallels between evolution and adaptability over time.

[74] "Experienced" utility corresponds to the original Bentham meaning of utility as relating to pleasure and pain, as opposed to more modern interpretations as a decision metric, corresponding to "decisional" utility. "Remembered" utility is the recall of "experienced" utility and typically informs the "decisional" utility for a decision maker. For motivating experiments and discussions on these types of utilities, see Kahneman, D. (2000). "Experienced Utility and Objective Happiness: A Moment-Based Approach". Choices, Values, and Frames. D. Kahneman. Cambridge, UK, Cambridge University Press: 673-708.

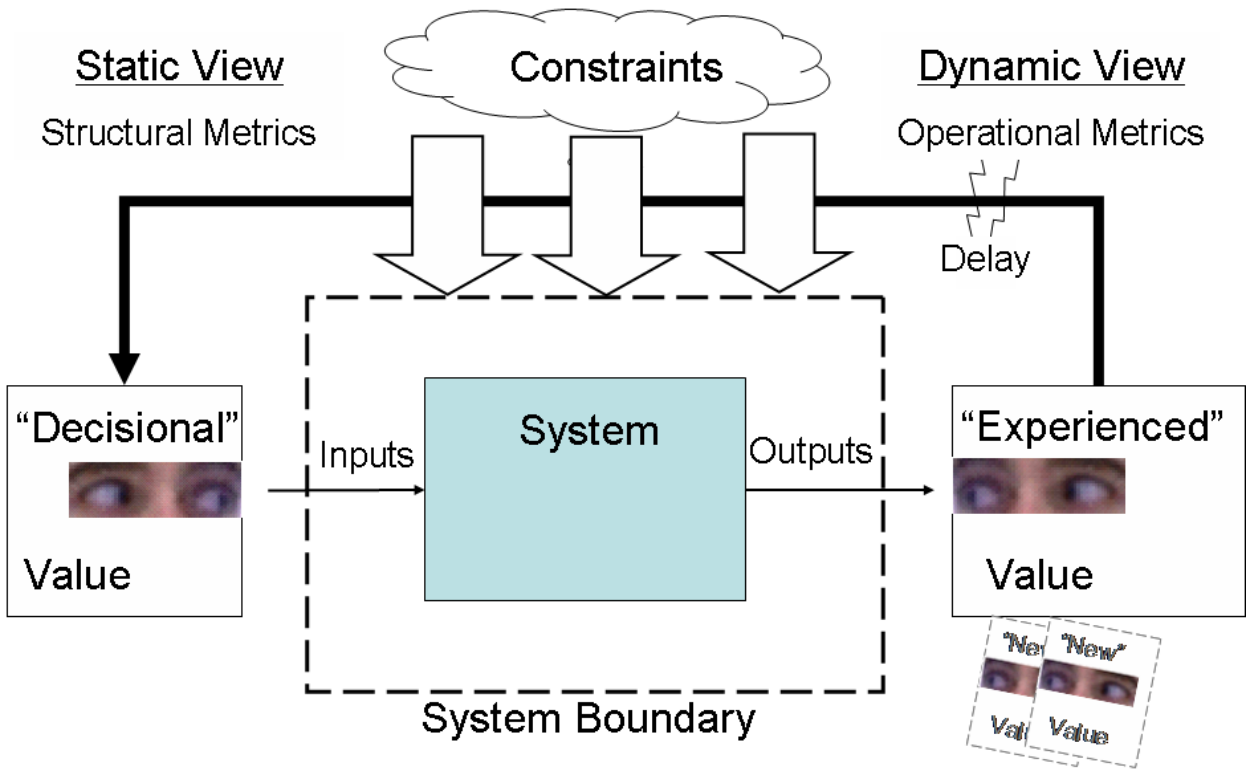


Figure 30 Dynamic value lenses: Decisional versus Experienced Value

One point to consider when making decisions about systems is to be aware of the nature of the metrics being used for the basis of the decisions. Structural metrics relate to the physical, or static, properties of the system. Operational metrics relate to the functional, or dynamic, properties of the system[75]. Since these metrics may be assessed at different ends of the system choice timeline, two different value lenses may inadvertently be applied to them, resulting in inconsistent perspectives.

5.4 Accounting for Time

Since static analysis tend to be more tractable and comfortable, removing, or at least hiding, the uncertainty associated with dynamics, several methods exist to remove time from explicit consideration.

5.4.1 Discounting

The method of discounting is the technique for finding, or calculating, the equivalent present value of a future or past event. The assumption in discounting theory is that people, in general, value an option more highly in the present than that same option at a future point in time. The premium that a person would be willing to pay in order to move a future event to the present represents the discount in value a future event has relative to the same event at present. Net Present Value analysis assumes a constant rate of discounting over future time periods in order to determine the present value. Net Present Value calculations include both the costs and benefits of future value streams and can be determined using:

[75] See Giachetti, Ronald E., Luis D. Martinez, et al. (2003). "Analysis of the structural measures of flexibility using a measurement theoretical framework." International Journal of Production Economics **86**: 47-62.

$$NPV = \sum_{i=0}^{n} \frac{B_i - C_i}{(1+r)^i},$$

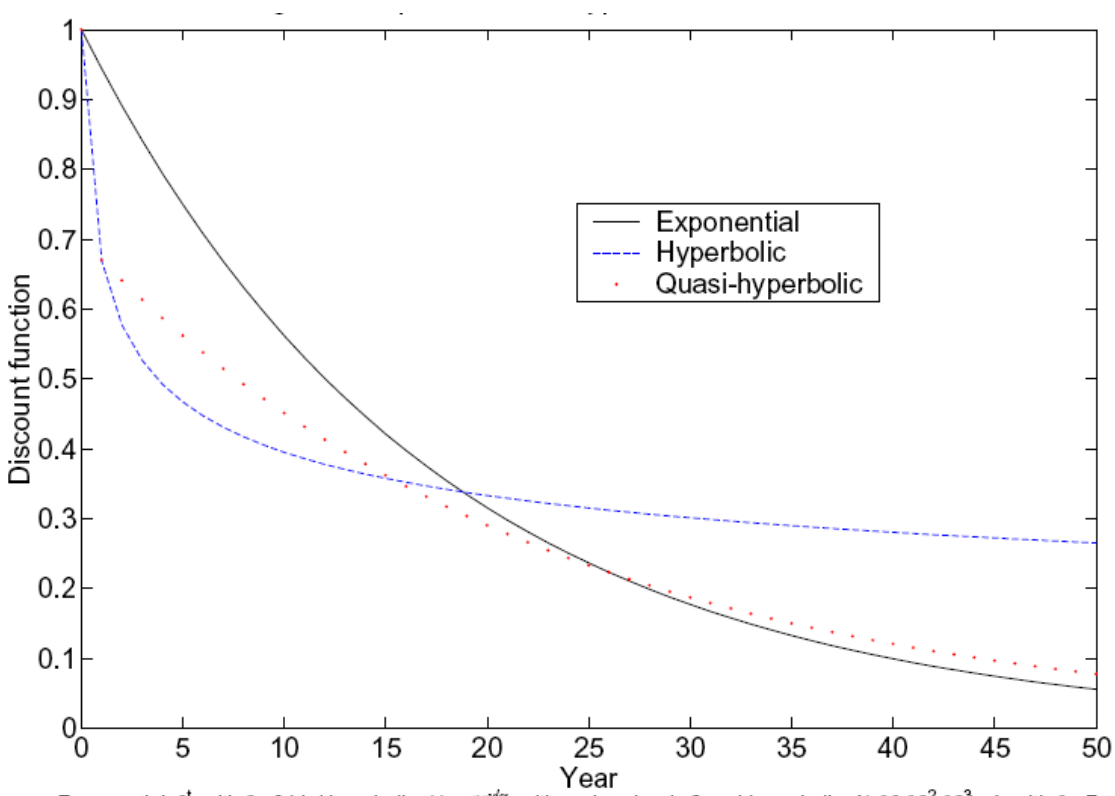
where r is the discount rate (expressed as a fraction), B_i is the benefit in period i, C_i is the cost in period i, and n is the number of periods in the value stream. This type of discounting is called "exponential" discounting due to the exponential nature of the discount rate multiplier over time.

A different form of discounting is called "hyperbolic" discounting, which reflects a non-uniform discounting strategy of the future value stream. In reality, people often do not view the future homogenously, but instead place far more emphasis on the present.

Instead of having a discount rate $\delta^t = (1+r)^{-t}$, hyperbolic discounting uses a discount rate that diminishes over time, such as

$$NPV = \sum_{i=0}^{n} \frac{B_i - C_i}{(1+\alpha \times i)^{\gamma/\alpha}},$$

Where α and γ are related to the "discount rate." Notice hyperbolic discounting results places much greater weight in the present than does exponential discounting (see Figure 31).



Exponential: δ^t, with δ=.944. Hyperbolic: $(1+\alpha t)^{-\gamma/\alpha}$, with α=4 and γ=1. Quasi-hyperbolic: $\{1,\beta\delta,\beta\delta^2,\beta\delta^3,...\}$, with β=.7 and δ=.957.

Figure 31 Exponential and hyperbolic discounting functions[76]

[76] Figure from Harris, Christopher and David Laibson. (2001). Hyperbolic Discounting and Consumption. Eighth World Congress of the Econometric Society, Seattle, WA, Econometric Society.

5.4.2 Forecasting

The method of forecasting is the technique of predicting future events or conditions from the present state. Predictions can be based on analogies, theory, logic, guesswork, expert opinion, past performance, historical data, or other information.

According to (Cook and Russel 1993), forecasting techniques can be cast into three categories: qualitative methods, time series methods, and causal methods. Qualitative methods use qualitative data, such as aggregate expert opinions to predict the future. Time series methods rely on historical data, "focusing on seasonal and cyclical variations and trend extrapolations." Causal methods "attempt to define relationships among independent and dependent variables in a system of related equations."[77] When choosing the type of forecast to use, the analyst must weigh the cost of performing the forecast versus the cost of inaccuracy in the forecast.

Forecasts are often done on events or conditions of the future outside of the control of the design engineer, but which have impact on the future value of the system. But calculating the forecast value alone is not sufficient. Since the future is uncertain, according to (Hazelrigg 1996), "to provide information on the future, we must have an estimate of the accuracy of the forecast as well as the forecast itself."[78]

An important tool in forecasting is the use of regression analysis. Calculating "best fit" curves to available data provide a convenient mathematical tool for prediction. One word of caution, however: fitted data reveal correlation, not causation. Blind reliance on regression-derived functions can lead to grossly incorrect conclusions. Previously unknown explanatory variables can suddenly become dominant and critically alter the real world results, out of line with the forecasted prediction. The analyst must seek causation models to help explain the actual mechanisms underlying a model. Often for complex systems, such bottoms-up, or "physics"-based models are too difficult to derive. Discretion must be used in these cases to contain the effects of unexpected results.

When historical data is unavailable, or the future is expected to differ from previous results, a forecast model can be constructed using logic. Such models are more fungible to specific situations, but require more extensive domain expertise and validation. It is often more difficult to estimate the uncertainty of such models as well. Use of Monte Carlo simulation can provide initial estimates of a model's input-output uncertainty relationship. Uncertainty regarding the model itself will be difficult to ascertain without comparison to actual world data.

The most important consideration when using forecasting models is the amount of uncertainty associated with their results. Model uncertainty, input uncertainty, as well as unknown uncertainties can all affect the accuracy of forecasts. The best an analyst can do is to seek to mitigate the uncertainty effects on their conclusions. In any case, forecasting seeks to bring knowledge of future states to the present in order to simplify contemporary decision-making.

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[77] pp. 502 Cook and Russel. Introduction to Management Science.

[78] pp. 181 Hazelrigg, George A. (1996). Systems engineering: An approach to information-based design. Upper Saddle River, NJ, Prentice Hall.

5.5 Individual Choice over Time

In spite of the efforts of analysts to remove the need to consider time in its proper place, people do, in fact, consider the effect of time on their choices. As opposed to strictly rational decision-making, as ascribed by neoclassical economics where an expected utility maximizing individual makes consistent choices over time, most decision makers are affected by non-rational effects. The bifurcation of utility into "experienced" and "decisional" can be further elucidated. According to (Loewenstein and Elster 1992), intertemporal choice depends upon not only the direct experience of the moment, or primary experience, but also upon memory and anticipation of past and future experiences, or nonprimary experiences. Nonprimary experiences can also be considered to include utility derived from the experiences of others.

Table 7 Nonprimary experience temporal effects on current utility[79]

Backward effect	Forward effect	Result
Consumption		Prefer to consume in present to maximize creation of good memories, overall want to maximize creation of extremely positive memories
Contrast		Create good memories that cannot be compared to present, create stream of improving experiences to remember improvement (present superior to any summary of past)
	Consumption	Put off good experiences to maximize savoring, continually improve, take bad experiences now
	Contrast	Continually improve or remain constant in present state so that future does not look too much better than present (reduce discontent with present)

Two axes of effects can be defined: consumption versus contrast, and backward versus forward. Table 7 shows these four effects and what happens when each is dominant. The *consumption effect* describes those effects on current utility by nonprimary experiences. (The effect includes the "reliving" of experiences in the mind of the individual, which then affects the current utility level.) This effect has the same hedonic sign as that of the experience and the impact does not depend strongly on the current context of the individual. Recalling a past positive memory evokes a positive feeling in the present, usually regardless of the present situation. The *contrast effect* describes those effects on current utility by nonprimary experiences due to changing the baseline against which the current context or experience is compared. (The effect includes the comparing of the current situation to a past or future situation to determine if a gain or loss has been experienced.) This effect has the opposite hedonic sign as that of the experience and the impact is indirect in that it changes the way an individual interprets primary experiences. Recalling the glory days of NASA evokes negative feelings in the present as older engineers lament the relatively worse state in which they now find themselves.

The *backward effect* describes the effect on current utility from contemplation of past memories. The *forward effect* describes the effect on current utility from contemplation of future experiences. *Savoring* relates to positive forward effects, while *dreading* relates to negative forward effects. In general, individuals will seek to savor, while avoiding dread, but the actual

[79] Based upon Loewenstein, George and Jon Elster, Eds. (1992). Choice Over Time. From "Utility from Memory and Anticipation." New York, Russell Sage Foundation. p.213-234

intertemporal choice of an individual will vary based on whether consumption or contrast effects dominate. (The strengths of the effects will vary from individual to individual.)

The "experienced" utility mentioned above is equivalent to primary experience effect on current utility; it is the utility during and immediately after the event. The "decisional" utility is equivalent to the nonprimary experience effect on current utility; it is the utility prior to the event. A key differentiator between past and future events is that memories are certain since the past has already occurred, while the future is uncertain since it has yet to occur. As such, anticipated experiences may not match actual experiences due to the uncertainty, as well as mistakes in actual anticipation of the experience itself.

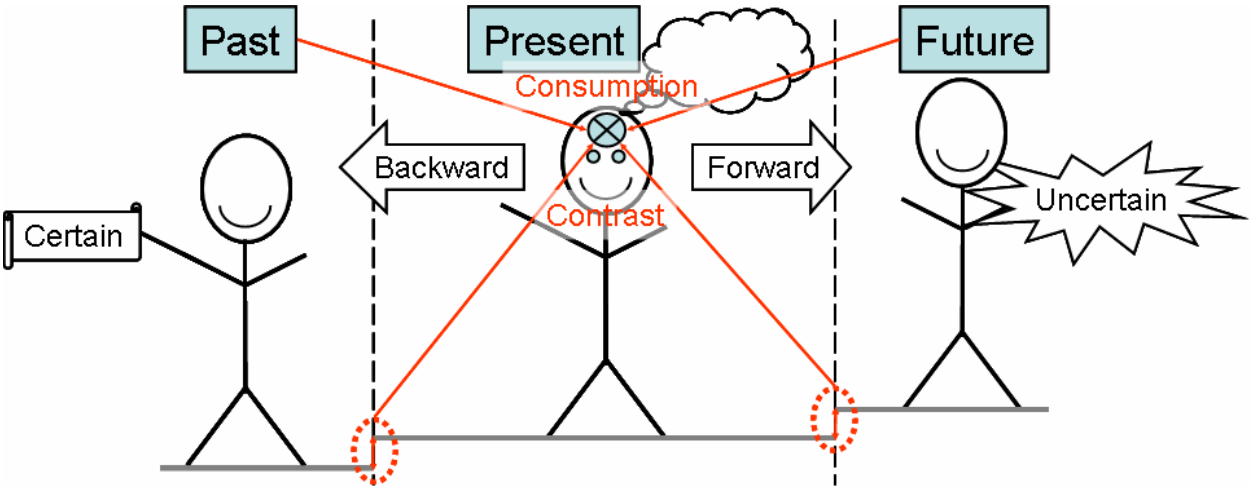

Figure 32 Consumption and contrast temporal effects on current utility

Two types of nonprimary experience based entirely in the mind that can affect the current baseline preferences are subjunctive and counterfactual. *Subjunctive experiences* are hypothetical experiences based on events outside of one's control. *Counterfactual experiences* are hypothetical experiences based on alternative choices that may have been made. Even though neither of these types of experiences have occurred to the present self, both can and do affect the current context in which past, present, and future experiences are interpreted. The subjunctive experiences provide the basis for sensitivity analysis on constraints: "what if policies or budgets change?" How will the outcomes differ? The counterfactual experiences provide the basis for sensitivity analysis on choices: "what if I went left instead of right?" How would the outcomes differ? Insight from the answers to these questions can change the expectations of the individual and therefore affect their utility, even if the experience never becomes primary.[80] (In other words, memories and thoughts, both real and imagined, can affect a person's tastes and preferences, altering current utility.)

It turns out that for events of relatively short duration, or for choices involving luxury goods, consumption tends to dominate contrast effects. Thus, people will tend to defer the consumption

[80] The "learning effect" relates to the effect experiences have on tastes and preferences, which remain even after memory of the actual experience dissipates. The effect on utility differs from consumption and contrast since it usually does not enter consciously into utility perception. See Loewenstein, George and Jon Elster, Eds. (1992). Choice Over Time. New York, Russell Sage Foundation., p. 221.

of luxury goods (in order to increase savoring) and consume negative, short duration goods as soon as possible (in order to reduce dreading). Both of these results run contrary to classical time discounting expectations, but are consistent with the forward consumption effect. Application to aerospace decision making should be considered by system designers: goods perceived as luxuries may cause more benefit in the mind of the decision maker if it is never realized since more time can be spent savoring the possibility of the system. On the other hand, aerospace systems are often not luxuries and users derive more utility from primary experiences, as opposed to nonprimary experiences, suggesting the need to deploy as soon as possible to maximize "experienced" utility.[81]

In the case where the future condition is inferior to the present condition, the consumption effect will tend to dominate, resulting in a mitigation of disutility caused by a contrast effect. This observation means people will tend to put off good experiences in order to savor them and raise their present utility to offset the expectation that the current context will get worse over time.

5.5.1 Applicability to Engineering Design

Some have said that many of the perverse or constraining aspects of actual decision theory do not apply to the engineering design endeavor. First, engineers are trained, rational thinkers who are not affected by emotions or irrationality, but rather follow rigorous, or at least logical, decision processes during their technical work. Second, they are not making personal decisions, but rather, are acting on behalf of other agents who are making technical, professional decisions. The engineering problem is not one of social choice or consumer choice, so social psychology and economics only indirectly apply.[82]

The response to the first argument is that even though engineers are trained in advanced mathematics, logic, and rational thought, the training does not result in a hyperrational individual who makes only rational decisions. As an example, consider the senior-level Psychology and Economics course taught at Harvard by renowned behavioral economist Professor David Laibson. Each class begins with an experiment, which requires each student to answer a set of questions. The questions are often posed in terms of making the best economic choice in a given described scenario, while under time constraints. The class ends with a discussion of the results of the previous class's experiment. The results consistently showed that most of the class failed to provide the "correct" rational answer, counter to the expectations of a class of trained Harvard economics majors. If trained economics majors cannot reliably apply rational processes to economics decisions, how can an engineer be expected to act rationally over many, potentially novel or unique decision problems?

The response to the second argument is that even though engineers are acting as agents, they are still human and are affected by emotion, incorporating perspectives of actual past and potential future events into their decision calculus. Until machines make all decisions, exclusion of "irrelevant" information and adherence to strict logical and rational decision processes is

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[81] 🖉🕮 potential research could apply the temporal theories of utility perception presented here to the domain of aerospace system acquisition.

[82] See Scott, Michael J. and Erik K. Antonosson. (2000). "Arrow's Theorem and Engineering Design Decision Making." Research in Engineering Design **11**(4): 218-228. for discussion of the applicability of Arrow's Social Choice problem.

unlikely. Additionally, the rationality of the engineer does not preclude the existence of an irrational decision maker defining the driving system need. The engineer must be aware of biases and non-rational effects on preferences in order to understand and potentially anticipate changing value propositions of the customer.[83]

Speaking with a group of experienced engineers at a recent Systems Engineering conference finds them quick to share stories of changing requirements and frustration over customers who do not know what they want. Evidently individuals changing preferences over time is a regular occurrence .The predictability of preference change should be embraced, or at least accepted, by design engineers instead of resisted since it is an inevitable aspect of human thinking. Through embracing change, the designer will soon realize that instead of change presenting risk, it actually presents opportunity for creating value.

5.6 Value Interaction over Time: Classes of Markets

A level above considerations of individual choice over time is the interaction of choice between individuals in the context of a market. The basic unit of dynamic value exchange occurs at the level of an individual decision maker “demander” and an individual system "supplier.” Two fundamental dynamic forces exist at this level: the changing value perception of the decision maker and the changing system offerings of the system “supplier.” Mutual exchange of value occurs when both the roles of supplier and demander are fulfilled by the same individuals and organizations. For example as a consumer looking for a new computer, that “demander” has certain preference regarding the attributes of the new computer. The system “supplier” could be a computer retailer selling computer systems. That computer retailer also “demands” compensation for the system and requires that the consumer “supply” money as payment. For simplicity sake, the “supplier” for the following discussion will be the system designer, perhaps acting on behalf of a larger entity. The “demander” will be the decision maker under consideration.

A basic model of the dynamics of interaction between the supplier and demander is as follows. Suppose a demander has Prior Preferences regarding a system’s traits. He knows what is good and what is bad and if given a set to choose from, would be able to order a list of alternatives from most to least appealing. Those Prior Preferences may change over time due to changes in individual taste or other forces. Suppose further that the Demander exists in a Context, which includes information and pressures that may affect how the Demander sees the world at that instant in time. The Context will vary at some possibly variable rate. According to (Baron 2000), some researchers believe that individual tastes and preferences have a Drift associated with random fluctuations in belief. Drift could be caused at the neurological scale, or subconscious level. The Demander’s current preferences will be some function of Prior Preferences, the Context, and Drift. Making a choice among alternative system options, the Demander “articulates” part of that current preference.[84]

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[83] For further discussions of descriptive models of choice, see sections on Prospect Theory and heuristics in Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design. .

[84] An interesting consideration relates to the case of the Demander with multiple personalities. Such individuals may have multiple or conflicting preferences, with the expression of “dominant” values changing over time. Congress as a single entity can be considered of this class since each individual member may have differing and conflicting preferences, yet the decisions articulated by Congress may or may not remain stable over time as

Suppose there is a Supplier who generates the system offerings for the demander. The set of options offered will change as a function of three forces: the Current Preferences of the Demander, delayed effects from the Context, and Infrastructure time scales. Presuming that the system Supplier desires to have her system offerings chosen by the Demander, the system offerings will seek to match the articulated value proposition of the Demander. The Supplier may also seek to glean insights from its Context, deriving new possibilities for systems or attempting to predict possible future demands. A delay exists between the current Context and its effect on the system offerings due to the need for processing and implementation of the information. The last force affecting the offerings is the infrastructure time scale, which relates to the fundamental constraints on the system offerings, such as political inertia, manufacturing limitations, and in-house knowledge and experience. The Supplier can introduce new or changed offerings on a time scale that is a function of the three forces. An important feedback loop is created as the system offerings themselves become part of the new Context faced by both the current and future Demander and Supplier.

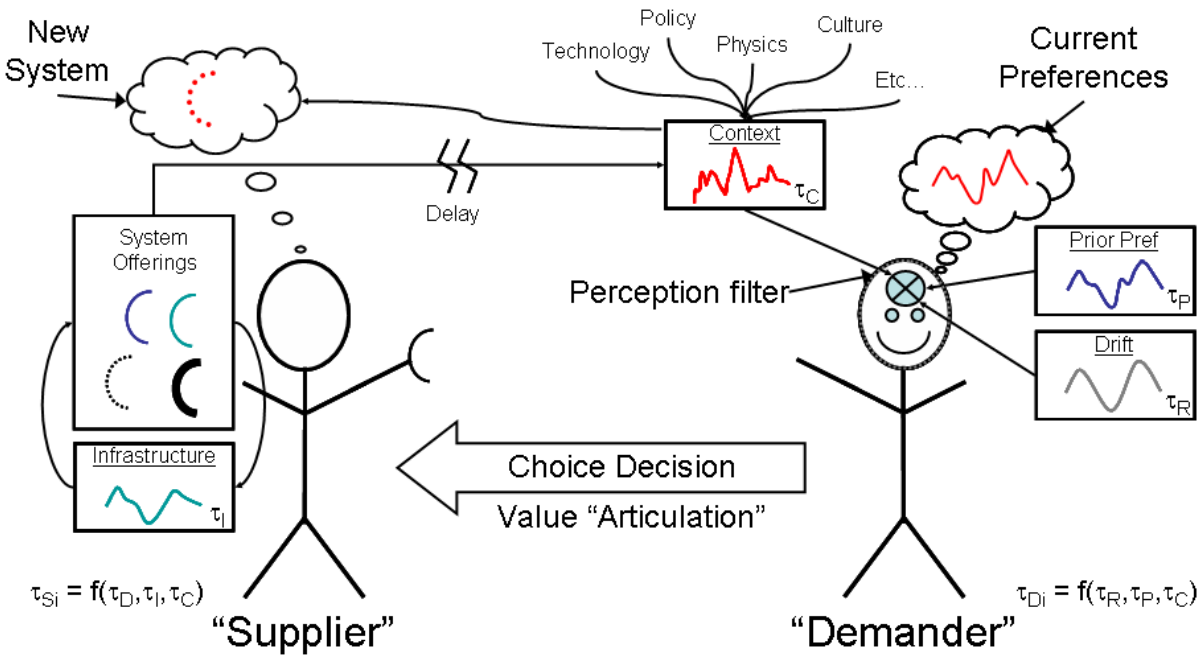


Figure 33 The roots of dynamic individual preferences

Using this relatively simple dynamic model of value transference through choice articulation, insights can be made into the interaction of various combinations and numbers of suppliers and demanders, revealing cases where value transference may be inefficient.

"dominant" Congressmen become the voice for the body. Treatment of Congress as a multiple Demander case may provide insight into the problem as well, but reality lies somewhere in between (has single demander effects, but multiple demander preferences). Further work should be considered in this area.

5.6.1 Many Suppliers, Many Demanders

In the first case, consider the market that is both a polyopoly (many suppliers) and a polyopsony (many demanders). In this case, the dispersion of preferences of the various demanders could "average out" since the suppliers need only meet the average demander in order to ensure choice of her offering. Additionally, the variability of the demander preferences will be smoothed out, assuming only weakly correlated preferences. The time constant of preference change for aggregated multiple demanders will be larger than that of an individual demander.

Many suppliers ensure a variety of choices, maximizing the likelihood that demanders will find offerings that deliver value. In effect, the time constant for offering set change is less than that of an individual supplier due to asynchronous individual offering change. The two time constants move towards a dynamically efficient situation, where aggregate preferences vary more slowly and aggregate new offerings vary more quickly, perhaps converging.

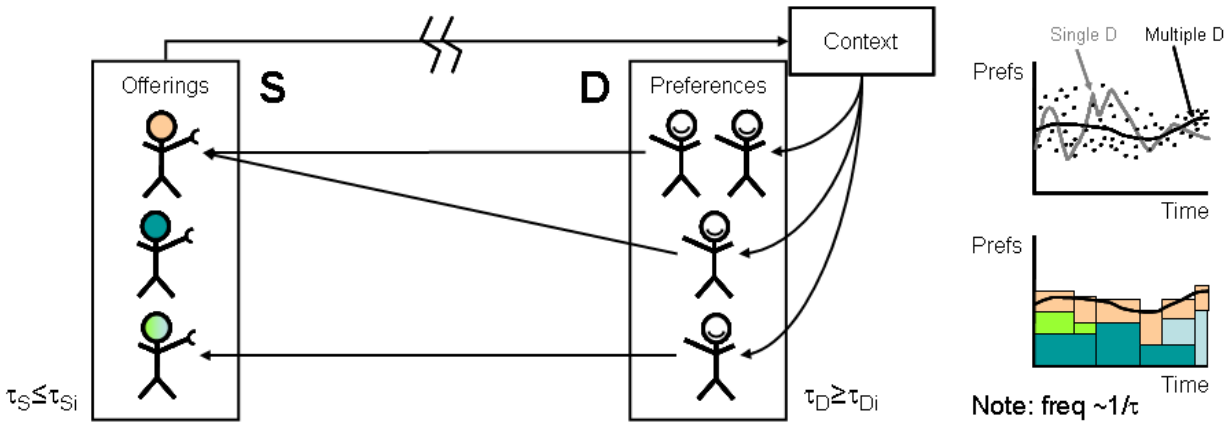


Figure 34 Market case 1: Many suppliers, many demanders

In the long run, the dispersion of preferences of demanders may collapse, resulting in preference synchronization. Such is the case when the choices of individuals affect the context as seen by future individuals, who may see prior choices as more attractive. Offerings may converge over time as well to meet the synchronized preferences. The effect is similar to reducing the number of suppliers and demanders. Perturbations introduced by the Context, however, may prevent any stable equilibrium from forming and re-disperse the demander's preferences.

This case is akin to perfect competition and is the most efficient situation for delivering value to demanders. In this case, the market determines the "price," or terms of the system offering choice. Figure 34 shows this market case one.

5.6.2 Single Supplier, Many Demanders

In the second case, consider the market that is both a monopoly (single supplier) and a polyopsony (many demanders). In this case, like the first case, the aggregate preferences of the demanders are smoother than those of the individual demanders. The aggregate system offering time is slower than in case one, however, as no other supplier can introduce a new offering during the "off" time for the competitor. Fewer offerings mean more dissatisfied demanders and less value delivered.

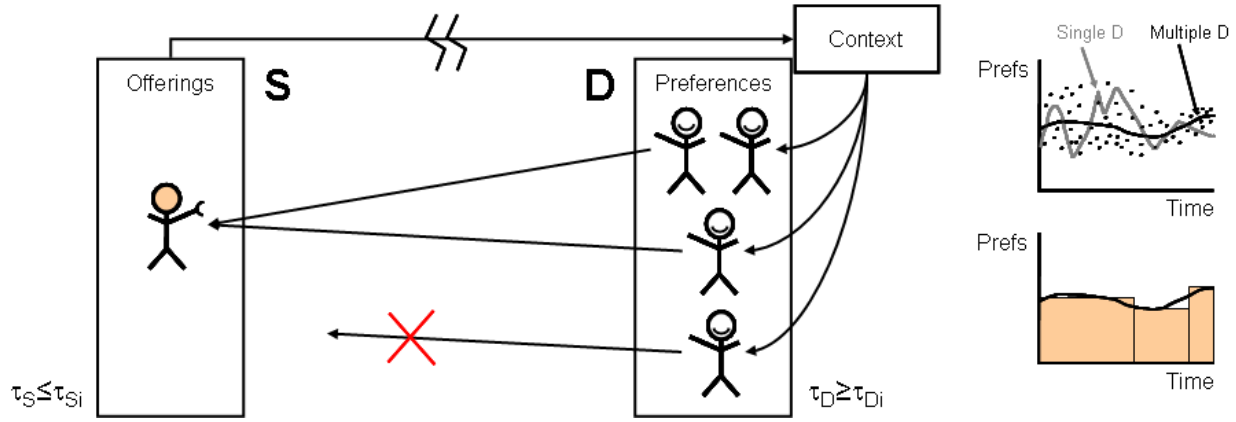


Figure 35 Market case 2: Single supplier, many demanders

In the long run, the demanders may synchronize their preferences to the offering set, or to each other. Likewise, the supplier may try to actively alter the demanders' preferences to synchronize with the offering set in order to increase net value transfer between suppliers and demanders.

This case is akin to monopoly markets and is much less efficient for delivering value to demanders, though it may deliver more value to the supplier than case one. In this case, the supplier determines the "price," or terms of the system offering choice. Figure 35 shows case two.

5.6.3 Many Suppliers, Single Demander

In the third case, consider the market that is both a polyopoly (many suppliers) and a monopsony (single demander). In this case, the aggregate preferences of the demander are the same as the individual preferences, with more variability than the many demander case. In the short run, the suppliers will have many offerings and an aggregate system offering rate faster than that of a single supplier. Since the demander will most likely only choose offerings from a subset of the entire supplier set, the suppliers seek to cater to the preferences of the demander as much as possible. Competition among the suppliers for the attentions of the demander will likely result in a decrease in the number of suppliers over time.

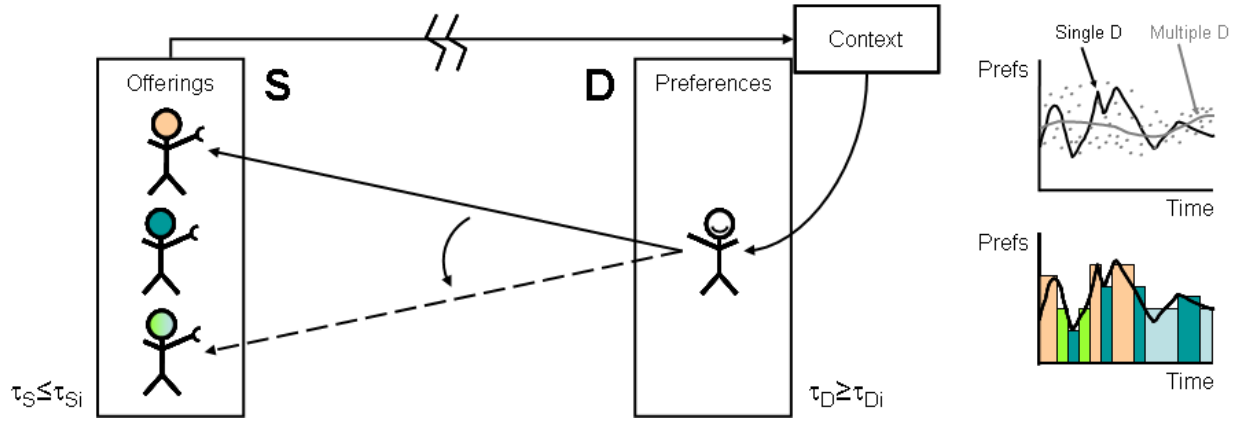


Figure 36 Market case 3: Many suppliers, single demander

In the long run, the demander will face a shrinking set of suppliers and thus an increase in the time constant for system offering set change. In the short run, the demander receives a large amount of value as the system offering set will likely meet many of the preferences and change relatively quickly to stay synchronized with any changes in the demander preferences. In the long run, however, the offerings will decrease in variety and rate of change and will likely deliver less value over time to the demander. The long run equilibrium tends toward few suppliers. Additionally, since the aggregate preferences of the demander are not averaged, the context may have a significant affect on the aggregate preferences. As such, the suppliers may seek to synchronize with the context in an attempt to anticipate the demander preferences.

The U.S. aerospace industry most likely fits this case, with at first a large number of aerospace companies vying for the attentions of the single demander (the U.S. government). Over time, the industry has seen massive consolidations down to a few suppliers that are alternatively selected by the government in order to ensure the existence of more than one supplier. The demander in this case is aware that more value may be lost if the set of suppliers further decreases.

This case is akin to monopsony markets and is much less efficient for delivering value to suppliers, though it may deliver more value to the demander than in case one. In this case, the demander determines the "price," or terms of the system offering choice. Figure 36 shows case three.

5.6.4 Single Supplier, Single Demander

In the fourth case, consider the market that is both a monopoly (single supplier) and a monopsony (single demander). In this case, the aggregate preferences are the same as the individual preferences, and the aggregate system offering set is the same as that of an individual supplier. Exactly opposite to case one, the time constants diverge, where the rate of change of preferences is smaller (faster change) and the rate of change of offerings is larger (slower change) than in an aggregated market. In order to create a system to deliver value that is articulated by the demander, the supplier often assumes static preferences. If the supplier expects that the demander will not choose an offering, the supplier may be better off not supplying at all. Likewise, if the demander expects the offerings to not deliver sufficient value, the demander may attempt to create the offering on his own.

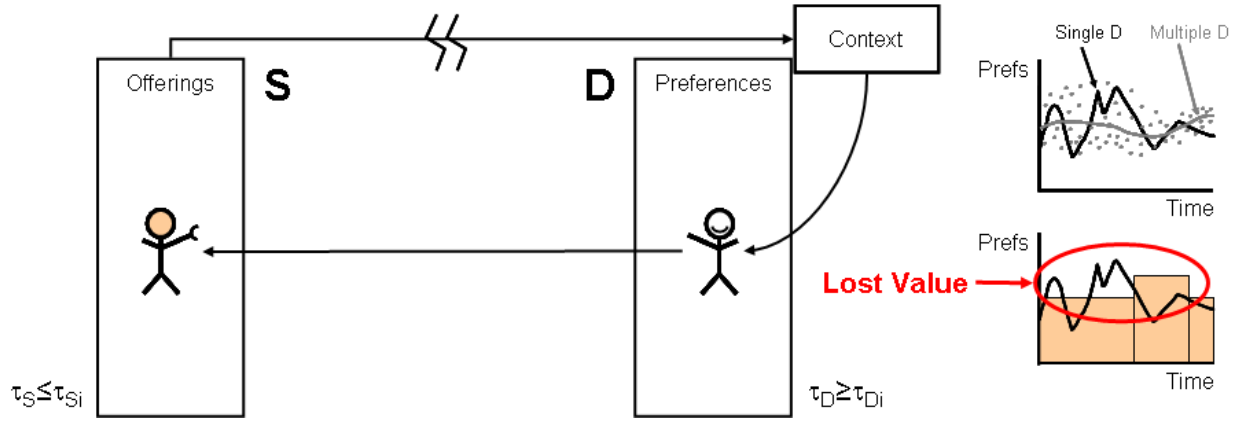


Figure 37 Market case 4: Single supplier, single demander

In the long run, strong coupling between the demander and the context may exist and the supplier may attempt to explicitly affect the context in order to increase the likelihood of continuing system demands. The modern U.S. Aerospace industry closely approaches this case, with the demander as the U.S. government. The government sometimes builds its own systems (JPL), and sometimes contracts out. Likewise, the sheer size of the Aerospace industrial job base, as well as direct lobbying of Congress, alters the context making continued government patronage more attractive than not.

This case is akin to single exchange interactions and has the most variation in efficiently delivering value to both supplier and demander. If the system offerings diverge from demander preferences, large value gaps will exist. In this case, negotiation determines the "price," or terms of the system offering choice. Figure 37 shows case four.

5.6.5 Discussion

Of the four cases of value interaction discussed, case four poses the largest opportunity for value delivery improvement.[85] The case described the interaction of a single supplier and demander, which closely approximates the case of system design for a decision maker. The goal should be to deliver maximum value to both the supplier and demander by matching the time constant for system offering change to the time constant of demander preference change. Figure 38 illustrates the differences between the cases, and highlights the largest value gap exists for case four.

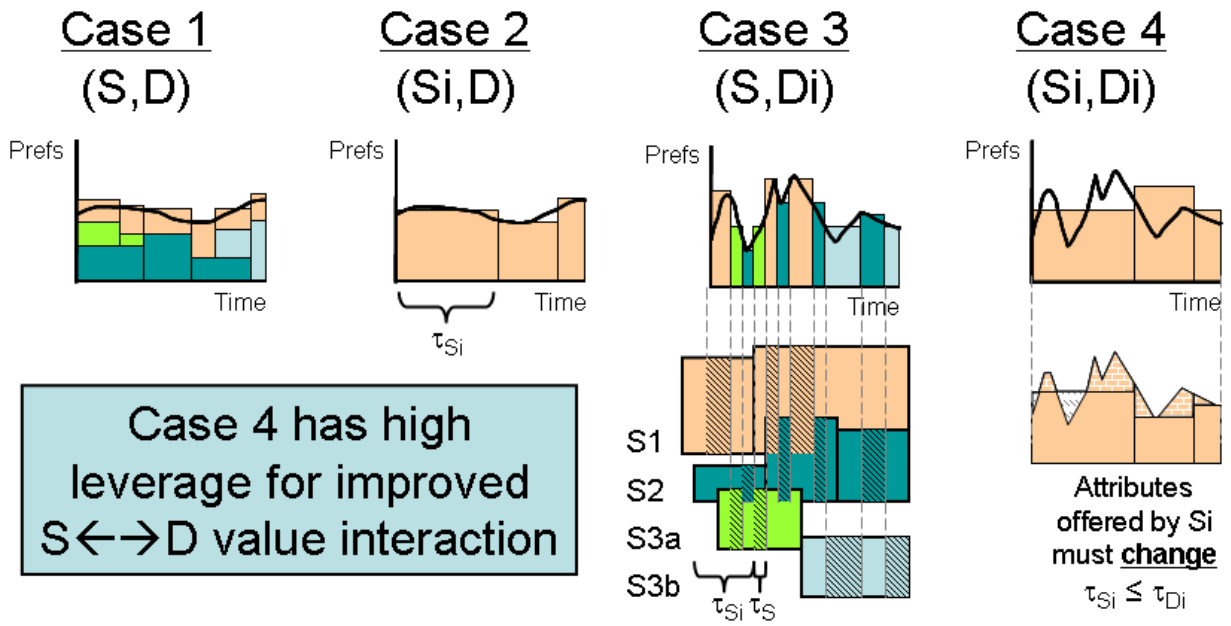


Figure 38 Value matching comparison for market cases

[85] An opportunity exists for applying the four market frameworks presented here to the U.S. Aerospace industry. An historical study analyzing the consolidation of the industry may provide insights into the forces at play in such a market model. Intervention at the market level could be proposed based on the model and desired system offerings and preferences sets.

In the MATE context, the attributes of the system offered by the supplier must change with a time constant less than or equal to that of the changing preferences of the demander. The system and its designer must embrace dynamicism in order to fill the value gap.

Chapter 6: System Properties: Ilities Defined

This chapter will introduce definitions for the system properties of flexibility, adaptability, scalability, modifiability, and robustness. Relationships between the definitions will be explored and the basis for rigorous quantification will be made in the context of application within MATE.

Much debate surrounds the definitions of system properties. Are they structural or operational metrics? Do they relate to static or dynamic affects? Are they lifecycle or short term applicable? In an effort to crystallize the debate, the system properties considered in this research will be interpreted from a value-centric perspective, and no assumption of temporal applicability will be made prior to their definition. The definitions are derived both from the technical literature and from common figurative usage.

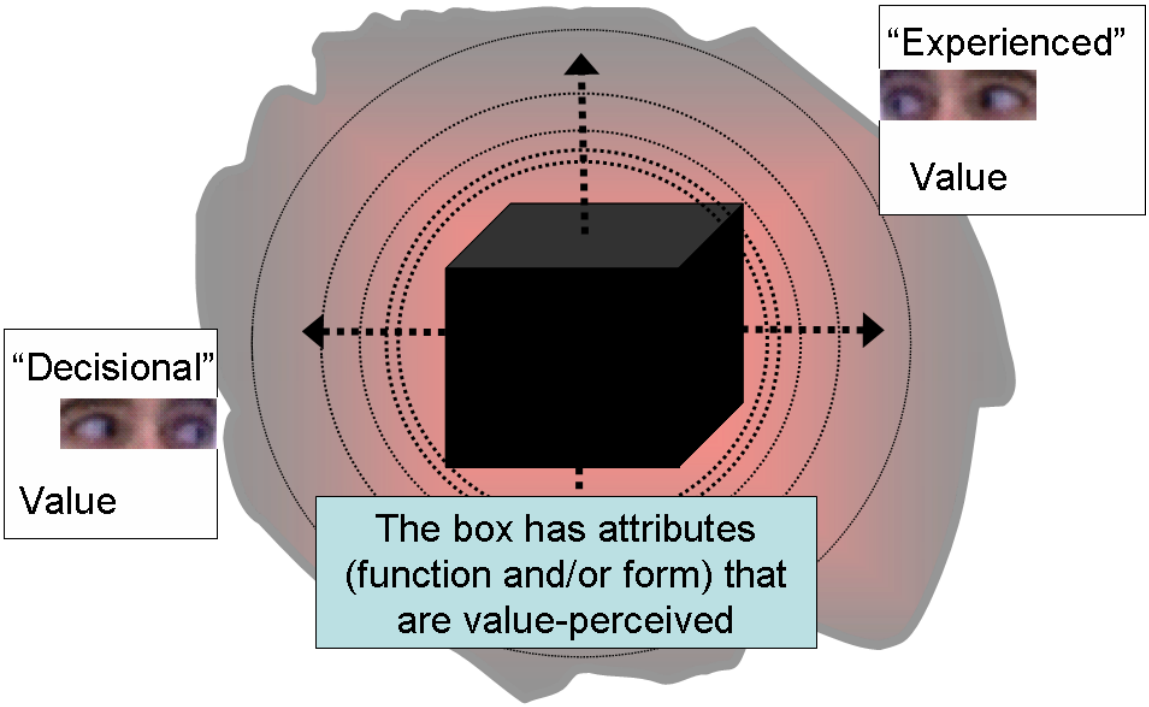


Figure 39 Black box system in its context

Suppose a system can be idealized as a black box. An outside observer has no information regarding the contents of the box; all that is seen is its output in response to inputs. The system boundary is the boundary of the black box. The black box floats in a reddish cloud, its context. See Figure 39 for a visualization of the black box concept. The box has attributes (function and/or form) that are value-perceived. The value perception can be in terms of both "decisional" and "experienced" value.

6.1 Individual Ility Definitions

A *changeable* black box is one that can have its design variable set, the level of a given design variable, its attribute set, or the level of a given attribute changed. The change results in the box being or doing something differently. (In terms of "having" an attribute, strictly speaking, a

decision maker's perceptions determine whether an attribute exists. In the context of the following concept, however, the existence of the attribute refers to the *potential* attribute set from which a decision maker could derive value if he decided that that attribute should be in his utility function. The "displayed" attributes include both actual and potential attributes that the box is and does.) Figure 40 below depicts the concept of changeability.

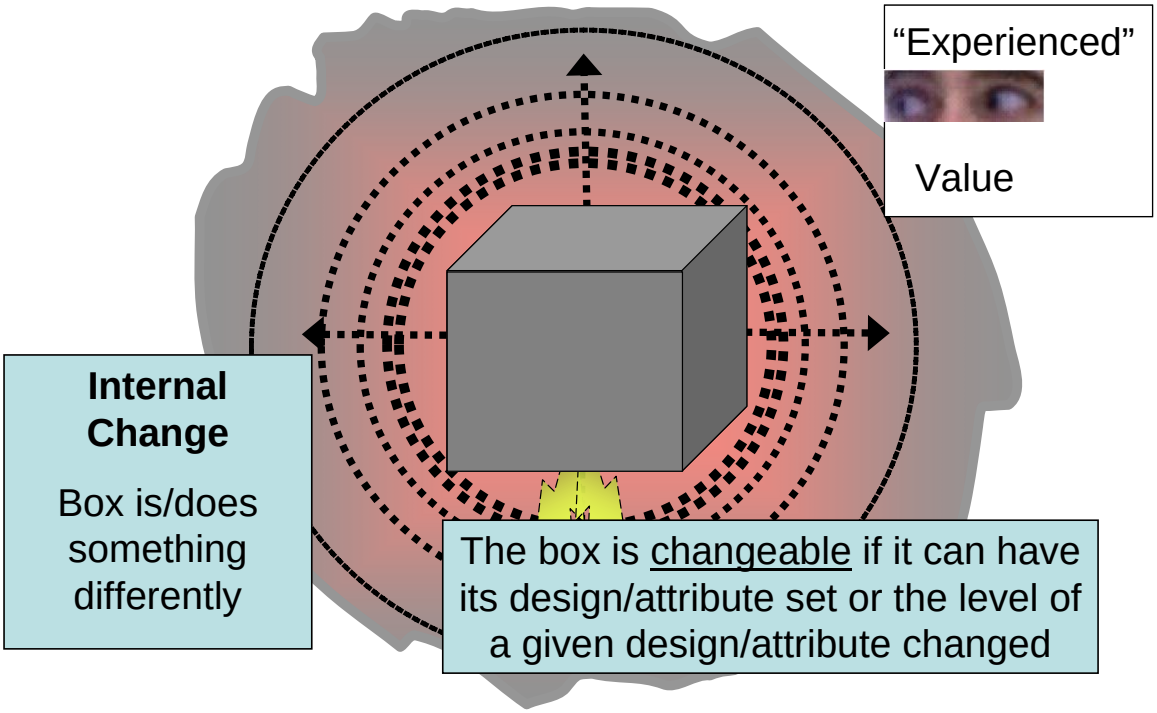


Figure 40 A changeable black box

In terms of design, or real-space, change, three types of changeability can be described: flexibility, adaptability, and rigidity.

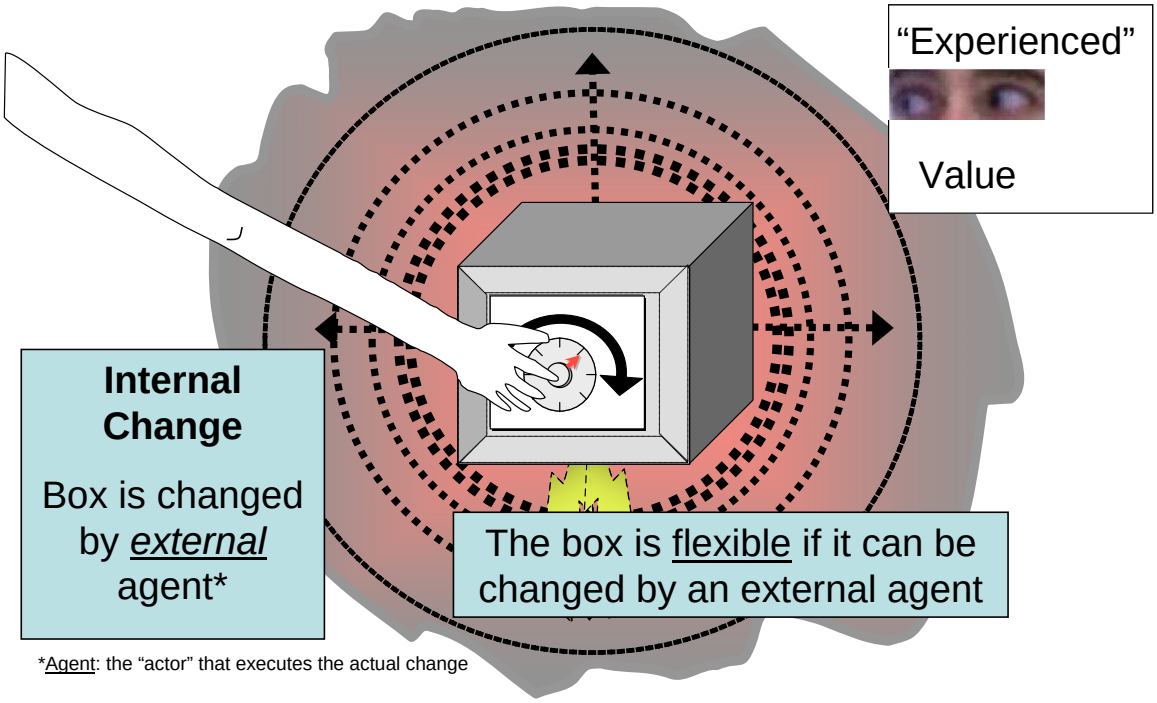


Figure 41 A flexible black box

A *flexible* black box is one that can be changed by an *external agent*. Figure 41 depicts the concept of flexibility. (An agent is the actor that causes the actual change.)

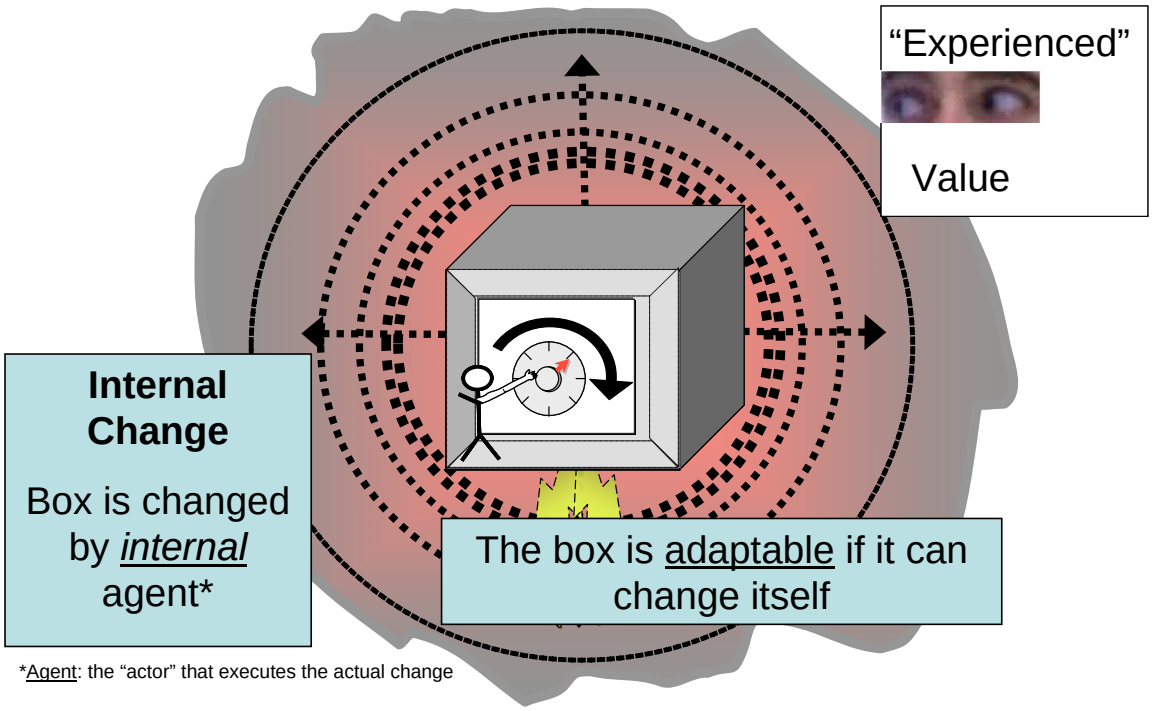


Figure 42 An adaptable black box

An *adaptable* black box is one that can be changed by an *internal agent*.[86] Figure 42 depicts the concept of adaptability.

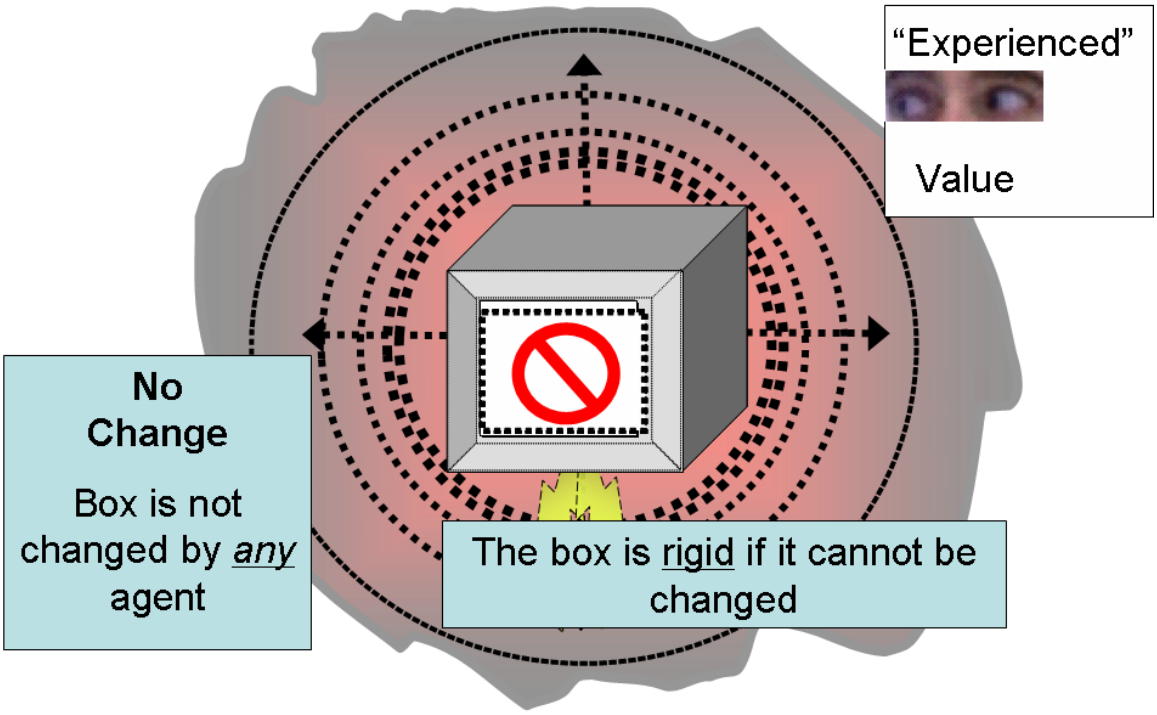


Figure 43 A rigid black box

A *rigid* black box is one that cannot be changed. Figure 43 depicts the concept of rigidity.

In terms of attribute, or value-space, change, three types of changeability can be described: robustness, scalability, and modifiability.

[86] It is important to note that the only difference between flexibility and adaptability is the location of the change agent with respect to the system boundary: inside (adaptable) or outside (flexible). Of course the system boundary could be redefined, changing a flexible change into an adaptable one, or vice versa. The fungible nature of the definition is often reflected in colloquial usage and sometimes results in confusion. If the system boundary and location of change agent are well-defined, confusion will be minimized.

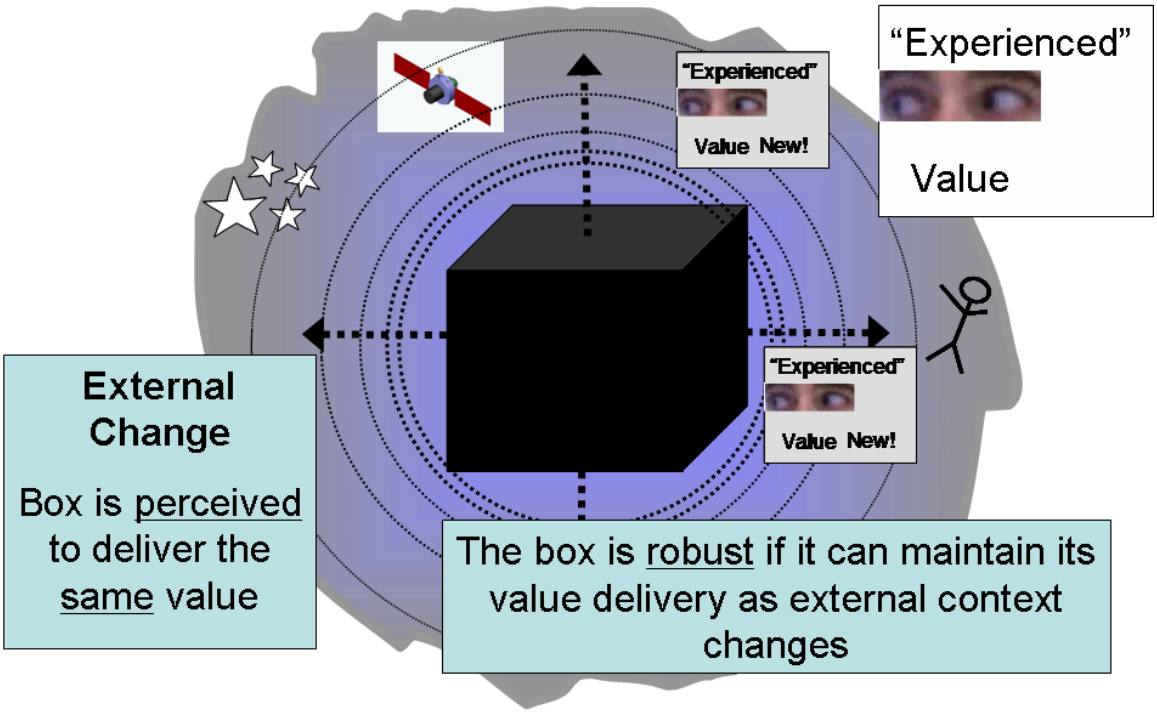


Figure 44 A robust black box

A *robust* black box is one that can maintain its value delivery *in spite of context* changes. Figure 44 depicts the concept of robustness.

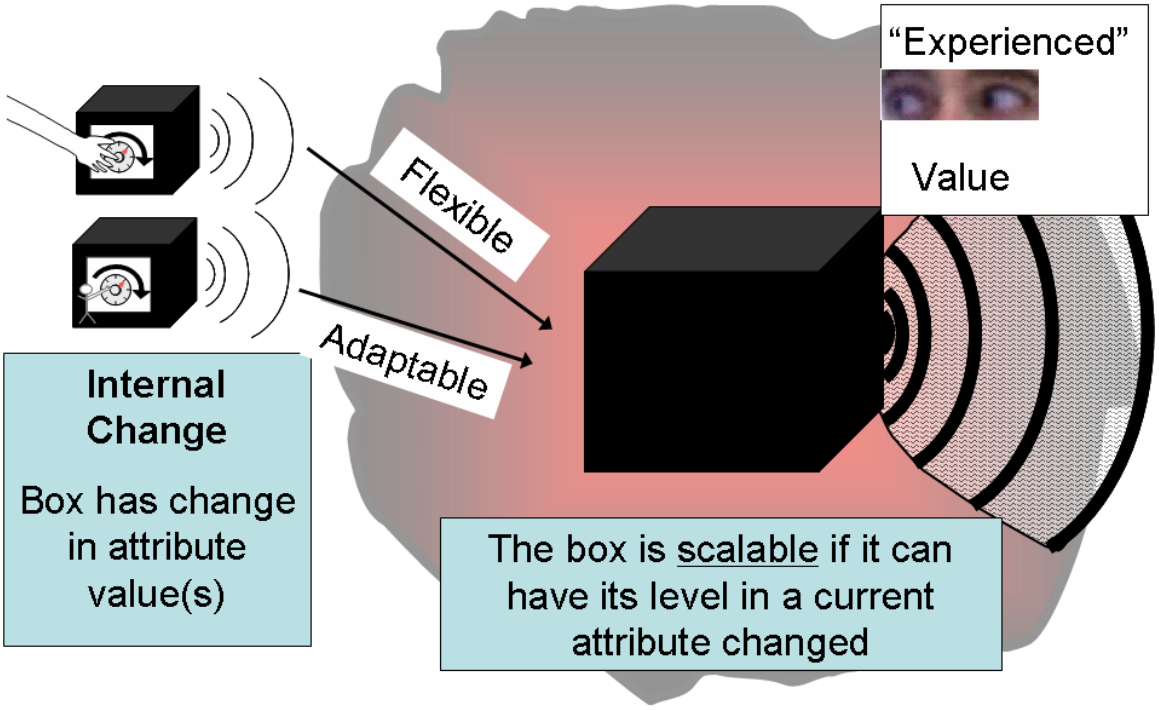


Figure 45 A scalable black box

A *scalable* black box is one that can have its *level* in a current attribute changed. Figure 45 depicts the concept of scalability.

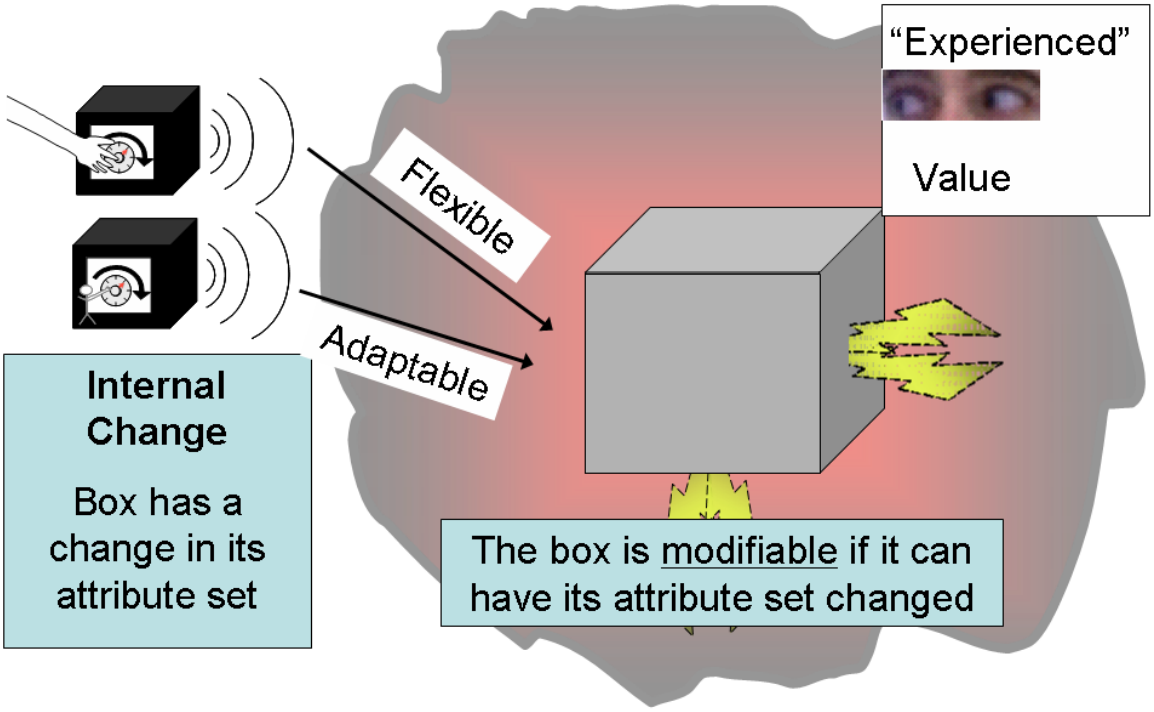


Figure 46 A modifiable black box

A *modifiable* black box is one that can have its attribute set changed. Figure 46 depicts the concept of modifiability.

Notice that from the above definitions, both flexible and adaptable relate to the box being changed by an agent, whereas both scalable and modifiable relate to a change in its attributes. The next section will make these definitions more precise and detail how these definitions relate to one another.

6.2 Relationships Among Ility Definitions

Changeability relates both to the design-space, or "real" space change, and to the attribute-space, or "perceived" (value) space change. Both flexible and adaptable relate to whether the box itself can be changed. In MATE terms, this means whether the design variable set or the level of a given design variable can be changed. Both scalable and modifiable relate to whether the box's attributes can be changed.[87]

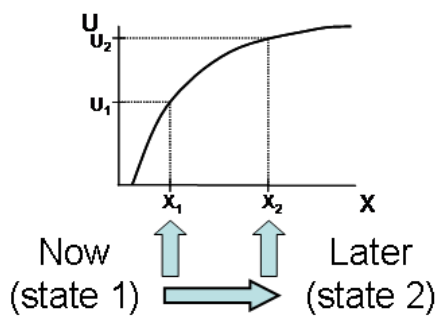
A flexible change is a change in a design variable set or level as caused by a system external agent. Thus a box can be quantified in terms of *flexible in* DV^i, i.e. can DV^i be changed from

[87] Strictly speaking, design variables could themselves be attributes if a decision maker has value perceptions over them. For example, if a decision maker cares about the number of satellites and that happens to be one of the design variables, number of satellites would be both a design variable and an attribute. Scalability in number of satellites would then be a reasonable goal, and could be accomplished through a flexible system that allows for the addition or subtraction of satellites.

DV^i_1 to DV^i_2, or can DV^i be added to or deleted from the design variable set, *by an external agent*?

An adaptable change is a change in a design variable set or level as caused by a system internal agent. Thus a box can be quantified in terms of *adaptable in* DV^i, i.e. can DV^i be changed from DV^i_1 to DV^i_2, or can DV^i be added to or deleted from the design variable set, *by an internal agent*?[88]

A scalable change is a change in an attribute level.[89] Thus a box can be quantified in terms of *scalable in* X^i, i.e. can X^i be changed from X^i_1 to X^i_2? Scaleable can reflect an *increase*, or a *decrease* in the level of an attribute.



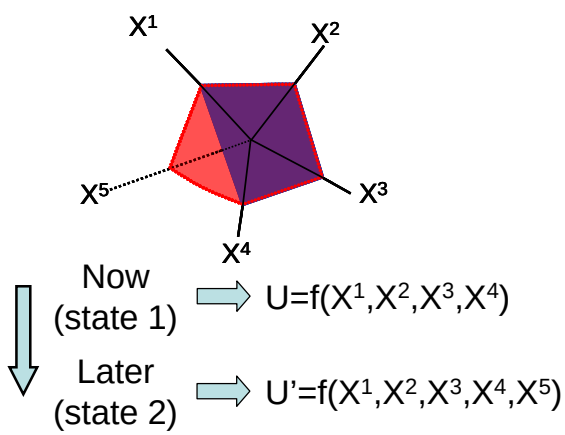
Change in attribute level

"Scalable"

A box can be quantified in terms of *scalable in* X^i

(i.e., can X^i be changed from X^i_1 to X^i_2?)

A modifiable change is a change in an attribute set. Thus a box can be quantified in terms of *modifiable in* X^i, i.e. can X^i be added to or deleted from the attribute set?



Change in attribute set

"Modifiable"

A box can be quantified in terms of *modifiable in* X^i

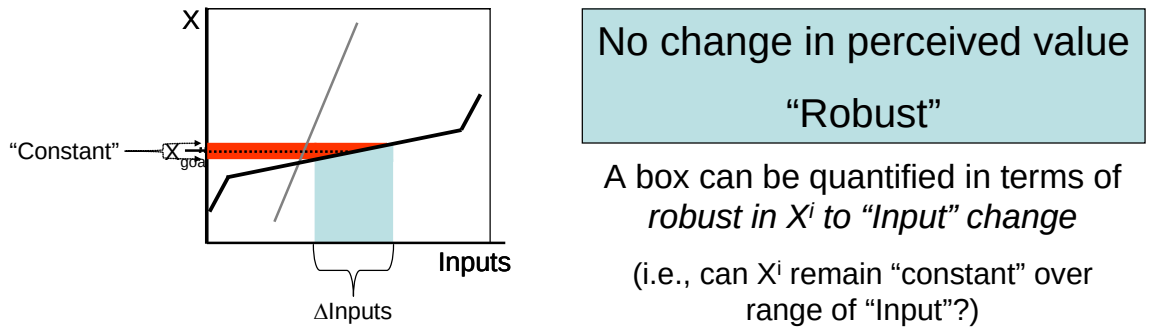
(i.e., can X^i be added to or deleted from the attribute set?)

---

[88] In order to effect a change, a change agent should have the following three abilities (in order of decreasing importance): Execution power (influence), information processing power (decision-making ability), information gathering (data observation). Influence is the act of making the change, decision-making ability is the act of deciding to exert influence, data observation is the act of accumulating information to foment and inform decision-making. Based on the Psychomotor, Intellectual, and Sensory/Perceptual abilities of humans and machines as characterized by Hall, Stephen B., Ed. (1985). The Human Role in Space: Technology, Economics and Optimization. Park Ridge, NJ, Noyes Publications..

[89] Note that attributes can encompass both form and function. If a decision maker wants to know if a system is scaleable in number of satellites, then number of satellites is the attribute. A similar example can be made for functions, such as beam intensity.

A robust system is one that is perceived to exhibit no change in something, in spite of changes in the "system," including the components or context of the system. Of particular interest for MATE is value robustness. A value robust system is one that has no change in perceived value, in spite of changes in components or context. Thus a box can be quantified in terms of *robust in X^i to "Input/Constraint" change*, i.e., can X^i remain "constant" over range of "input/constraint"?



Developing a quantitative framework for the ilities flows naturally from the decomposition of a tradespace. The two axes of a 2D tradespace are utility and cost, proxies for the Need and Resources, which are the two tensions balanced by the system designer. Cost is a functional transformation of the design instantiation, while Utility is a functional transformation of the attribute levels.

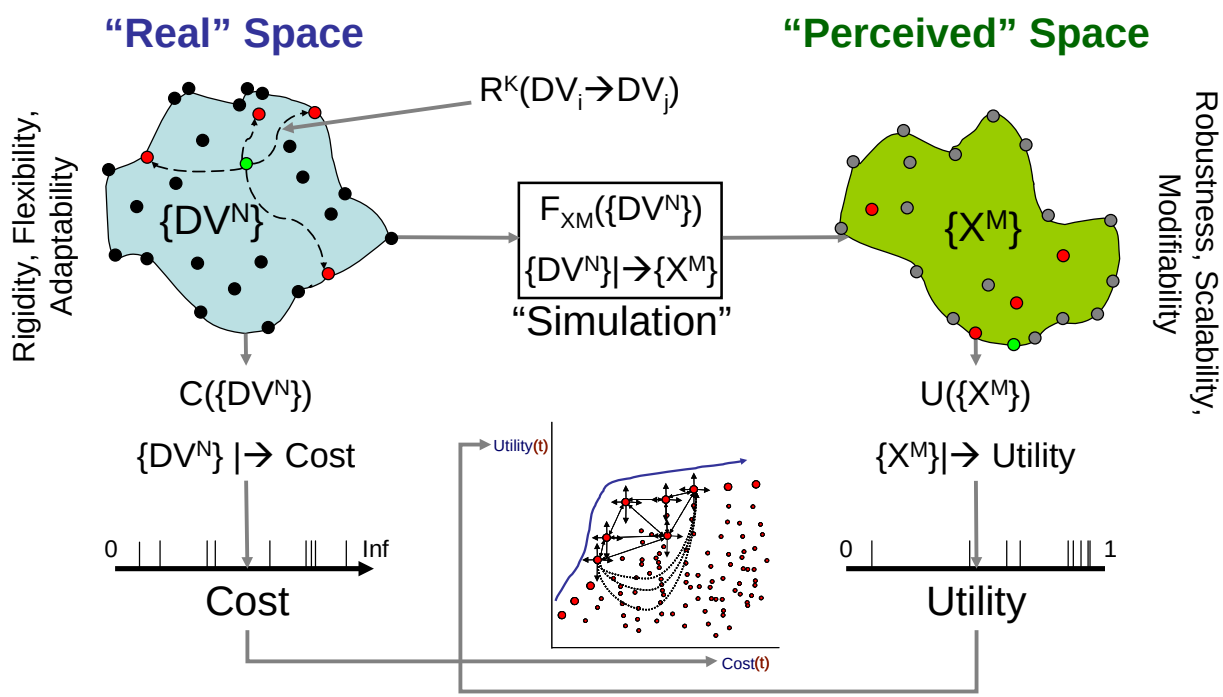


Figure 47 MATE key functions and variable mappings

Let $\{DV^N\}$ be the design variable set, representing the physical system. Where DV^i is a particular design variable,

$$DV^i \in \{DV^N\}, \text{ and } \dim\{DV^N\}=N.$$

Then a cost function can be defined, $f_c(\{DV^N\})$,

$$f_c : \{DV^N\} \rightarrow C,$$

which maps the design vector to a cost scalar. Unfortunately the inverse is not a well-defined function and in fact represents the design process itself (allocating resources to create a design).

$$f_c^{-1} : C \rightarrow \{DV^N\}, \text{ ill-defined: the Design Process}$$

The span of the design space, or $\{DV^N\}$, represents the space of all possible designs, or "real" space options. Of course the actual size of this space includes both actual specified design variables sets and potentially specified variables. In practice, the design-space will only consider the actual span of explicitly defined design variables. In terms of the changeability definitions from above, flexibility, adaptability, and rigidity relate to whether designs are "connected" in design space. A "connection" implies transitionability of designs from one state to another. The connection is allowed through specified rule sets, $\{R^K\}$, which specify how one design vector can transition to another.

$$R^k : DV_i \rightarrow DV_j,$$

where $DV_i \equiv \{DV^N\}_i$ is a particular instantiation of the design vector $\{DV^N\}$. (See Notation Glossary for help with notation and examples.) The output of the application of R^k is the "cost" of the connection between DV_i and DV_j, T_{ijk}. ("Cost" refers to the resources necessary to execute the connection, typically dollars and time.) The "cost" for change is an important decision criterion for determining *whether* a path in design-space *should* be taken.

The "real" space span of designs is then evaluated in terms of its achievement in attribute space. The attribute-space, or "perceived" space is spanned by the attribute set $\{X^M\}$, but the only points of interest are the achievements of the design space, which is a subset of the full space. (See Figure 47 for example of subspace of X-space). The evaluation process is usually done by physical system models and simulation, but can be represented in shorthand by the vector function F_{XM},

$$F_{XM} : \{DV^N\} \rightarrow \{X^M\}, \text{ the System Simulation,}$$

which typically is not analytic. The inverse of F_{XM}, F_{XM}^{-1}, would provide ideal information to a designer, showing exactly how the attribute-space can be accessed through physical design. Unfortunately finding the inverse is often not possible due to the non-uniqueness of the mapping, necessitating creativity to find designs that meet the need.

$$F_{XM}^{-1} : \{X^M\} \rightarrow \{DV^N\}, \text{ ill-defined, the Design Process}$$

The inverse mapping, $\{X^M\} \rightarrow \{DV^N\}$, is *multi-valued*, meaning that elements in X^M can be mapped to more than one element in DV^N. (Achievement in attribute space may be non-unique.) In fact both F_{XM}^{-1} and f_c^{-1} capture the two goals of the designer: meeting need while utilizing resources.

Once the attribute-space, $\{X^M\}$, has been calculated, it can then be mapped to the value function, utility, or

$$f_u : \{X^M\} \rightarrow U ,$$

which is sometimes written as $f_u(\{X^M\}) \equiv U(X)$. Movement, or connectivity, in "perceived" space relates to the attribute change system properties of scalability, modifiability, and value robustness. Unfortunately for the system designer, the attributes themselves typically cannot be changed directly; instead, the design variables must be altered. Thus a "real" space change must occur to affect a "perceived" space change. In this way, flexible, adaptable, or rigid changes must occur to affect a scalable, modifiable, or robust change. The mapping of $\{R^K\}$, which determines the connectivity of $\{DV^N\}$, must be evaluated through F_{XM} to determine the connectivity of $\{X^M\}$. The MATE formulation of system design and decision-making provides a framework though which these mappings can be assessed and compared.

Whether a change can occur is only half of the question when assessing changeability. The cost, of change must also be assessed since the decision to make a change is dependent on both the cost and benefit for doing so. *Acceptability* for these decisions will be *subjectively* defined by the decision maker within the context of the particular change decision to be made.

6.2.1 Ilties Revisited

Using the above notation, the definition of scalability, modifiability, and robustness can be more concisely defined.

<u>Scalability</u>

Previously scalability was put in terms of scalability in X^l, but as mentioned, the change in the attribute-space must be caused by a change in design-space. Let

$${}_i\Delta_j X: X_i \rightarrow X_j,$$

and ${}_i\Delta_i X^m$ is a change in attribute m from state i to state j. Then scalability in X^m can be stated as:

$$\text{scalability}_{ij}^{m}: {}_i\Delta_i X^m \text{ for acceptable cost}$$

Since $\{X^M\}$ is a mapping of $\{DV^N\}$, the design space can be explicitly included in the definition through the mapping function F_{XM}.

$${}_i\Delta_j X: F_{XM}(DV_i) \rightarrow F_{XM}(DV_j)$$

Or,

$$\text{scalability}_{ij}^{m}: [F_{XM}(DV_i) \rightarrow F_{XM}(DV_j)]^m \text{ for } T_{ijk} \text{ acceptable}$$

Notice that T_{ijk} is a tensor, containing K matrices, one for each rule R^k, describing the connectivity of DV_i to DV_j. Thus there could be multiple and different costs associated with the transition between these two states depending on the rule followed. Typically a decision maker will prefer the minimum cost rule in a given situation, but no assumption is made in the derivation at this point. Let the maximum acceptable cost level be C_{thresh}, or $\hat{C}$.

If a destination state j is unknown, the scalability of state i would incorporate the summation over all possible destination states for comparison to other initial states. Then,

$$\text{scalability}_{i}^{m}: [F_{XM}(DV_i) \rightarrow F_{XM}(DV_j)]^m \text{ for } T_{ijk} < \hat{C}, \forall j \text{ in tradespace, TS}$$

Notice that

$$_{i}\Delta_{j}X: F_{XM}(DV_i) \rightarrow F_{XM}(DV_j)$$

can be determined by calculating $(X_j\text{-}X_i)^k$ through $T_{ijk} < \hat{C}$, with cost determined by the value of T_{ijk}. Since the attribute values of X_j are the same regardless of the path taken, one strategy pursued by a decision maker would be to choose the minimum path cost over applicable rules.[90] Since the time and cost for the paths may run counter to one another, using the minimum cost strategy is not always the best option.

<u>Modifiability</u>

Similar to scalability, modifiability and robustness can be defined. The modifiability for design i for attribute m is:

$$modifiiability_i^m: F_{XM}(DV_i) \cap F_{XM}(DV_j) = X^m \text{ for } T_{ijk} < \hat{C}, \forall j \text{ in TS}$$

Here the intersection of attribute sets between state i and state j is the attribute to be added to or subtracted from the set, X^m. The intersection must exist for a change cost less than the threshold for acceptability, and summed over all possible destination states j in the tradespace, TS.

<u>Robustness</u>

Robustness in value is a slightly more general notion, but can be similarly defined:

$$robustness_{ij}: \left| U_{t2}(F_{XM,t2}(DV_j)) - U_{t1}(F_{XM,t1}(DV_i)) \right| \approx 0, \text{ for } T_{ijk} < \hat{C}, \forall j \text{ in TS}$$

In this definition, the perceived value of state j and state i are approximately the same. State j can be in a different time period than state i ($t_2 \neq t_1$). It is possible that the value function changes between states, or even the mapping function F_{XM} (i.e., $U_{t2} \neq U_{t1}$, or $F_{XM,t2} \neq F_{XM,t1}$). In any case, robustness can be achieved by having either $DV_i = DV_j$ or $DV_i \neq DV_j$, depending on the context change.[91]

[90] In addition to the minimum cost change strategy, one could pursue maximum utility, minimum time, or other change strategies.

[91] Two value robust strategies can be defined: former case with $DV_i = DV_j$ is called passive value robustness, while the latter case with $DV_i \neq DV_j$ is called active value robustness.

6.3 Simple Examples

The following are a few examples to illustrate the changeability concepts introduced in this chapter.

6.3.1 Flexible Change

A debate often cited within MIT circles entails the apparent conflict between two professors' definitions of flexibility. On the one hand, Professor A believes that networks, such as a computer network, are highly flexible, while a space system is not. Professor B believes that a space system that can be changed from halfway across the solar system to be able to perform a new mission is flexible, where the comparison to the flexibility of a computer network is irrelevant. The definition for flexibility given above reconciles these two views and provides a good example for the definition.

The question of whether a system is flexible is the same as asking whether $\text{cost}(DV_i \rightarrow DV_j) < (\hat{C}, \hat{t})$, *as accomplished by a system-external agent*. For the computer network question, the physical change could correspond to physical network changes (wires=arcs), computers (nodes), or informational, such as routing of packets. For these classes of changes of a computer network, the cost to change can vary from thousands of dollars down to the order of pennies, or $\$10^3$-$10^{-2}$. Additionally, the time for a change can vary from hours down to fractions of a second, or 10^3-10^{-2} min. For the space system in question, the physical change could correspond to the change of on-board payloads, or loaded operational software. For these classes of changes of a space system, the cost to change can vary from billions to hundreds of thousands of dollars, or $\$10^9$-$10^5$. Additionally, the time for a change can vary from years to days, or 10^6-10^3 min. The key point here is the subjectively set threshold for change acceptability, $\hat{C}$, $\hat{t}$, cost and time respectively. For Professor A, these thresholds are probably on the order of 10^{-1} and 10^{-1}, respectively, while for Professor B, these are probably on the order of 10^6 and 10^5, respectively. In a sense, both professors are correct and consistent in their definitions. An important distinction to make, however, is that if the change agent for these two cases is located inside the system boundary, the change is considered an adaptable one. For this example I considered outside human intervention as the cause for change, though one could imagine a self-changing network or autonomous satellite, especially if the time scales for change are beyond the capabilities of a human.[92]

6.3.2 Adaptable Change

As highly adaptable systems, humans constantly employ their Psychomotor, Intellectual, and Sensory/Perceptual abilities to create change of themselves. Consider weight-training and other exercise as a long term change from an "out-of-shape" system to a "fit-as-a-fiddle" system. Those people (systems) who perceive the cost of doing such an adaptable change as acceptable, execute on it, i.e, the question of whether to pursue an adaptable change through the exercise mechanism is whether $\text{cost}(DV_i \rightarrow DV_j) < ?(\hat{C}, \hat{t})$, *as accomplished by a system-internal agent* (the self). In other "words": $(\text{cost}(DV_{outofshape} \rightarrow DV_{fitasfiddle}) <?$ (*maximum_willingness_to_pay_gym/trainer, maximum_willingness_to_wait_for_results*). The general consensus that humans are highly adaptable is because over a very large range of possible and actual changes, people decide that the cost is acceptable (i.e. the cost of self-change

[92] See Hall, Ed. The Human Role in Space. for examples of time scale and spatial scale comparison of human and machine task abilities and limitations.

is reasonable, both in terms of dollars and time). Making a person more adaptable entails either decreasing the actual cost for the change, or increasing the cost threshold for the change. Personal training can have either effect (by increasing the number of mechanisms for personal growth on the one hand, and by increasing a person's patience on the other hand).

6.3.3 Scalable Change

Suppose a consumer has a camera and cares about its megapixel rating, $X^{Megapixel}$. The current rating for the camera is $X^{Megapixel}_{current}$ = 4.0. He now desires that the camera have $X^{Megapixel}_{future}$ = 7.0. The change in a level of a current attribute, megapixel rating, is an example of a scalable change. The question facing the consumer is whether $\text{cost}(X^{M}_{current} \rightarrow X^{M}_{future})$ <? (Ĉ, tˆ). The mechanism for achieving the change must be determined through the inverse mapping F_{XM}^{-1}, $F_{XM}^{-1} : \{X^{M}\} \rightarrow \{DV^{N}\}$, for each attribute current and future. What design parameters need to change and what does it cost in order to effect a scalable change in megapixels? Possible answers include modification of the optics and charge-coupled device (CCD) photon receiver in the current camera, or throwing out the current camera and purchasing a new one (depending on the consumer, the costs for these mechanisms may vary, as will the subjective cost threshold… a do-it-yourself engineer may prefer the modification route, while the typical user may prefer the new purchase). In any case, if the cost for change is acceptable, the camera system has undergone a scalable change for the megapixel attribute.

6.3.4 Modifiable Change

A simple example of a modifiable change is that which is often done to a personal computer. Suppose a decision maker has a standard computer with a monitor, keyboard, mouse, and hard drive, all of the standard features of a computer purchased circa 1999. Changes occur in the market place, with new technologies being offered to enhance computer capabilities. The decision maker decides at some point later in time that he really would like to be able to burn DVDs. That capability was absent from the original computer system, but with a simple change to the computer, that capability can be added. The decision problem posed to the decision maker is whether $\text{cost}(\{X^{M}\} \rightarrow \{X^{M}\} U \{X^{DVDburning}\})$ <? Ĉ. In order to determine the answer, the inverse mapping F_{XM}^{-1}, $F_{XM}^{-1} : \{X^{M}\} \rightarrow \{DV^{N}\}$, must be determined. Luckily the design problem has already been solved through modular design. All that is needed is the addition of an external (or internal) DVD-R drive. In this case, the mapping between design- and value-space is straightforward, $X^{DVDburning} \rightarrow DV^{DVDburner}$. Thus, is the addition of the $DV^{DVDburner}$ < Ĉ? (Of course, this is the question posed by most consumers when shopping for computer additions.) The beauty of modular design is that the cost of additional modules is often relatively low, thereby increasing the likelihood that the cost for change is less than Ĉ.

6.3.5 Value Robustness

Suppose a decision maker looking to procure a new box has two attributes: size and loudness. Four system offerings exist and are given in Figure 48 below. Size is more important than loudness. Within size, big is preferred to small. Within loudness, loud is preferred to quiet. Applying these preferences, the systems can be ordered according to their utility:

$$U(3) > U(2) > U(1) > U(4).$$

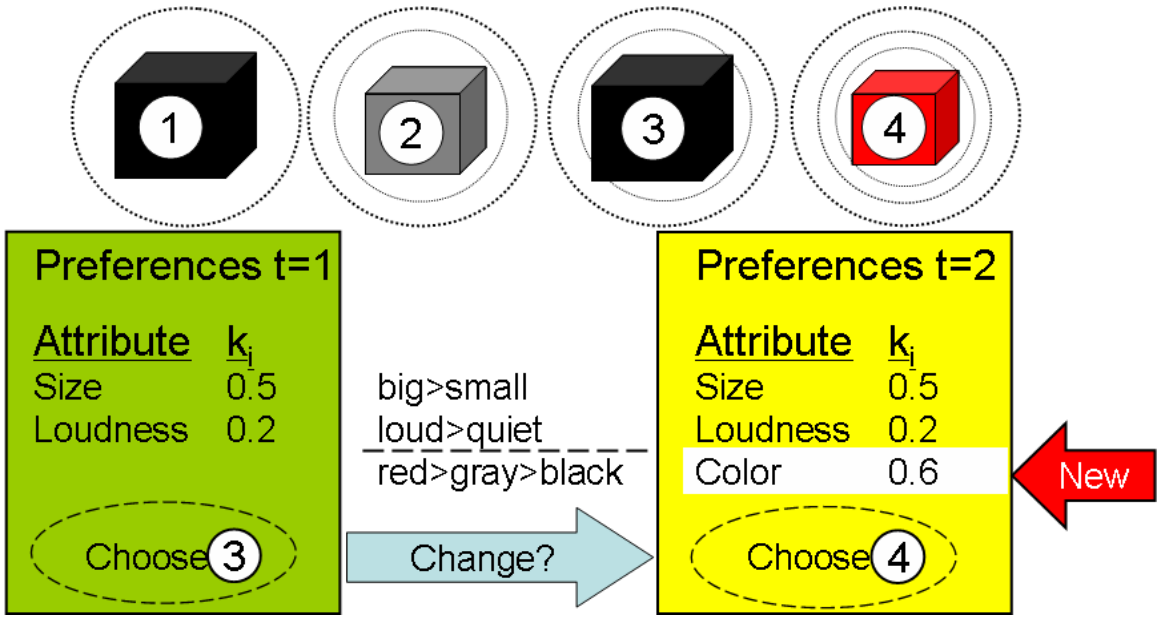


Figure 48 Example value robustness: Choosing boxes

Thus the decision maker should choose system offering (3) in order to maximize his value. Suppose something happens and the decision maker now cares about color as well as size and loudness. Color is about as important as size, which is more important than loudness. Within color, red is preferred to gray is preferred to black. Applying these new preferences, the systems can be ordered according to their utility at time t=2:

$$U(4) > U(2) > U(3) > U(1).$$

Notice that at time t=2 the decision maker should choose system (4) in order to maximize his value. If, however, the decision maker must choose a system at time t=1, the best choice is to choose system (3) and then change it to system (4) at time t=2. If the switching costs are high, however, the net value to the decision maker might be less than choosing system offering (2), which is second best in both time periods and entails no switching cost. Offering (2) is robust in value under this preference change. In this example, $U_{t2} \neq U_{t1}$, and value robustness can be achieved by having $DV_i = DV_j$ when switching costs are high, i.e., $\text{cost}(DV_3 \rightarrow DV_4) > \hat{C}$. Or can be achieved by having $DV_i \neq DV_j$, when switching costs are low enough, i.e., $(\text{cost}(DV_3 \rightarrow DV_4) < \hat{C}$. The first case suggests the decision maker choose $DV_i = DV_j = DV_2$, and the second case suggests the decision maker choose $DV_i = DV_3$, and $DV_j = DV_4$.

6.4 Corollary Concepts

At least two corollary concepts can be derived from the preceding system property definitions. The first concerns the nature of robustness, the other the nature of modifiability.

6.4.1 The System Shell

A key distinction drawn between scalability, modifiability, and robustness concerned the type of change necessary to achieve value. Scalability necessitated a change in the level of a current attribute. Modifiability necessitated a change in the composition of the current attribute set.

Robustness is related to an apparent lack of change in perceived value delivery, in spite of changes either internal or external to the system itself. The last point merits further discussion.

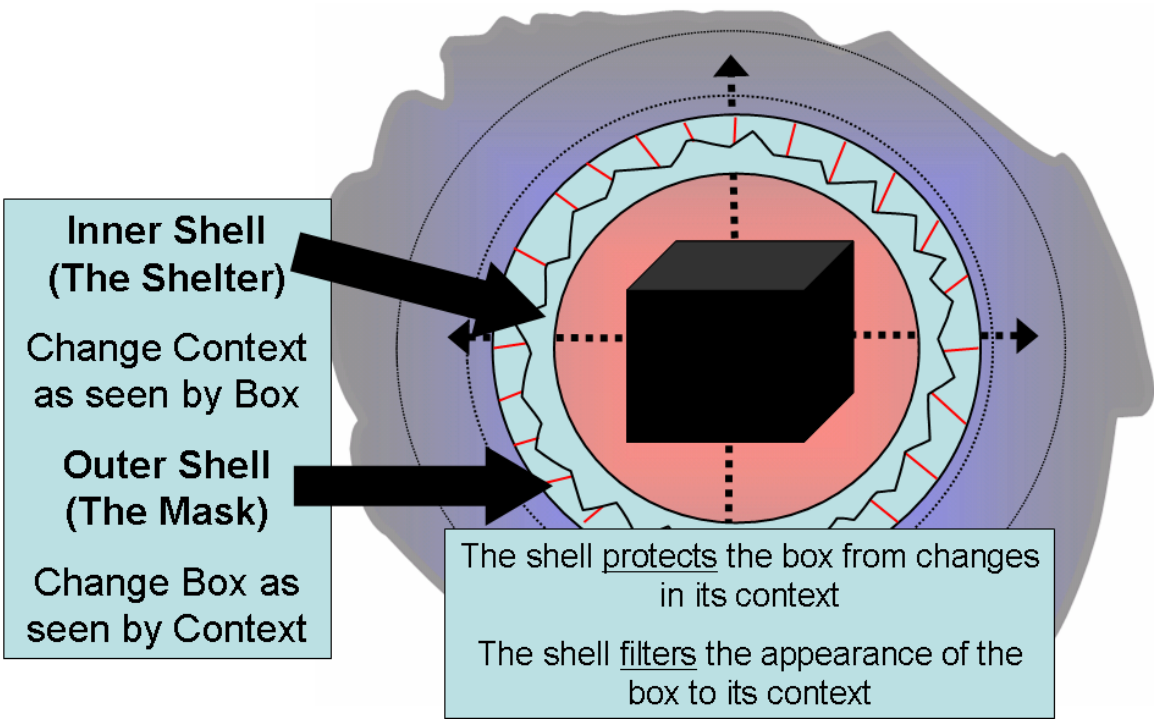


Figure 49 The System Shell concept

As pointed out during the derivation of robustness, two types of robustness can occur: one in which the system remains "constant" and the other in which the system changes in order to be perceived as "constant." These two perspectives can be captured as an inside-out and an outside-in interpretation. In the inside-out interpretation, the system sees a change in its outside, or context, and must decide whether to change in order to continue to deliver value. In the outside-in interpretation, the system itself is seen as changed due to a new context-filtered perception. A system shell is a concept attempting to codify these two types of robustness strategies into a single entity. An illustration is in Figure 49.

The system shell consists of two layers: the inner shell, or "shelter," and the outer shell, or "mask." The purpose of the shelter is to prevent the system from seeing changes in its context. It "protects" the system from change, thereby ensuring constancy of operating environments. An example of a shelter is clothing or a home for humans. Instead of redesigning the human to be able to operate in temperature extremes, clothing and homes provide shelter to the human system, creating an artificially stable context in which to operate.

The mask changes the systems as seen by the context. It "masks" the true system to prevent the system itself from having to change to meet external changing perceptions. An example of a mask is a software wrapper module, which standardizes the appearance of code so that it can be manipulated by programmers who do not need to know the specific of that particular code. The concept of a system shell is powerful in that it decouples the system itself from changes in its

context. It may be the case that system shells can be developed or modified much more readily than the system itself. In the context of systems of systems, the system shell concept can allow the incorporation of legacy systems into a larger system without having to perform costly modifications or redesign.[93]

6.4.2 Fundamental Attributes

Based on the definition of modifiability, which relates to the ease of adding or removing attributes from the current set, and classes of attributes discussed in section 4.5, the concept of fundamental attributes can be defined. Recall that attributes of a system exist in both the potential and current set, with the current set being defined by the articulated needs of current decision makers. The potential set includes all attributes that are "displayed" by the system. Since class 2 attributes are those that are formed by the low "cost" recombination of class 0 and class 1 attributes, a goal for a designer could be to maximize the potential size of the class 2 attribute set, which in theory would vastly increase potential future value of the system. (The "cost" to "articulate" class 2 attributes is relatively low, certainly lower than class 3 attributes which necessitate actual system change for articulation.)

Let us define fundamental attributes as those attributes that cannot be "broken down." Suppose they are the building blocks of all other attributes. If a system displays all of these fundamental attributes as class 0 or 1 attributes, then the class 2 attribute set will include all other possible attributes. Even if a complete set of fundamental attributes cannot be displayed, the more that are displayed, the more likely the system will be capable of displaying a desired future attribute at low cost. This leads to the principle of fundamental attributes.

6.4.2.1 The Principle of Fundamental Attributes

The more fundamental a displayed attribute set, the more <u>modifiable</u> the design

A hypothesis based on this principle is that the GPS system is a highly modifiable system because its class 0 and 1 attributes are highly fundamental (i.e., many class 2 attributes can be formed, thereby providing potential value to stakeholders who have these "new" attributes). GPS provides time and position information at a very low cost and high reliability. Time and position information are fundamental attributes. The complete set of fundamental attributes must include these quantities as well as others. Physics is one field that has encountered the idea of fundamental quantities and can inform the discussion.

The National Institute of Standards and Technology describes the fundamental physical quantities used in physics[94]. The SI units, standard units used in physics, are based on "seven base quantities assumed to be mutually independent" and from which all other units are derived.

These units include:

- Length (m)
- Mass (kg)

[93] Further work should be done applying the system shell concept to a variety of systems to identify how the concept has been or could be applied to improve system robustness.
[94] See http://physics.nist.gov/cuu/Constants/index.html, 2/8/06

- Time (s)
- Electric current (A)
- Thermodynamic temperature (K)
- Amount of substance (mol)
- Luminous intensity (cd)

Other possible fundamental attributes can be gathered from engineering systems discussions regarding flows, characterizing four classes of flows[95]:

- Matter (kg/s)
- Information (bits/s)
- Energy (J/s)
- Value ($/s)

In thinking about fundamental attributes, the designer should ask himself, "what characteristics are true of or describe all things?" Everything has a position in 4-space (x,y,z,t) coordinates. Everything has a mass, temperature, charge (which is current x time), etc. Thinking in this way suggests a few other fundamental attributes:

- Location (x,y,z)
- Shape (distribution of x,y,z? f(x,y,z)?)
- Angular rate (yaw, pitch, roll)

Other fundamental attributes most likely exist and developing a complete theory of fundamental attributes and their implication on system design is beyond the scope of this work.[96]

6.5 Asking the Question

One of the motivations for this work is to clarify the question of determining whether a system is (fill in the ility of your choice). The answer is that it depends! The answer is partly subjective. It is really not whether the system can change, but to what extent (how much does it "cost"?).

Revisiting the goal of design from section 3.1, the key parameters encapsulated in that statement are the following:

Efficient (resource usage)	→	C, t
Creation of system (design)	→	$\{DV^N\}$
Fulfill need (value)	→	$\{X^M\}, U$
Given context (constraints)	→	Constraints

In section 6.2, the relationship between these quantities and the ilities was discussed. Since the motivation of ility question is often value-derived, the first focus will be on the value-centric ilities: scalability, modifiability, and robustness.

[95] See pp 23 of Magee, Chris L. and Olivier L. de Weck. (2002). An Attempt at Complex System Classification. ESD Internal Symposium, Cambridge, MA, MIT.

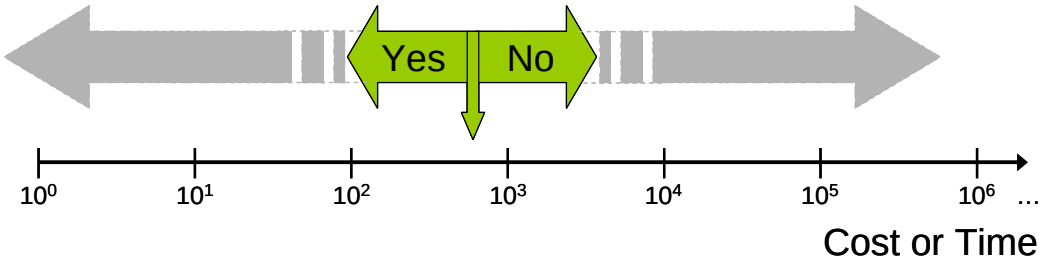
[96] Further theoretical research should be done defining, validating, and/or proving a complete set of fundamental attributes.

Suppose the desire is to know whether a system is scalable. Since scalability must be stated in terms of *scalable in* X^i, it is necessary to include that phrase in the statement. Additionally, the subjective part of the question must be included, which is the decision maker's tolerance for resource expenditure, be it time or money. Actually achieving the change in attribute-space, however, necessitates a change in design-space. Thus, a flexible or adaptable change is necessary in order to effect a scalable change. The origin of the change agent determines whether it is a flexible (external to system boundary) or adaptable (internal to system boundary) change.

Putting those steps all together, in order to ask if a system is scalable, first the subjective resource expenditure cut-off must be set, second the change agent origin must be set (internal/external), and lastly the attribute to be scaled must be specified. Similarly to scalability, modifiability and robustness can be defined.

More generally:

1. Set the subjective scale



2. Choose the location of change agent

Change agent:	External (Flexible),	Internal (Adaptable),	None (Rigid)

3. Ask the perceived change question

Desire change

_____ in _____ for _____

"ility"	metric	resource
Scalable	X^i	Cost
Modifiable		Time

Desire no change

_____ in _____ to _____

"ility"	metric	perturb.
Robust	X^i	ΔDV
	Rank (Pareto Efficient)	ΔConstraints
	Cost/Time	ΔConst.
		ΔPreference set

Chapter 7: Dynamic Tradespace Experiments

This chapter will explore the concepts of change within a tradespace framework by looking at the effect of changing preferences on a tradespace. Exploratory in nature, the dynamic tradespace experiments show how quantitative computer modeling and visualization techniques can be used to reveal insight into the dynamic structure of a tradespace and suggest mechanisms for quantifying value robustness across change scenarios.

7.1 Changing Preference Contexts

One of the main drivers for desiring system change is a change in preferences. Over time, decision makers may change their perceptions of the system and thus even if the system continues to perform its intended function, it may deliver less value over time. In an effort to better understand how tradespace analysis could be used to quantify the ilities, a number of computation experiments were conducted. The data set used for these analyses come from the X-TOS project, which was a MATE study of a low Earth orbit satellite system with a mission to in-situ measure atmospheric density[97].

7.1.1 Single Decision Maker

7.1.1.1 Overview

In the single decision maker case, four classes of preference experiments were conducted.

a. Major change: addition or subtraction of attributes, $\{X^M\} \rightarrow \{X^L\}$, $L \neq M$
b. Moderate change: change in k_i relative attribute importance
c. Subtle change: change in the shape of $U^i(X^i)$
d. Evaluative change: change in the value function used

The questions asked were:

1. How does the Pareto Set change?
2. How does the tradespace change (Spearman's Rho statistic)

7.1.1.2 Tradespace Experiment Concepts Defined

In each of the experiments, a set of tradespace data was post-processed by applying new utility functions. The cost for each design was not altered, only the utility value changed. The independent variables in the experiments were the value function parameters, such as attributes considered, k_i weights in the multi-attribute utility function, the shape of the utility functions, and the functional form of the utility function.

For completeness, the multi-attribute utility function is:

$$KU(\underline{X})+1=\prod_{i=1}^{M}\left[Kk_i U^i(X^i)+1\right], \text{ where } K+1=\prod_{i=1}^{M}\left[Kk_i+1\right]$$

[97] See Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design. for a more complete discussion of X-TOS.

and $U(\underline{X})$ is the multi-attribute utility function, K is a normalization constant, k_i is the relative weight for attribute X^i, and $U^i(X^i)$ is the single attribute utility function for attribute X^i.(Keeney and Raiffa 1993)[98]

The dependent variables considered in each experiment were the designs contained in the Pareto Set, captured in terms of the Design Vector identification numbers, and the Spearman Rho statistic, which is a ranked list correlation measure, applied to the utility along iso-cost bands in the tradespace. Iso-cost bands of approximately $0.5M were used. Designs falling into that cost band were treated as equivalent cost and were ordered into a ranked list based on utility values, with the first ranked design being the highest utility. The tradespaces before and after the preference perturbation were then compared to see the effect of the change.

The Spearman's Rho statistic is defined as

$$\rho_s = 1 - \frac{6D}{n(n-1)(n+1)}, \text{ where } D = \sum_{1}^{n} (d_i)(d_i).$$

d_i is the difference between ranks in lists, n is the number of items in list, and ρ_s is the Spearman's Rho statistic. Spearman's Rho value varies from +1 to –1, with +1 corresponding to identical rankings and –1 corresponding to anti-correlated rankings.

7.1.1.3 Experiments Outlined

Experiment 1a: Major change case (Attribute set, $X^i \in \{X^M\}$)

This experiment approximates the case where a decision maker may not reveal all of the attributes of interest, but may articulate them at a later point in time, where

$$\{X^M\}_{t1} \cap \{X^M\}_{t2} = \{X^{NEW}\}.$$

The original attribute set $\{X^M\}$ = {Data Lifespan, Latitude Diversity, Equator Time, Latency, Sample Altitude} = {DL, LD, ET, L, SA}. The attribute sets were varied in this experiment.
The original k_i corresponding to X^i belong to k^M = [0.3, 0.125, 0.175, 0.1, 0.425].

Six new attribute sets were considered as depicted in Figure 50. Shaded boxes represent included attributes, with the value corresponding to the k_i for each included attribute.

[98] See Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design. for more discussion on $U(\underline{X})$.

Exp1a:	1	2	3	4	5	6	7
DL	0.3	0.3	0.3			0.3	0.3
LD	0.125				0.125	0.125	0.125
ET	0.175	0.175			0.175	0.175	0.175
L					0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425	0.425	0.425
SM						0.2	

Figure 50 Exp1a runs: varying attribute sets

Experiment 1b: Moderate change case (Attribute weight, k_i)

This experiment approximates the case where a decision maker changes his priorities for articulated attributes.

The original attribute set $\{X^M\}$ = {Data Lifespan, Latitude Diversity, Equator Time, Latency, Sample Altitude} = {DL, LD, ET, L, SA}, were kept fixed in this experiment.
The original k_i corresponding to X^i belong to k = [0.3, 0.125, 0.175, 0.1, 0.425]. The k_i were varied in this experiment.

Three sub-experiments were conducted in this experiment. According to the original X-TOS preference data, the two most important attributes were Data Lifespan and Sample Altitude. Two sub-experiments held the k_i for the other attributes fixed and varied the k_i individually for either Data Lifespan or Sample Altitude. The third sub-experiment varied the k_i for both Data Lifespan and Sample Altitude simultaneously while holding the other k_i values fixed. For experiment 1b32, the "old" X-TOS preferences of the original decision maker are included for comparison.

The first sub-experiment considered 9 combinations of k_i values (listed in Figure 51).
The second sub-experiment considered 10 combinations of k_i values (listed in Figure 52).
The third sub-experiment considered 13 combinations of k_i values (listed in Figure 53).

Experiment 1b1 Reuse original dataset sau values, recalculate mau only with new k values

Run number	Data life span	Latitude Diversity	Equator Time	Latency	Sample Altitude	Notes	k sum
1	0.1	0.125	0.175	0.1	0.425	Vary data life span k value	0.925
2	0.2	0.125	0.175	0.1	0.425	Vary data life span k value	1.025
3	0.3	0.125	0.175	0.1	0.425	Original set	1.125
4	0.4	0.125	0.175	0.1	0.425	Vary data life span k value	1.225
5	0.5	0.125	0.175	0.1	0.425	Vary data life span k value	1.325
6	0.6	0.125	0.175	0.1	0.425	Vary data life span k value	1.425
7	0.7	0.125	0.175	0.1	0.425	Vary data life span k value	1.525
8	0.8	0.125	0.175	0.1	0.425	Vary data life span k value	1.625
9	0.9	0.125	0.175	0.1	0.425	Vary data life span k value	1.725

Experiment 1b2

Reuse original dataset sau values, recalculate mau only with new k values

Run number	Data life span	Latitude Diversity	Equator Time	Latency	Sample Altitude	Notes	k sum
1	0.3	0.125	0.175	0.1	0.1	Vary sample altitude k value	0.8
2	0.3	0.125	0.175	0.1	0.2	Vary sample altitude k value	0.9
3	0.3	0.125	0.175	0.1	0.3	Vary sample altitude k value	1
4	0.3	0.125	0.175	0.1	0.4	Vary sample altitude k value	1.1
5	0.3	0.125	0.175	0.1	0.425	Original set	1.125
6	0.3	0.125	0.175	0.1	0.5	Vary sample altitude k value	1.2
7	0.3	0.125	0.175	0.1	0.6	Vary sample altitude k value	1.3
8	0.3	0.125	0.175	0.1	0.7	Vary sample altitude k value	1.4
9	0.3	0.125	0.175	0.1	0.8	Vary sample altitude k value	1.5
10	0.3	0.125	0.175	0.1	0.9	Vary sample altitude k value	1.6

Experiment 1b3

Reuse original dataset sau values, recalculate mau only with new k values

Run number	Data life span	Latitude Diversity	Equator Time	Latency	Sample Altitude	Notes	k sum
1	0.3	0.125	0.175	0.1	0.425	Original set	1.125
2	0.1	0.125	0.175	0.05	0.425	Old X-TOS prefs	0.875
3	0.2	0.125	0.175	0.1	0.3	Vary data life,sample alt k val	0.9
4	0.1	0.125	0.175	0.1	0.2	Vary data life,sample alt k val	0.7
5	0.4	0.125	0.175	0.1	0.3	Vary data life,sample alt k val	1.1
6	0.5	0.125	0.175	0.1	0.2	Vary data life,sample alt k val	1.1
7	0.425	0.125	0.175	0.1	0.4	Vary data life,sample alt k val	1.225
8	0.4	0.125	0.175	0.1	0.1	Vary data life,sample alt k val	0.9
9	0.1	0.125	0.175	0.1	0.1	Vary data life,sample alt k val	0.6
10	0.2	0.125	0.175	0.1	0.1	Vary data life,sample alt k val	0.7
11	0.1	0.125	0.175	0.1	0.3	Vary data life,sample alt k val	0.8
12	0.2	0.125	0.175	0.1	0.2	Vary data life,sample alt k val	0.8
13	0.4	0.125	0.175	0.1	0.2	Vary data life,sample alt k val	1

Expb1:	1	2	3	4	5	6	7	8	9
DL	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LD	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175
L	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425
SM									

Figure 51 Exp1b1 runs: varying k_i for data lifespan

Expb2:	1	2	3	4	5	6	7	8	9	10
DL	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
LD	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175
L	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SA	0.1	0.2	0.3	0.4	0.425	0.5	0.6	0.7	0.8	0.9
SM										

Figure 52 Exp1b2 runs: varying k_i for sample altitude

Expb3:	1	2	3	4	5	6	7	8	9	10	11	12	13
DL	0.3	0.1	0.2	0.1	0.4	0.5	0.425	0.4	0.1	0.2	0.1	0.2	0.4
LD	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175
L	0.1	0.05	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.3	0.2	0.3	0.2	0.4	0.1	0.1	0.1	0.3	0.2	0.2
SM													

Figure 53 Exp1b3 runs: varying k_i for data lifespan and sample altitude (plus "original" attribute k_i)

Experiment 1c: Subtle change case (Utility linearization, $U^i(X^i) \rightarrow a\underline{X^i}+b$)

This experiment represents the case where the decision maker changes his risk or value perceptions on particular attributes, or the case where analysts approximate single attribute utility functions, including bypassing formal utility interviews.

The original attribute set $\{X^M\}$ = {Data Lifespan, Latitude Diversity, Equator Time, Latency, Sample Altitude} = {DL, LD, ET, L, SA}, was kept constant for this experiment.
The original k_i corresponding to X^i belong to k = [0.3, 0.125, 0.175, 0.1, 0.425], was kept constant for this experiment.

Fifteen utility evaluations were investigated through substitution of a linear single attribute utility curve instead of the elicited curve. Neither the k_i nor the attribute sets were altered, only the "shape" of the single attribute utility curves. Figure 54, Figure 55, and Figure 56 show the original "shapes" of the elicited utility functions.[99]

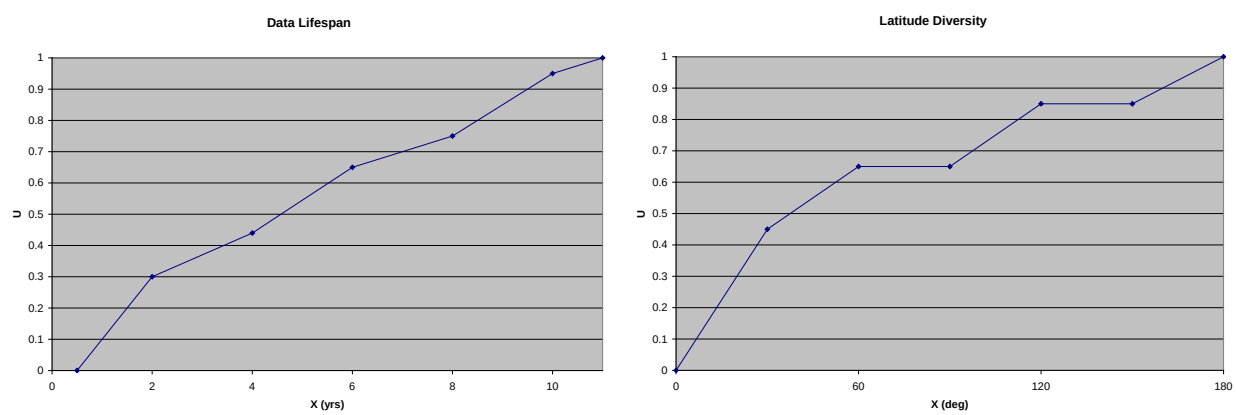


Figure 54 Single attribute utility curves for Data Lifespan and Latitude Diversity

[99] These utility curves were elicited from a science user through a formal utility interview process and is discussed in Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design.

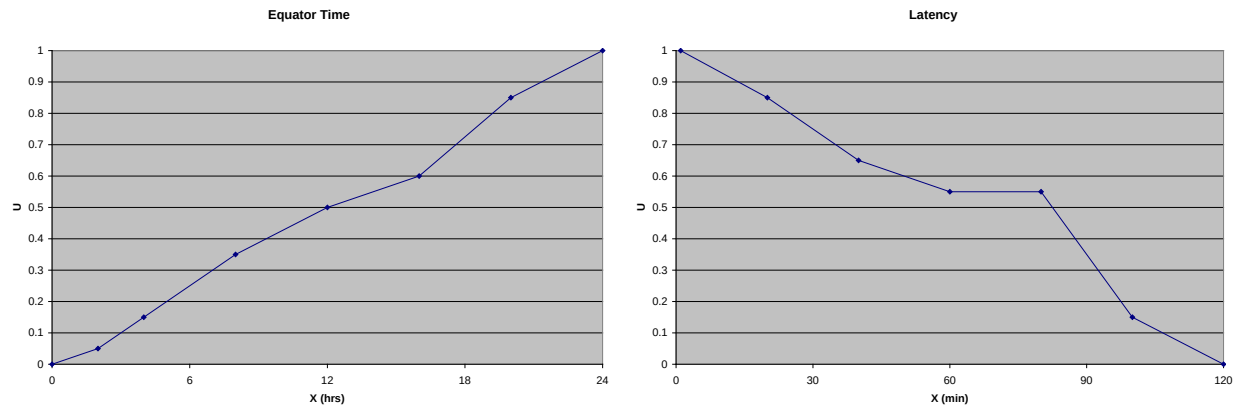


Figure 55 Single attribute utility curves for Equator Time and Latency

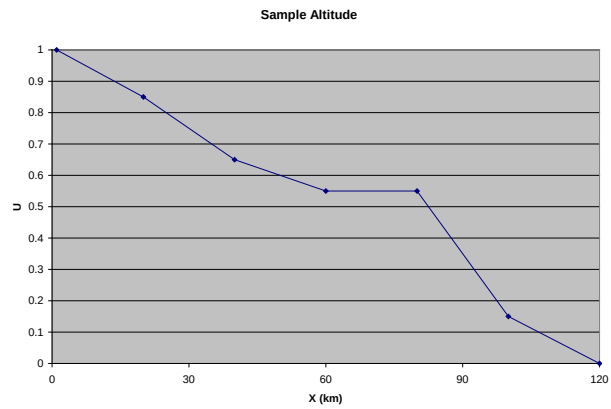


Figure 56 Single attribute utility curve for Sample Altitude

The 15 cases considered are depicted in Figure 57. Boxes with diagonal lines represent attributes for which a linear curve was substituted.

Expc:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
DL	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
LD	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175
L	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425
SM															

Figure 57 Exp1c runs: linearization of select single attribute utilities

Experiment 1d: Evaluative change case (Utility functional form, $U(\underline{X}) \rightarrow G(\underline{X})$)

This experiment represents the case where analysts use various aggregate utility functional forms, including weighted linear sums.

The original attribute set $\{X^M\}$ = {Data Lifespan, Latitude Diversity, Equator Time, Latency, Sample Altitude} = {DL, LD, ET, L, SA}, was kept constant for this experiment.
The original k_i corresponding to X^i belong to k = [0.3, 0.125, 0.175, 0.1, 0.425], was kept constant for this experiment.

Five evaluation functions were tested to reorder the tradespace. These functions represent relaxations of the multi-attribute tradespace function, including common aggregation methods used in engineering decision analysis, such as the weighted sum.

Function 1, MAUF: $$U = \frac{\left(\prod_{i=1}^{N}\left[Kk_iU_i + 1\right]\right) - 1}{K}$$

Function 2, M1: $$U = \prod_{i=1}^{N} k_iU_i$$

Function 3, M2: $$U = \prod_{i=1}^{N}\left[k_iU_i + 1\right]$$

Function 4, M3: $$U = \sum_{i=1}^{N} k_iU_i$$

Function 5, M4: $$U = \prod_{i=1}^{N}\left[Kk_iU_i + 1\right]$$

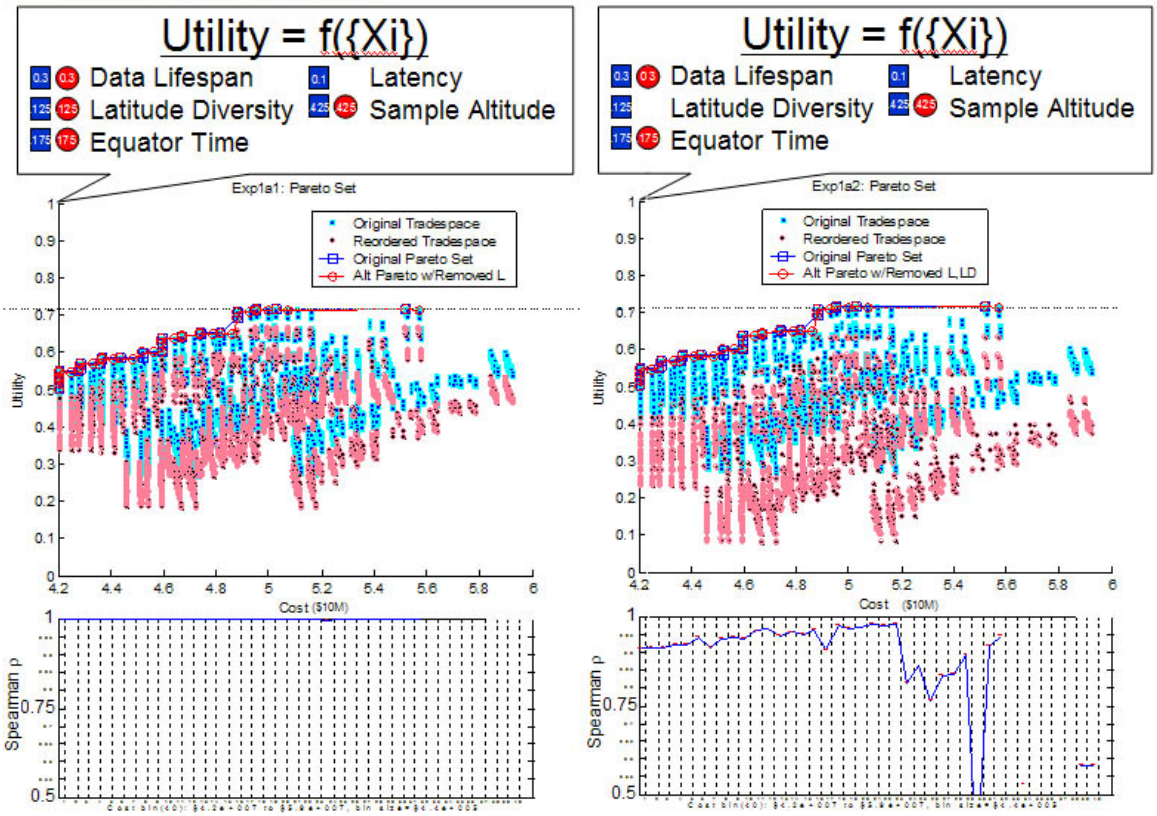
7.1.1.4 Experiments' Results

Only the results of Experiment 1a are included here for consideration. For readers interested in the details of the full results of all four experiments, they can be found in Appendix D: Single Decision Maker Experiments Results. The results are very information dense and have been moved for the sake of thesis pacing.

Experiment 1a: Major change case

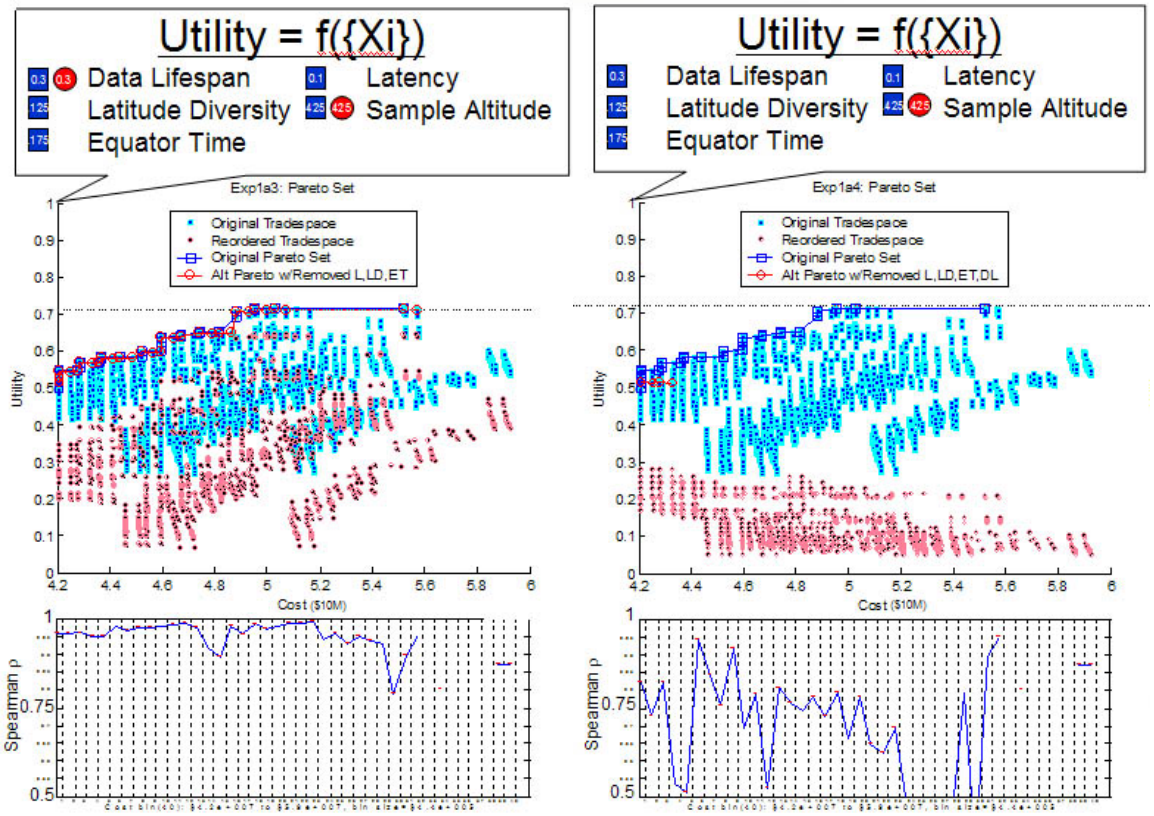
The results of this experiment are shown in Figure 58 through Figure 60. The original tradespace is shown in small blue boxes, with the reordered tradespace shown in small red circles. The components of the attribute set for each tradespace is shown above, and the Spearman's Rho statistic is plotted along the bottom. In order to get a sense of the Spearman statistic, the maximum and minimum Spearman values are included, as is the size of the Pareto Set. (Note: cost bins that do not have a Spearman value shown have fewer than 10 items, so the statistic is not valid and has been excluded.[100])

[100] See Spaulding, Timothy J. (2003). Tools for Evolutionary Acquisition: A Study of Multi-attribute Tradespace Exploration (MATE) Applied to the Space Based Radar (SBR). SM thesis in Aeronautics and Astronautics. Massachusetts Institute of Technology. Cambridge, MA: 142. for discussion on Spearman Rho statistic applied to tradespace comparisons and statistical validity.



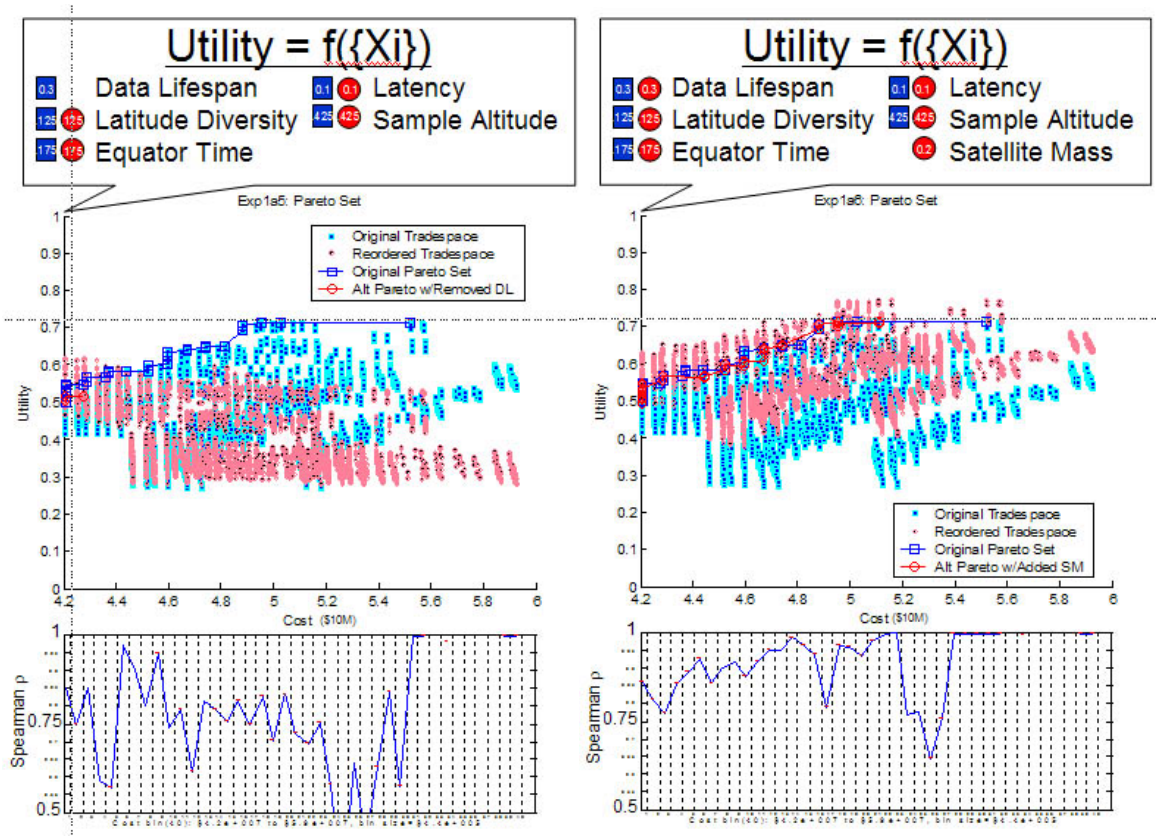
Max Spearman	1.0	Max Spearman	0.9806
Min Spearman	0.9985	Min Spearman	0.3367
Size Pareto Set	47	Size Pareto Set	35

Figure 58 Exp1a results: tradespace shifts, Spearman Rho statistic, and Pareto Set size (runs 1 and 2)



Max Spearman	0.9915	Max Spearman	0.9525
Min Spearman	0.7904	Min Spearman	0.1936
Size Pareto Set	31	Size Pareto Set	4

Figure 59 Exp1a results: tradespace shifts, Spearman Rho statistic, and Pareto Set size (runs 3 and 4)



Max Spearman	0.9976	Max Spearman	0.9995
Min Spearman	0.2983	Min Spearman	0.6435
Size Pareto Set	4	Size Pareto Set	42

Figure 60 Exp1a results: tradespace shifts, Spearman Rho statistic, and Pareto Set size (runs 5 and 6)

Looking at the changes in the tradespace begs the question of how to select a design in the original tradespace that still delivers value in the reordered tradespace. The question is akin to trying to discover value-robust designs in the face of changing preferences. A simple proxy for value robustness is being a part of the Pareto Set. These designs are the maximum utility systems at a given cost. If a design appears in more than one set, it is robust to that particular change. Figure 61 shows that upon inspection, four designs appear in four or more Pareto Sets. Design id 2471 appears in all seven Pareto Sets, while designs 903, 1687, and 2535 appear in five sets each. Pareto Set tracing is the practice of following designs across tradespace orderings looking for designs "surfing" the best region in all tradespaces.

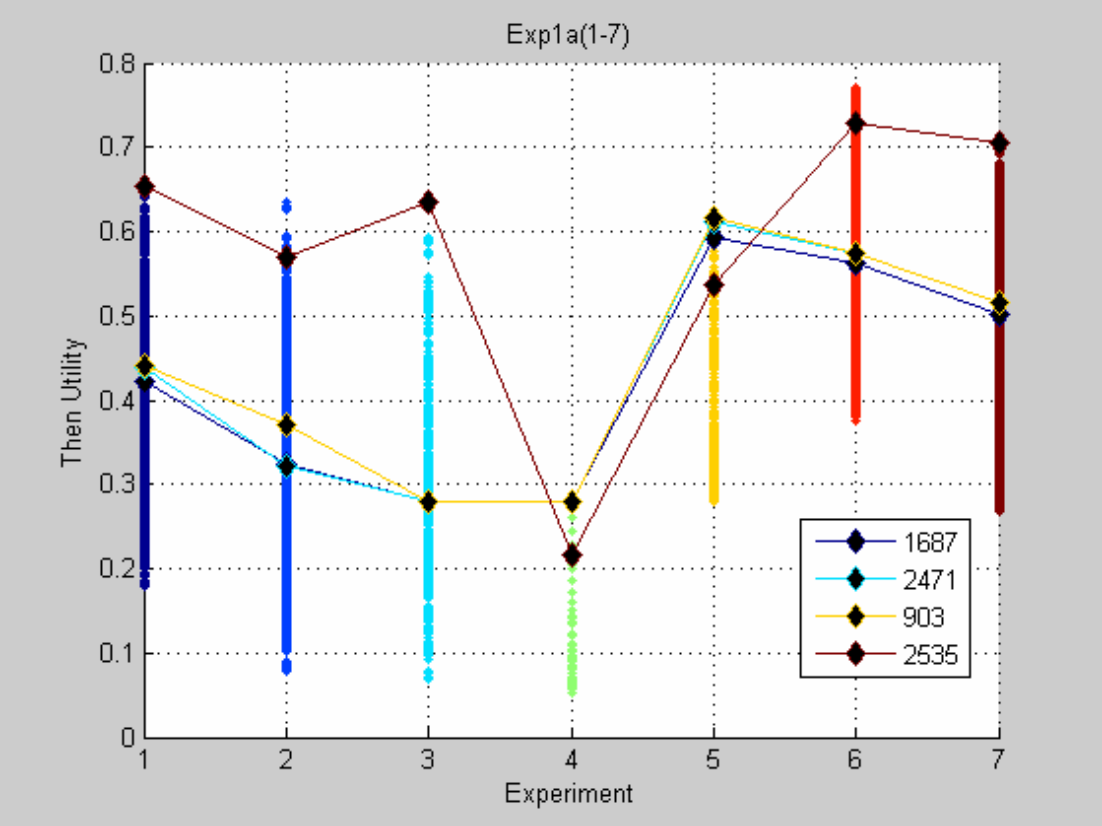


Figure 61 Two dimensional Pareto Set Tracing for Exp1a (Experiment-Utility). Four designs appear in five or more Pareto Sets across the experiments.

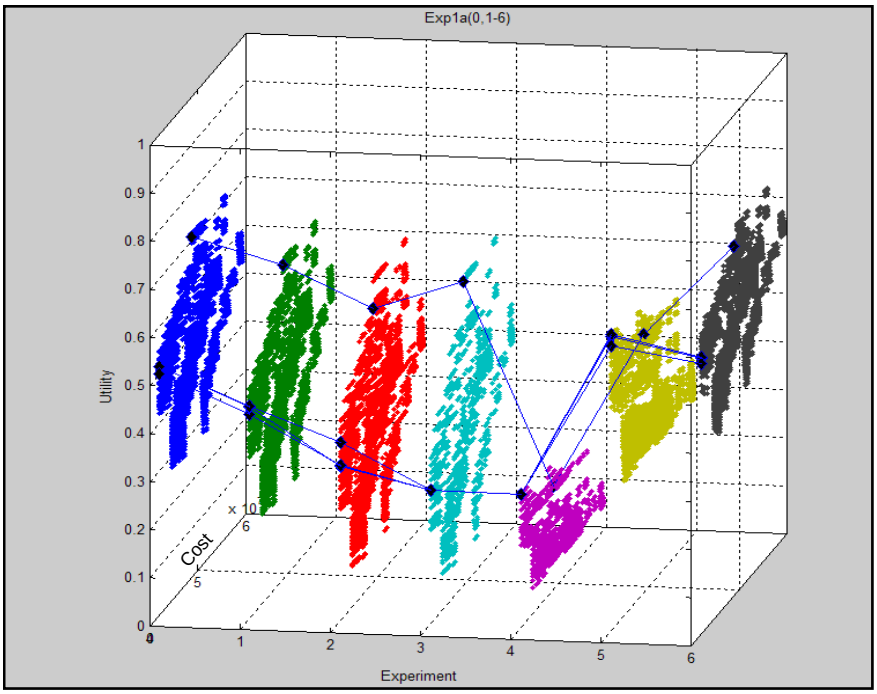


Figure 62 Three dimensional Pareto Tracing for Exp1a (Experiment-Cost-Utility). Exp1a0=Exp1a7 (Original, unaltered preferences)

The concept of Pareto Set tracing can be taken farther by generating Figure 63, which shows the distribution of Pareto Set commonality (Pareto Trace number) versus number of designs. Designs appearing in a large fraction of Pareto Sets are more value robust than other designs. For this experiment, one design appears in 7 sets, none appear at 6, 3 more appear at 5, and 16 appear at 4, as shown in Figure 64 and Figure 65.

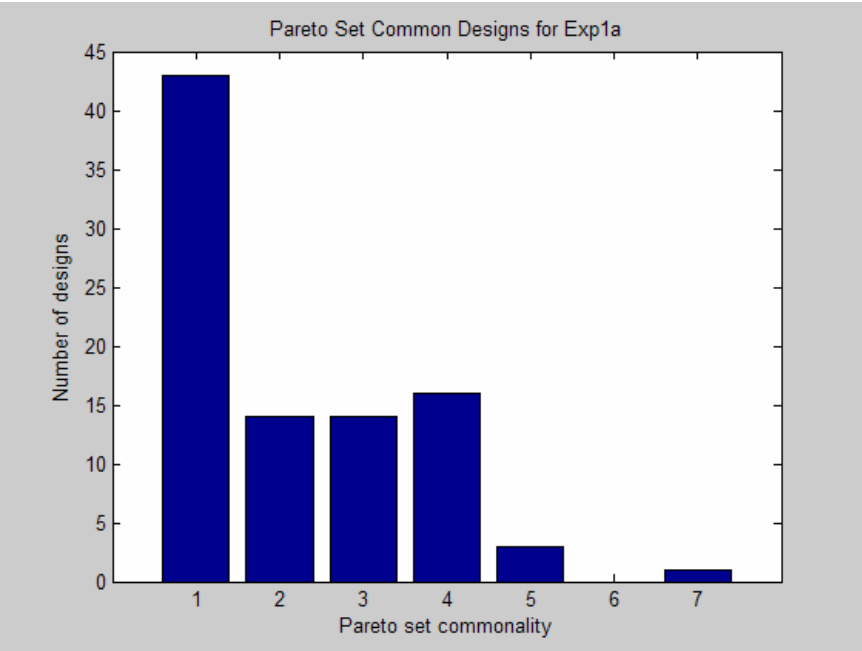


Figure 63 Distribution of Pareto Set commonality (Pareto Trace number) for Exp1a

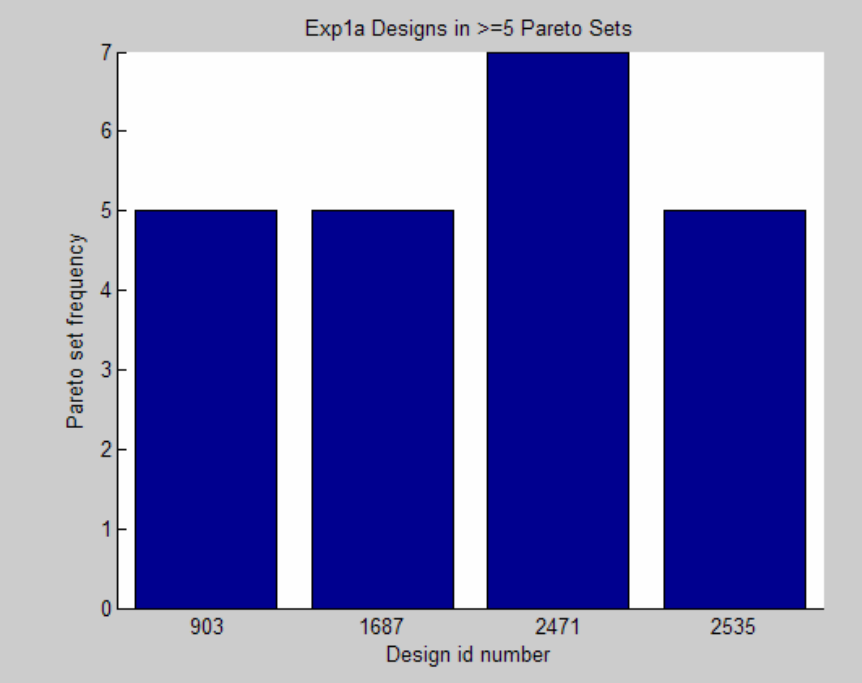


Figure 64 Design ID number versus Pareto Trace number for Exp1a (only Pareto Trace >=5)

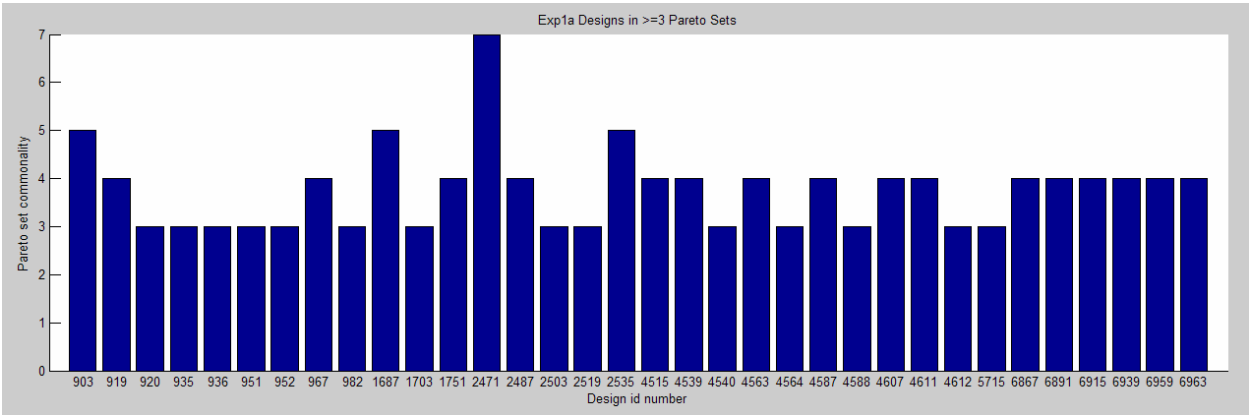


Figure 65 Design ID number versus Pareto Trace number for Exp1a (only Pareto Trace >=3)

After locating the existence of designs that remain value robust, the designer can inspect the particular properties of the designs to look for common features. Figure 66 lists the four value-robust X-TOS designs, highlighting their similarities and differences. More discussion about the reason for robustness will be done in Section 7.2, "Discussion" below.

DV	2471	903	1687	2535
Inclination	90	30	70	90
Apogee	460	460	460	460
Perigee	150	150	150	290
Com Arch	TDRSS			
Delta V	1200			
Prop Type	Chem			
Pwr Type	Fuel Cell			
Ant Gain	Low			

Figure 66 X-TOS Exp1a robust design variable comparison

Recognizing the properties of value-robust designs may suggest strategies to the designer for achieving the robustness, either through initial design, or through changeability at a later point in time (changing a system to a passively value-robust configuration may be more cost effective than continually changing a system to maintain high value delivery).

For results of Experiments 1b, 1c, and 1d, please see Appendix D: Single Decision Maker Experiments Results.

Synthesizing the results from all of the single decision maker preference experiments results in the distribution shown in Figure 67. Figure 68 reveals that one design appears in all of the Pareto Sets, and thus has the highest (best case) Pareto Trace number of 60: design 2471. Four other designs have Pareto Trace numbers over 57: 903, 967, 1687, and 2535. The possible reason for the high Pareto Trace numbers will be discussed below in Section 7.2, "Discussion."

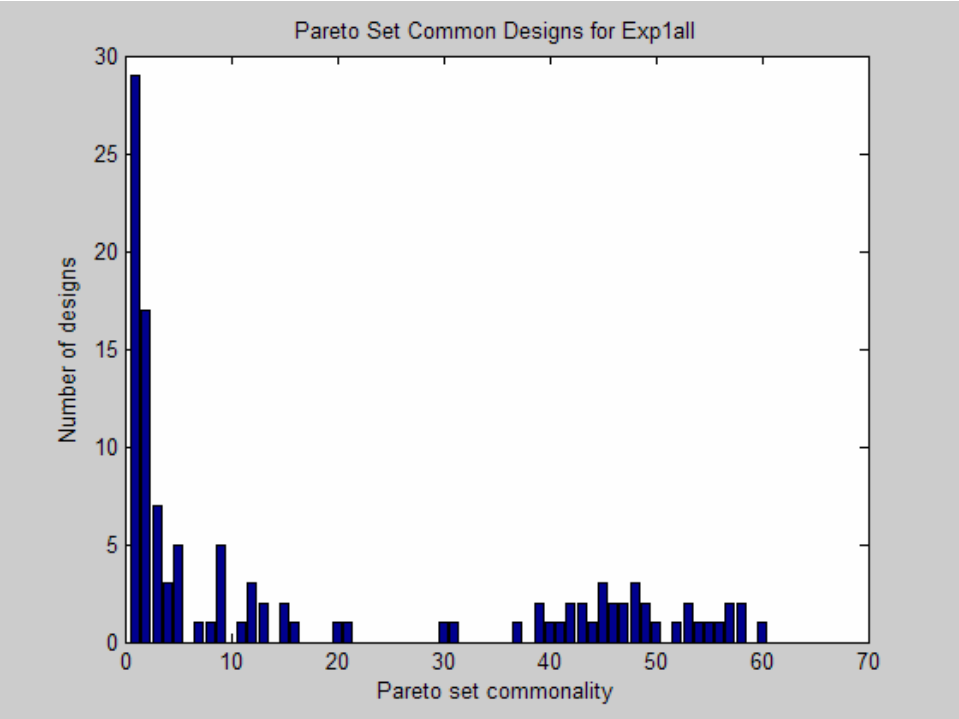


Figure 67 Pareto Trace distribution (all Exp1)

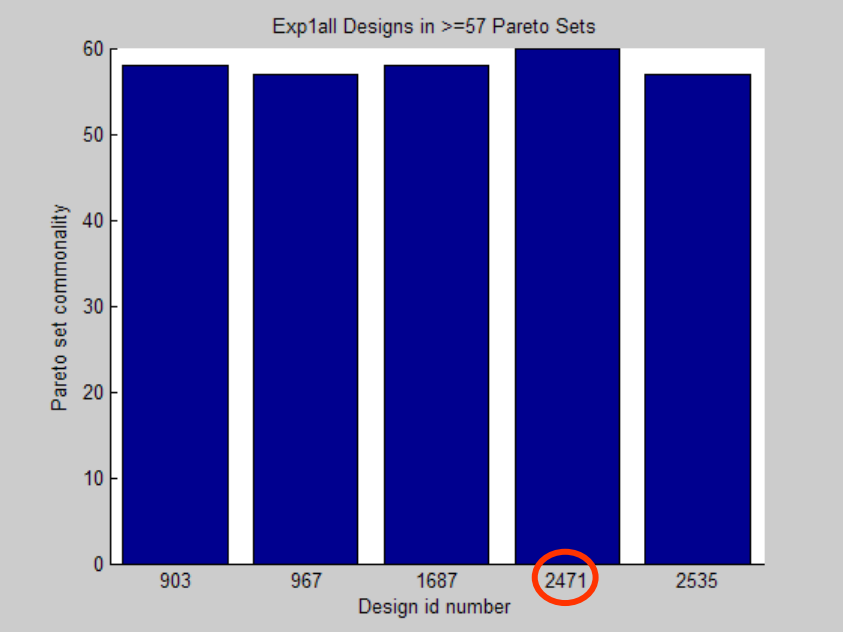


Figure 68 Design ID number versus Pareto Trace number (all Exp1a)

7.1.2 Two Decision Makers

7.1.2.1 Overview

In the two decision maker case, three classes of preference experiments were proposed:

a. Static Pareto Set determination
b. Orthogonality of attribute sets (vary $X^i \in \{X^{M1}\}_{DM1}$, $X^j \in \{X^{M2}\}_{DM2}$)
c. Changes in priorities (vary k_i for each DM)

The questions asked were:

1. How do the Pareto Sets compare between the decision makers (individually and jointly)?
2. How do the Pareto Sets change?

During experimentation it was realized that the single decision maker experiments would be reproducible at the two or more decision maker level, so only the static 2-DM experiment was conducted due to time considerations. (The static insight of the 2-DM experiment is extended to the dynamic regime in the same manner that static 1-DM experiment was extended.)

7.1.2.2 Tradespace Experiment Concepts Defined

The concepts in the two decision maker experiments are identical to that of the single decision maker, except each design is evaluated in terms of not only utility and cost, but also utility of the second decision maker. The concept of the Pareto Set is extended to additional dimensions, with non-dominated designs requiring a degradation of one or more other objectives in order to improve a given one.

7.1.2.3 Experiment Outlined

Experiment 2a: 2DM Static Pareto Case

This experiment gives a static baseline for multiple decision maker tradespace exploration, which has been referenced in prior MATE work, but not actually conducted. It also approximates the case where an additional decision maker enters the preference space and now must be considered.

The first decision maker in this experiment is identical to the "original" decision maker in the one decision maker experiments in the prior section. A second decision maker was added to the analysis, approximating a "Customer", as opposed to the "User" as the first decision maker.[101]

Each design is evaluated in terms of Cost, Utility_{DM1}, and Utility_{DM2}.

The DM1 attribute set $\{X^{M1}\}$ = {Data Lifespan, Latitude Diversity, Equator Time, Latency, Sample Altitude} = {DL, LD, ET, L, SA}.

The DM2 attribute set $\{X^{M2}\}$ = {IOC Cost, Development Time, Satellite Lifetime, Satellite Mass} = {IOC, DT, SL, SM}.

The DM1 k_i corresponding to X^i belong to k^{M1} = [0.3, 0.125, 0.175, 0.1, 0.425].

[101] Please see Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design. for a discussion of decision maker roles including User, Customer, Designer, Firm, and External.

The DM2 k_i corresponding to X^i belong to k^{M2} = [0.4, 0.3, 0.2, 0.2].

Figure 69 depicts this experiment enumeration.

Exp2a:	1	
	DM1	DM2
DL	0.3	
LD	0.125	
ET	0.175	
L	0.1	
SA	0.425	
IOC		0.4
DT		0.3
SL		0.2
SM		0.2

Figure 69 Exp2a run enumeration

The Spearman Rho statistic was not calculated for this experiment since ranked lists no longer exist due to the need to trade Utility_{DM1} versus Utility_{DM2}. Pareto Set comparison could be done, however, as well as a tracing between the single and dual decision maker case.

7.1.2.4 Experiment Results

Experiment 2a: 2DM Static Pareto Case

Representation of the results of this experiment requires venturing into additional dimensions. Since explicit aggregation of multiple decision makers is to be avoided, each decision maker's utility must be kept as a separate dimension in the ensuing analysis.

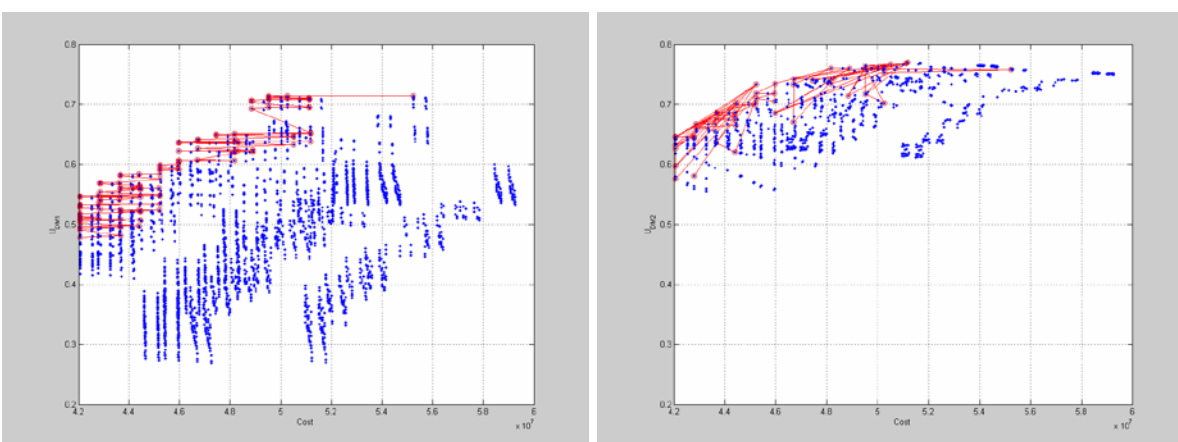


Figure 70 2-dimensional projection of U_{DM1}-Cost and U_{DM2}-Cost views of tradespace, with Pareto Set indicated by red line

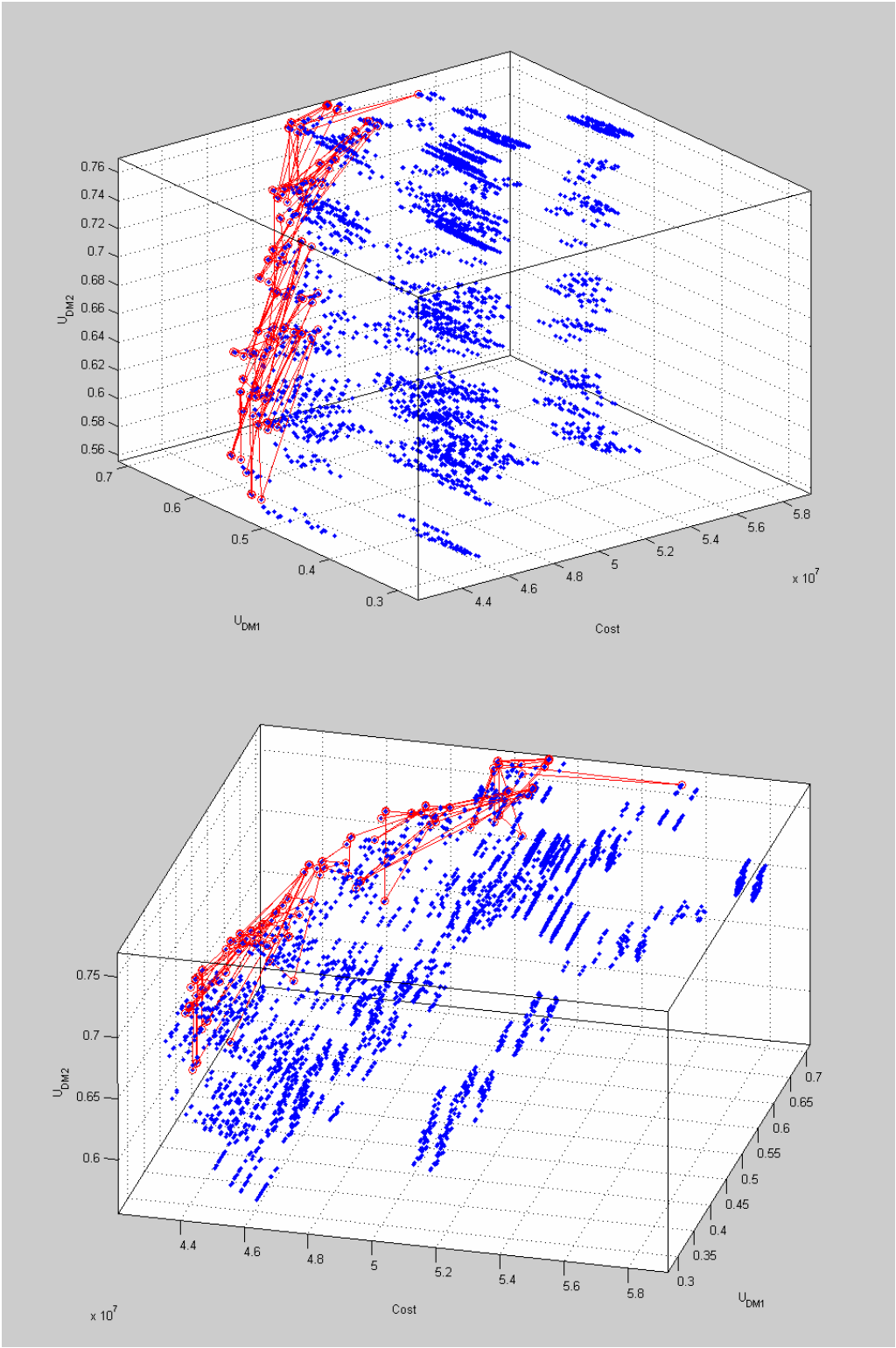


Figure 71 Exp2a results: Multi-dimensional tradespace representations ($Utility_{DM1}$-$Utility_{DM2}$-Cost)

The results of this experiment were a bit unintuitive. It was expected that the Joint Pareto Set of the two decision makers would be less than the sum of the individual Pareto Sets due to the increased constraints on the designs by having to provide value to another individual. This effect

is the case when considering the designs within an individual Pareto Set and its likelihood of appearing in the Pareto Set of the other individual. Figure 72 shows that while 36 and 26 designs exist in Decision Maker 1 and Decision Maker 2 individual Pareto Sets respectively, only 6 designs appear in both sets. The Joint Pareto Set, however, has 122 designs. Figure 71 shows how the greater number is possible. When viewing the tradespace in three dimensions, the trade-off surface clearly contains both the individual Pareto Sets (as determined by a projection onto the appropriate Utility-Cost planes) as well as other points that would not project onto the individual Pareto Set. These points exist at the trade-off between utility of the decision makers and represent the "compromise" value solutions. (In Figure 70 these compromise solutions appear as dominated solutions when viewed in a single decision maker-centric tradespace.)

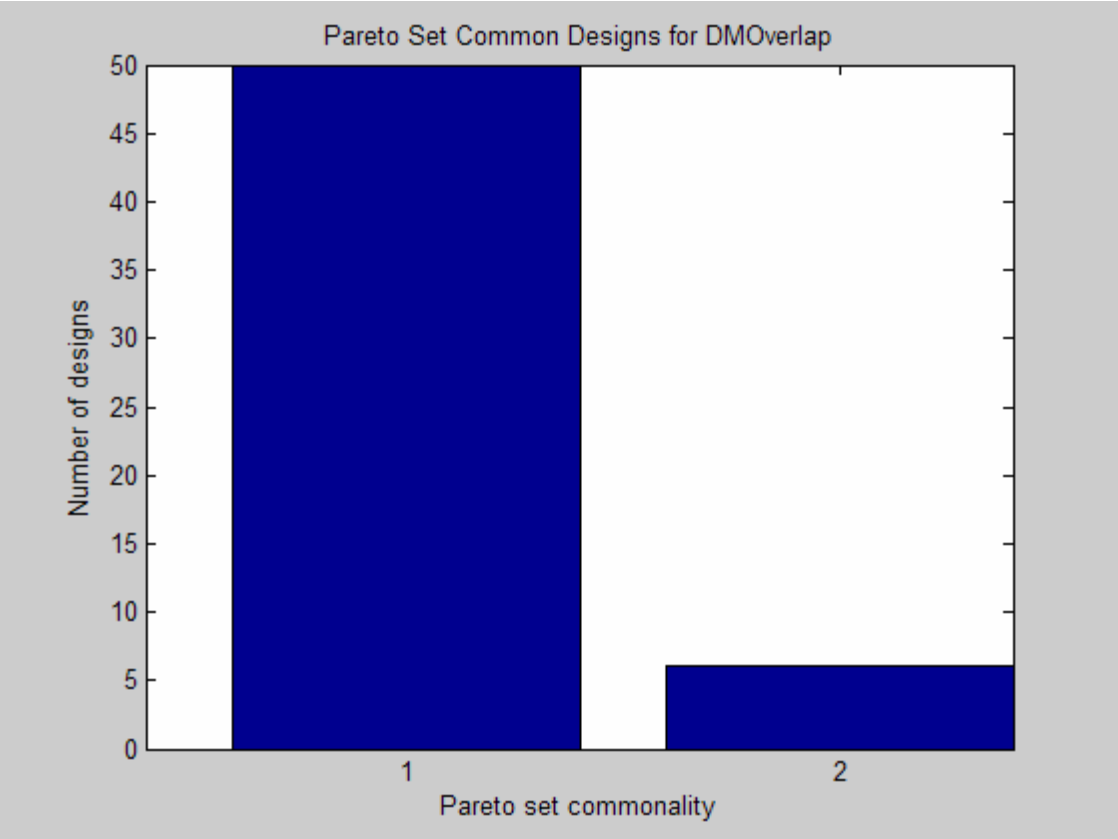


Figure 72 Pareto Trace number distribution for commonality between two decision makers' individual Pareto Sets

Figure 73 and Figure 74 below show the Venn diagrams of the individual Pareto sets, their intersection, and their relation to the Joint Pareto Set. In this representation, the counter-intuitive increase in efficient (best value for given cost) solutions becomes clearer.

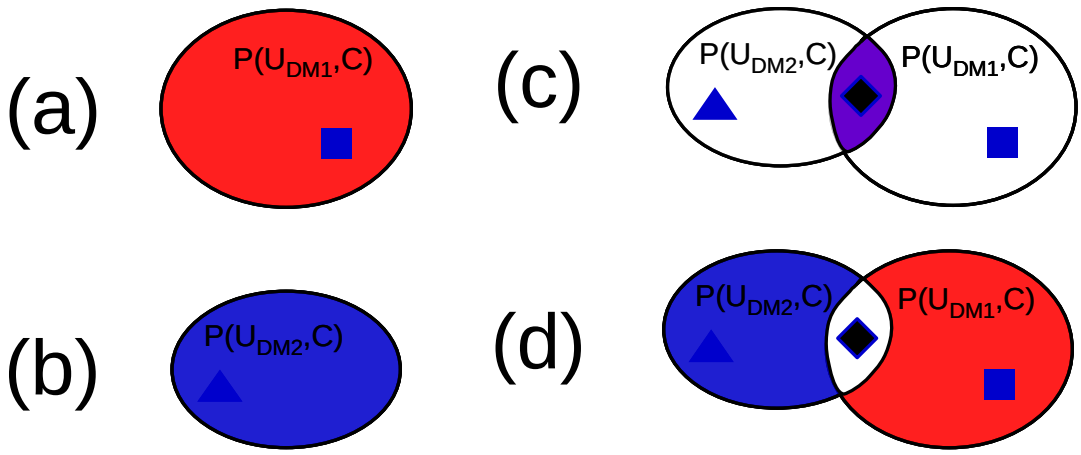


Figure 73 Venn diagrams showing a) Pareto Set for DM1, b) Pareto Set for DM2, c) Common Pareto Set for DM1&DM2, d) Exclusive Pareto Set for DM1orDM2

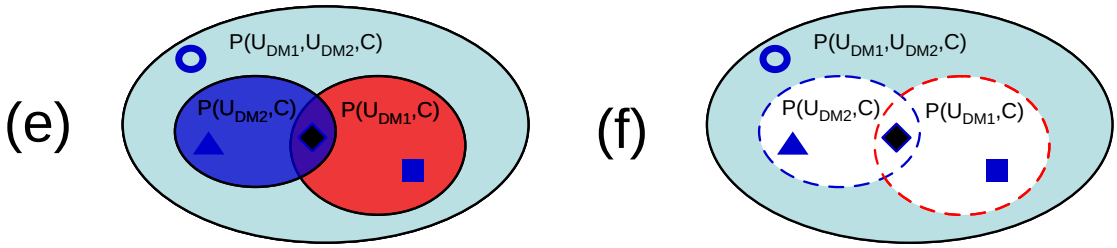


Figure 74 Venn diagrams showing e) the Joint Pareto Set for DM1&DM2, including "compromise" solutions, f) "Compromise" Pareto Set

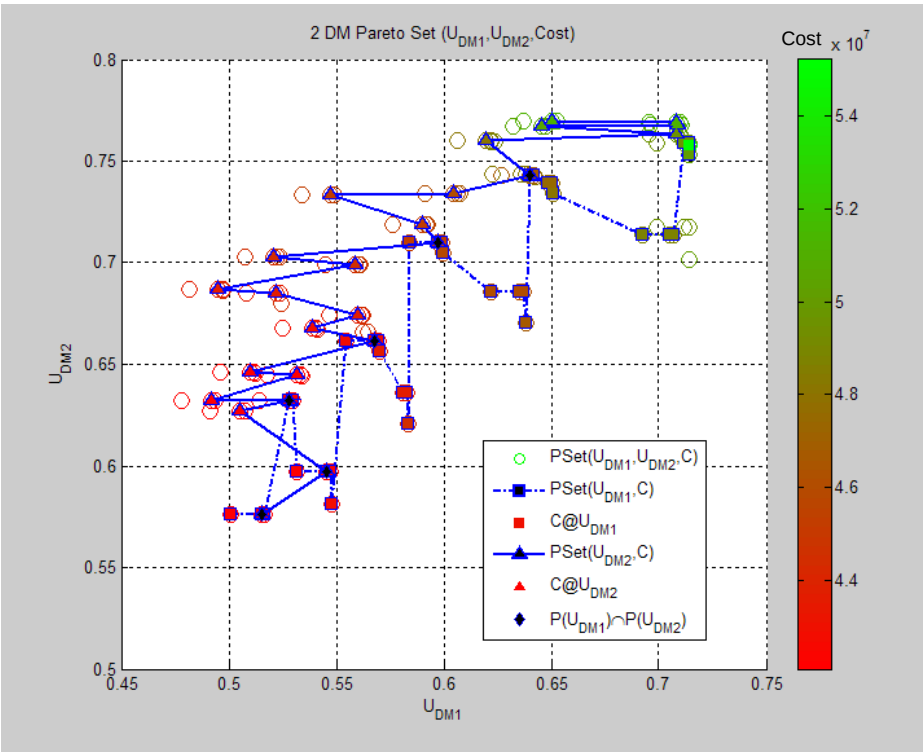


Figure 75 Joint Pareto set in Utility-Utility space (Exp2a)

The utility-utility plot suggested by prior work is shown in Figure 75, including both the individual Pareto Set points, as well as the Joint Pareto Set points. The confounding issue preventing a simple convex utility-utility trade-off curve on this plot is the existence of the cost trade-off as another decision metric. A lower cost at a particular utility-utility level may encourage movement from a higher cost, high "value" utility-utility level. Thus the Joint Pareto Set includes both the individual Pareto sets, as well as new "compromise" solutions that trade off utility between the decision makers for cost.

The Pareto Tracing technique employed for the single decision maker case works well here as well, providing a list of designs included in both decision makers' Pareto Sets. The tradespace as perceived by each decision maker can be treated as the same tradespace, but varying over time (complete swapping of preferences). Finding a robust solution to both problems entails a similar problem-solving approach. The tracing of Pareto Set designs from Decision Maker 1 to Decision Maker 2 is shown in Figure 76 and Figure 77.

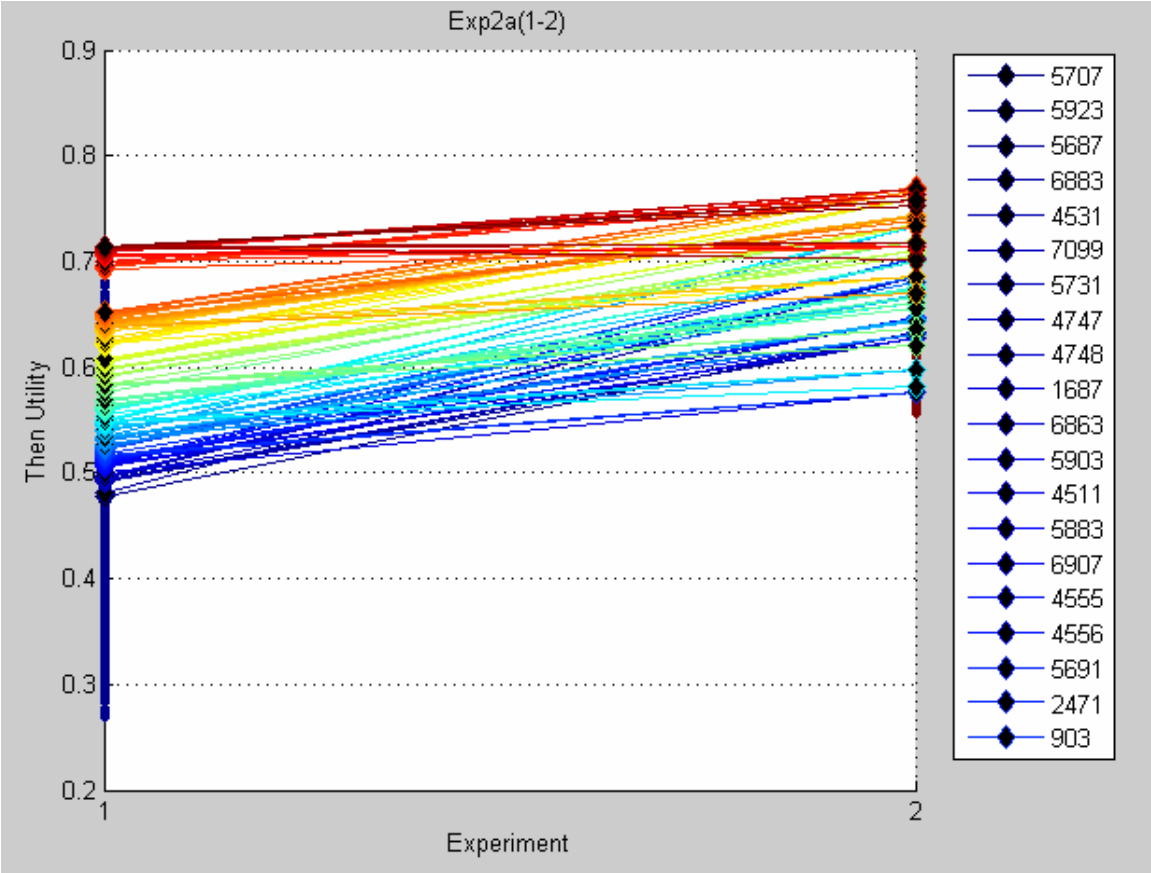


Figure 76 Two dimensional Pareto Tracing Exp2a (DM1-DM2)

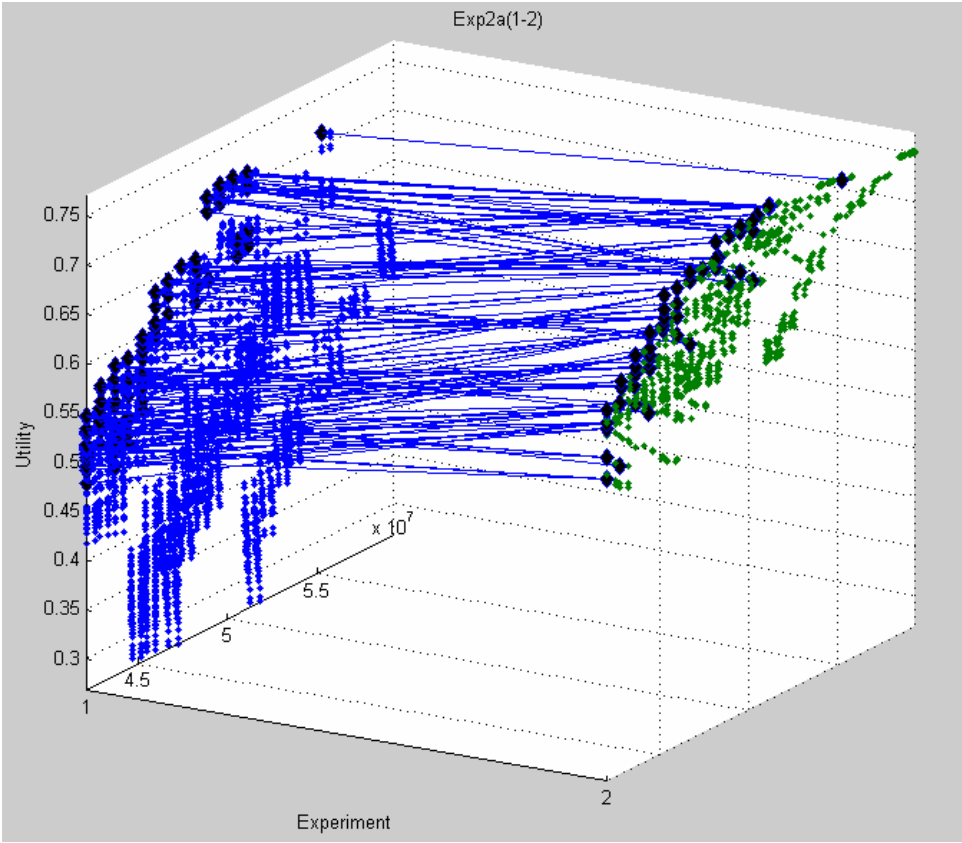


Figure 77 Three dimensional Pareto Trace (DM1-DM2-Cost)

Looking at Figure 78, it is interesting to note that design 2471 is one of the six designs appearing in both decision makers' Pareto Sets. Since all four designs, 2471, 903, 1687, and 2535 are in the Pareto Set for Decision Maker 1, they are also in the Joint Pareto Set, as shown in Figure 79.

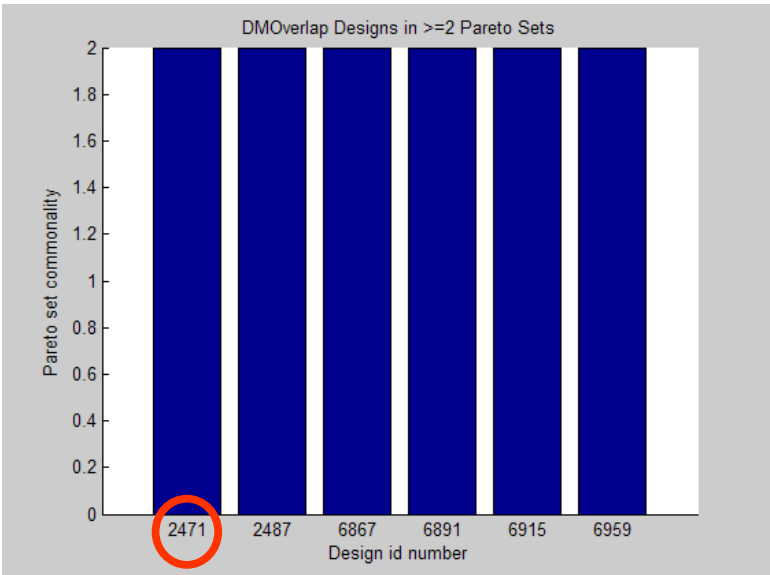


Figure 78 Overlap between individual DM Pareto Sets in Exp2a (Pareto Trace >=2)

Designs in Joint Pareto Set

DM1 Pareto Set DM2 Pareto Set Compromise Pareto Set

903	919	920	933	935	936	951	952	965	967	981
982	983	984	997	1687	1703	1735	1749	1751	1765	1767
1781	2471	2487	2501	2503	2519	2533	2535	2549	2551	2565
4511	4515	4531	4535	4536	4539	4540	4555	4556	4559	4560
4563	4564	4579	4580	4583	4584	4587	4588	4603	4604	4607
4608	4611	4612	4627	4628	4631	4632	4633	4707	4708	4727
4728	4747	4748	4771	4773	4795	4796	4797	5687	5691	5707
5711	5715	5731	5735	5739	5755	5759	5779	5783	5787	5803
5807	5809	5883	5903	5923	5947	5949	5971	5973	6863	6867
6883	6887	6891	6907	6911	6915	6931	6935	6939	6955	6959
6963	6979	6983	6985	7059	7079	7099	7123	7125	7147	7148
7149										

Joint Pareto size: 122 designs

Figure 79 Membership of Joint Pareto Set for DM1 and DM2 (blue=DM1 PSet, black=DM2 PSet, Red=Compromise PSet, White=Both Indiv Pset)

Conduct of the two decision maker static preference experiment revealed the interesting concept of Compromise Pareto Set, which contains design options not in an individual decision maker's Pareto Set. These "compromise" solutions are efficient in being best value at a given cost, but make no assumptions about the relative "weight," or importance of the individual decision makers. Designs appearing in both individual Pareto Sets, of which six existed in this example, provide a clear win-win set requiring little negotiation. For this particular example, one of the designs in both individual Pareto Sets was 2471, which is also the design with the highest Pareto Trace number for decision maker 1 through the single decision maker experiments previously conducted. What makes this design so robust is not understood. The existence of such agreeably robust solutions for general problems is not known to be guaranteed.[102]

7.1.3 Multiple Decision Makers

Originally this research intended to investigate the three decision maker case. While conducting the two decision maker case, however, it became apparent that the analysis can be generalized to "N" decision makers. It is a relatively simple matter to calculate the N-dimensional Pareto Set of designs and Pareto Trace to determine designs appearing in various numbers of Pareto Sets. Visualization of the trade-off surface, however, will become more difficult and possibly impossible for N greater than 4 or 5.[103] Additionally, it would seem that the larger the number of distinct decision maker preferences, the larger the size of the "compromise" Pareto Set, making more difficult the tractability of finding "best" solutions (more to be discussed below.)

[102] Further research should be done across multiple case studies to understand whether the existence of high Pareto Trace designs can be made predictable.

[103] See Lotov, Alexander V., Vladimir A. Bushenkov, et al. (2004). Interactive Decision Maps: Approximation and Visualization of Pareto Frontier. Boston, Kluwer Academic Publishers. for a discussion of the visualization of multi-dimensional Pareto surfaces for decision-making and limitations on dimensionality communication.

7.2 Discussion

A surprising result from the single decision maker experiments was the existence of four designs that appeared in all but one Pareto set (1+6+8+9+12+15+4=55).[104] Designs 2471, 903, and 1687 appear in all 55 single DM sets, while design 2535 appears in 54 sets. Design 2471 additionally is one of only six designs to appear in both decision makers' Pareto Sets of the 2DM experiment. The aforementioned four designs are "robust" to many types of preference variation and may give the designer some physical insights into how to deliver value in the face of changing perceptions. (Figure 80 below recaps the high Pareto Trace designs.) The revealed robust (high Pareto Trace number) designs 2471, 903, 1687, and 2535 are described in Figure 81. What follows is an attempt to discern the reason for these designs' apparent robustness to changing preferences. One hypothesis is that each of these designs in some way has "excess capability" so that changes in preferences, while altering the designs' perceived value, do not move it into a less acceptable reason. (The design in a sense would have "margin" to lose.)

[104] The actual total number of Pareto Sets is 60, however that double counts the baseline Pareto Set, which was repeatedly calculated for comparison. Of the 60, 55 are unique.

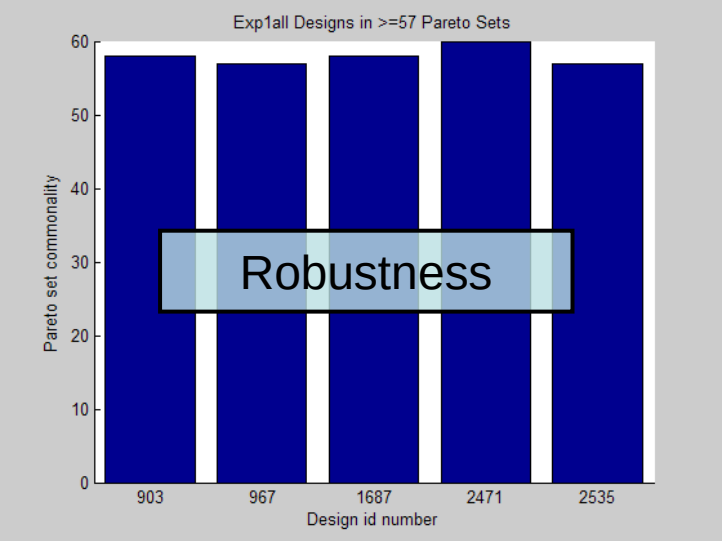


Figure 80 Pareto Trace Number for X-TOS robust designs

DV	2471	903	1687	2535
Inclination	90	30	70	90
Apogee	460	460	460	460
Perigee	150	150	150	290
Com Arc	TDRSS	TDRSS	TDRSS	TDRSS
Delta V	1200	1200	1200	1200
Prop Type	Chem	Chem	Chem	Chem
Power Type	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Ant Gain	Low	Low	Low	Low
Data Life	0.51	0.51	0.51	10.05
Lat Div	180	60	140	180
Equator Time	5	11	6	5
Latency	2.27	2.27	2.27	2.30
Sample Alt	150	150	150	290
Cost	4.21	4.21	4.21	4.88
Utility	0.5151	0.5165	0.5012	0.7054

Figure 81 X-TOS revealed robust (High Pareto Trace Number) designs

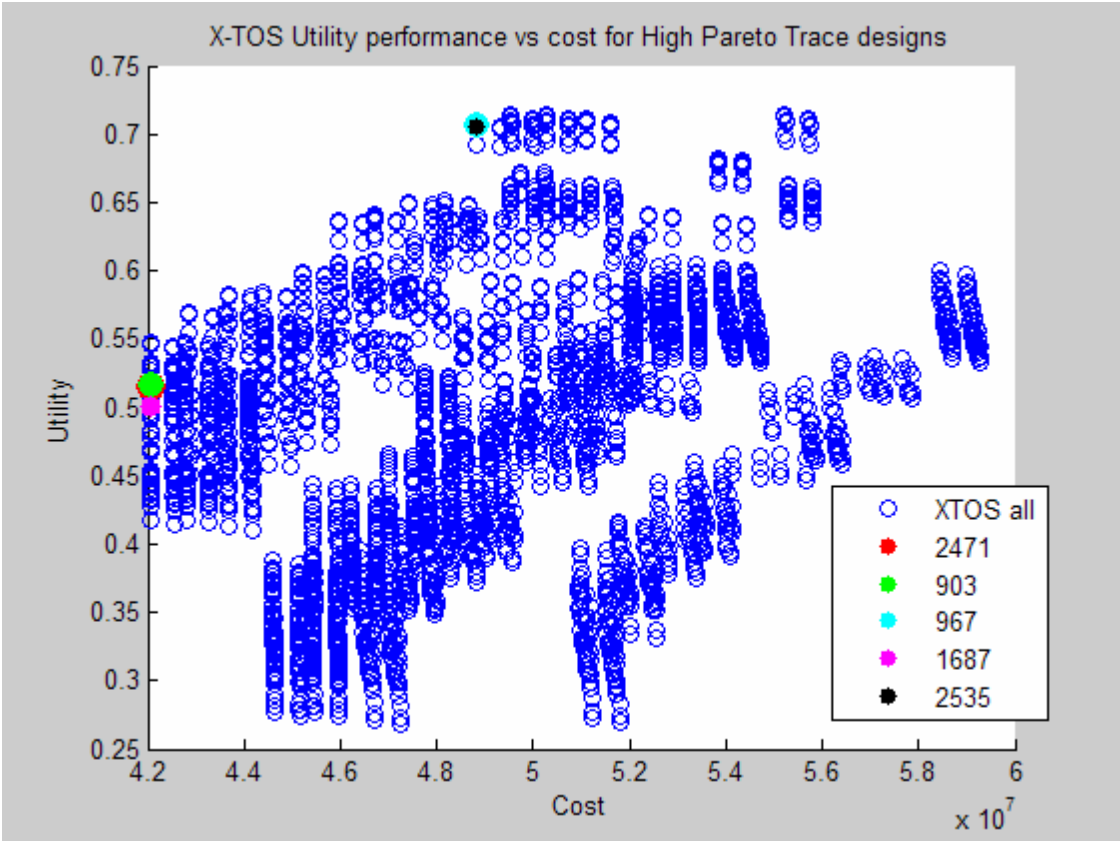
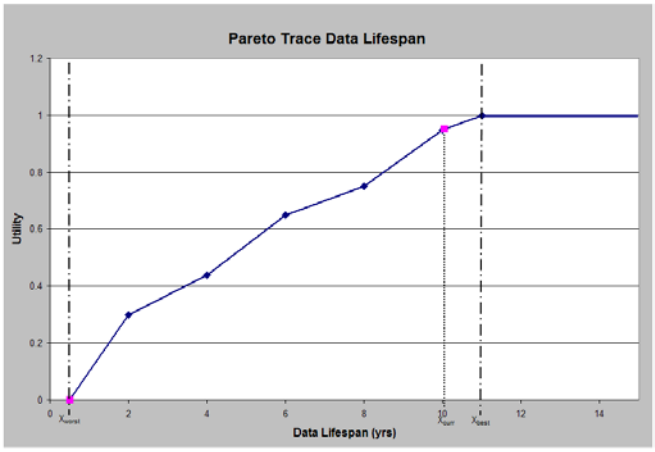
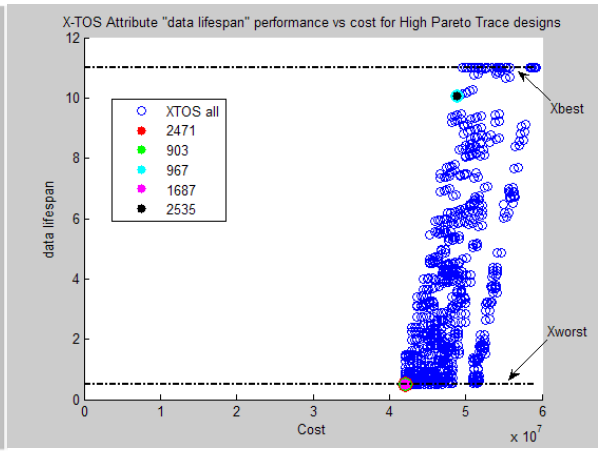
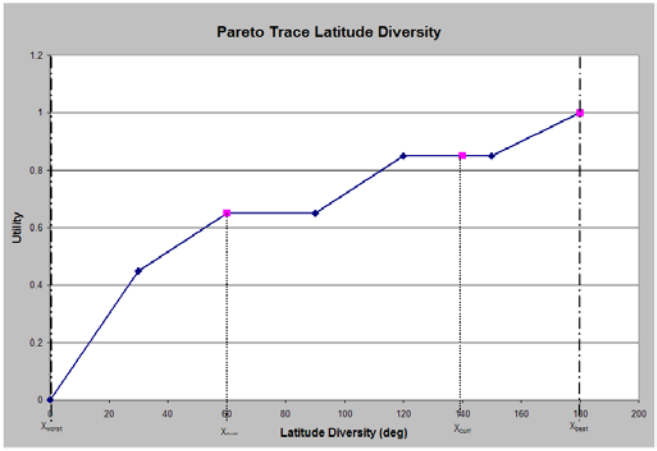


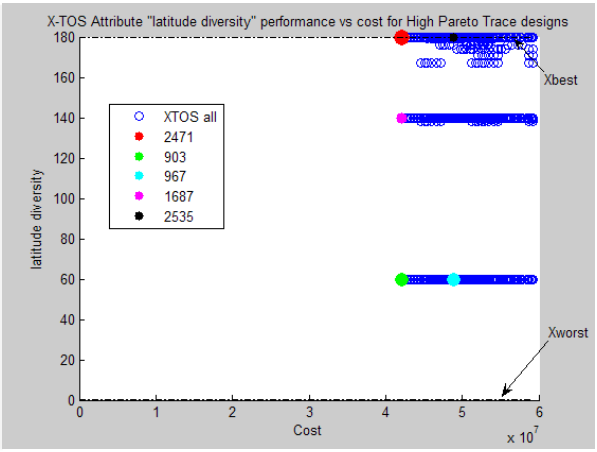
Figure 82 X-TOS Tradespace with High Pareto Trace designs indicated

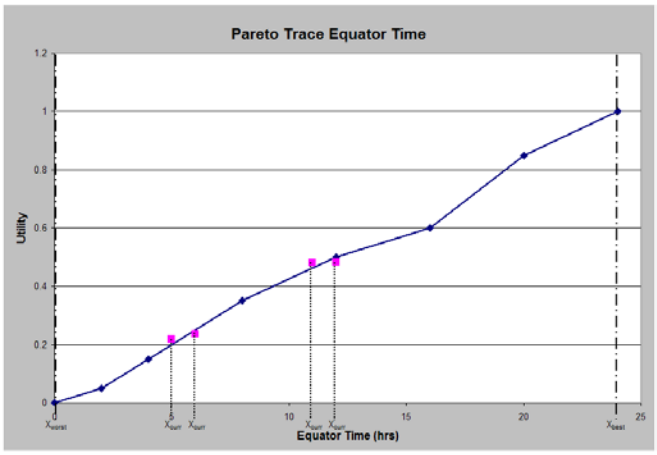
The location of the High Pareto Trace designs in the overall X-TOS tradespace is shown in Figure 82. The designs appear to come from two distinct regions of the tradespace: the lowest cost that is close to maximum tradespace utility, and the lowest cost Pareto designs. The following figures (Figure 83 below) compare the attribute values of the designs to the entire tradespace, indicating their relation both to the attribute acceptability range and their location on the elicited utility function. Excess capability would be shown as attribute values beyond the "best" or "worst" attribute acceptance levels. Another possible source of robustness would be location on a "flat" part of the utility curve, meaning that a local change in attribute values would result in a small change in utility.

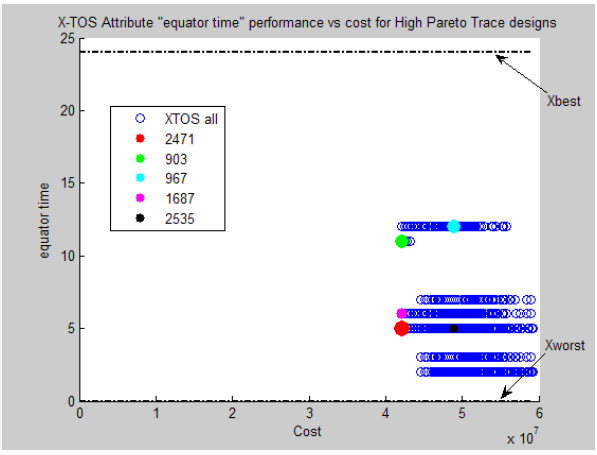

Pareto Trace Data Lifespan
Utility
Data Lifespan (yrs)


X-TOS Attribute "data lifespan" performance vs cost for High Pareto Trace designs
XTOS all
2471
903
967
1687
2535
Xbest
Xworst
data lifespan
Cost
x 10^7


Pareto Trace Latitude Diversity
Utility
Latitude Diversity (deg)


X-TOS Attribute "latitude diversity" performance vs cost for High Pareto Trace designs
XTOS all
2471
903
967
1687
2535
Xbest
Xworst
latitude diversity
Cost
x 10^7


Pareto Trace Equator Time
Utility
Equator Time (hrs)


X-TOS Attribute "equator time" performance vs cost for High Pareto Trace designs
XTOS all
2471
903
967
1687
2535
Xbest
Xworst
equator time
Cost
x 10^7

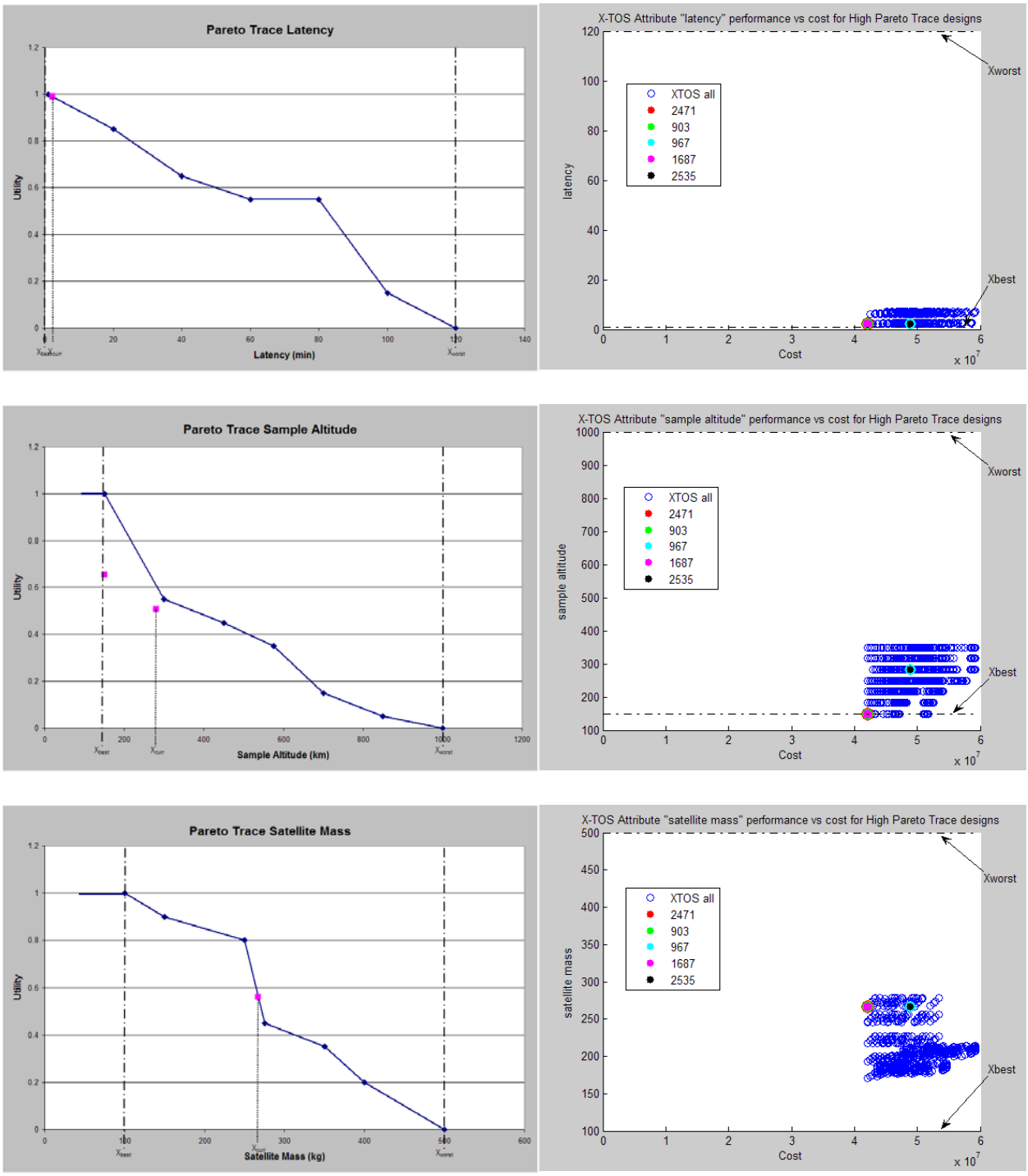


Figure 83 X-TOS Attribute value to Utility function mappings for all six attributes, with High Pareto Trace designs indicated

Inspection of Figure 83 reveals no obvious cause for these designs' apparent robustness. The change scenarios considered in the preference experiments did not alter the attribute levels of a given design, nor the acceptable attribute ranges, so the excess capacity argument is weak at best. Likewise, the flatness argument would have little effect, especially since the utility function shape was altered in one of the experiments. It appears these designs are in a sense "clever" and

happen to perform well for these considered context changes. More analysis should be done to discover if such performance could be predictable, and whether intentionally robust designs would score as highly as these "clever" designs.

The robustness of these designs is most likely the result of the confluence of the "physics" of the system design and performance, and the value-perception of the decision maker. Further study should be done to determine if the existence of such robust designs is guaranteed, or at least under what conditions such designs can be expected.[105]

7.2.1 Pareto Tracing

The technique of Pareto Tracing has been shown to be very useful for determining constancy of value across changing tradespaces. (See Figure 84 below for review of Pareto Trace Number definition.) Those designs appearing in all or most Pareto Sets represent options that deliver the most utility at a given cost (resource-level). Such efficient design choice enabled by Pareto Tracing is coincident with the goal of design described in 3.1. Examination of the physical similarities of designs in the Pareto Trace will give designers the ability to focus on key drivers of system value in response to a changing context.

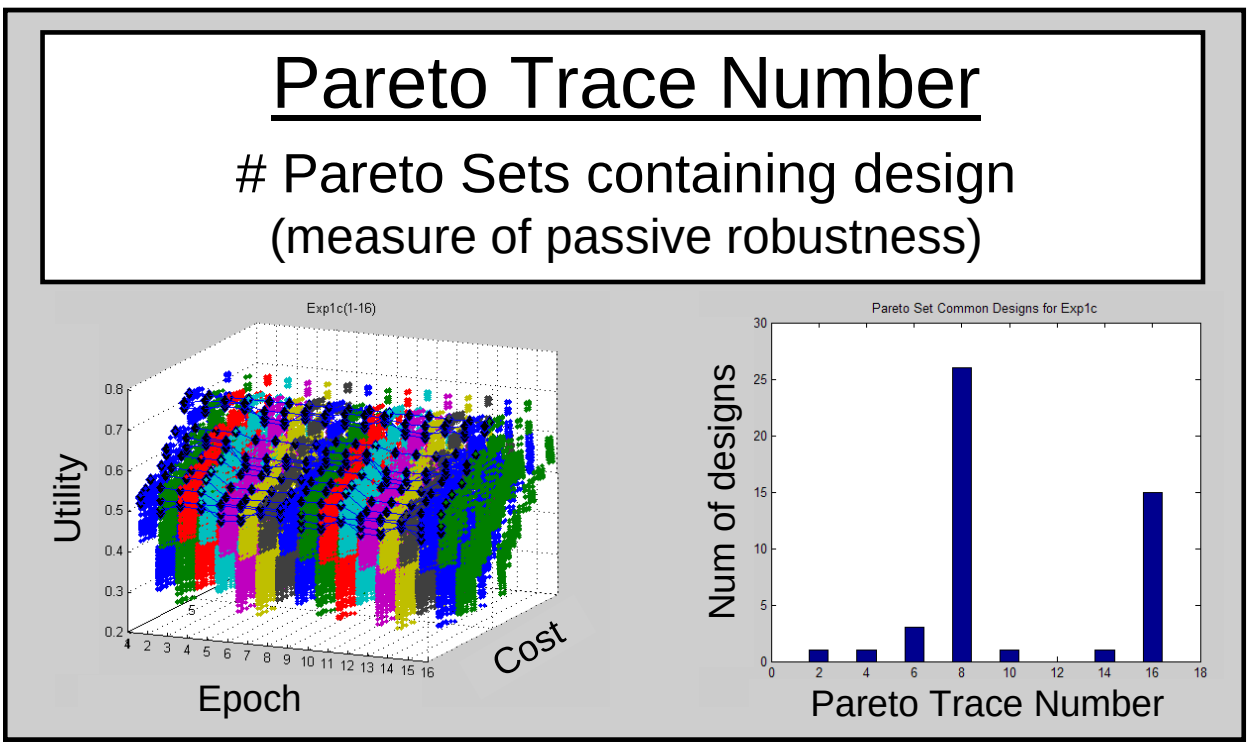


Figure 84 Pareto Trace Number definition

The Spearman Rho statistic is useful for gathering a high-level appreciation of the variation across two tradespaces. Its usefulness will be degraded however, when costs are no longer

[105] Further work should be done to uncover the true cause of the apparent robustness of these designs, including analysis of the utility functional form and mathematical effect of altering k_i and X^i.

assumed to be static, as will be the general case. Pareto sets are readily defined in such cases, but ranked lists are not (as an iso-cost utility listing).

The addition of multiple decision makers to the analysis has revealed some key issues. The first is the fact that the joint Pareto Set of two decision makers is greater than the union of the Pareto Sets of each individual decision maker. The additional design options are the "compromise" solutions that only exist in the context of a true value trade-off. As the number of distinct decision makers (and their diversity of preferences) goes up, the number of options within the Joint Pareto Set will increase, eventually encompassing the entire tradespace. While at first disturbing and non-obvious, this result can be seen in the marketplace for any good with more than one option. Inevitably, someone will find a particular good to be "best" value. In the limit of infinite shoppers, their diverse tastes will enable the creation of an infinite number of options that will enable each individual to find his best choice. In the case of a tradespace, the more decision makers, the better various options will look to different people.[106]

A simple solution to the problem of finding the best options for the group is to look for designs that exist in all Pareto Sets (the Pareto Trace). These options do not require much negotiation since it is clear they are efficient (value versus resource). Lower order Pareto Traces (those that do not touch all Pareto Sets, but rather a number less than "N"), could be the next best option to consider. Another option is to only look at the individual Pareto Sets for each decision maker and use those as the basis for direct negotiation between decision makers. The "compromise" set of options in the Joint Pareto Set will be better than the individual Pareto Sets since they are more "efficient" in terms of the group of decision makers, however the size of the "compromise" set will grow very large. The role of the analyst in these cases is to determine the proper trade-off between efficient value delivery and sheer size and complexity of the information needed to be conveyed for decision-making.[107]

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[106] A physical interpretation of this point is to consider a two-dimensional utility-utility tradespace. Suppose a third decision maker enters the set and his utility function differs from the original two. The displacement of each point into the third dimension does not depend on its value in the other two dimensions. As more decision makers are added, the possibility that a point will become highest utility at a given cost will increase. Since the Joint Pareto Set includes the individual Pareto Set options, the question can be posed alternatively as: Is it possible to define a utility function to move an arbitrary option i to the Pareto Front? The answer is yes. The only exception would be a hypothetical option identical to another option in ALL aspects except cost. In that case, that particular higher cost option would not be viewed as best under any utility transformation. In the real world, such identical, but costly, options probably do not exist. Likewise, the number of diverse preferences evaluating the system is bounded, but the insight into diverse evaluation remains useful.

[107] A note of caution should be made, however. Since space systems are typically developed by the government, the problem of cost-benefit distribution is a real one. Since Congress typically bears the cost, while others reap the benefit, Congress can impose an aggregation constraint onto the decision makers. This constraint takes the form of a required compromise under the threat of no funding for failure. If decision makers have directly counter preferences, it is possible to find a Joint Pareto Set that is equal to the sum of non-overlapping Individual Pareto Sets. This means no "compromise" solutions exist and the solutions will only satisfy a subset of the decision makers, violating the Congressional constraint. It is particularly important for the designer to elicit the value propositions of the decision makers early to determine if this "null compromise set" problem exists. If it does, early revelation can reduce the time and effort wasted on development that will be scrapped once Congress (or the Funder) discovers the violated group benefit constraint. Instead, time can be spent trying to discover mutually valuable aspects to add to the system in order to create "compromise" solutions, linking the Individual Pareto Sets and satisfying the decision maker set.

Chapter 8: Dynamic MATE Analysis

This chapter will attempt to encapsulate dynamic MATE analysis into a framework and process, while addressing the motivating research questions posed in section 1.2.1. Where possible, examples of concepts will be applied to the X-TOS project to provide continuity and relevance to the reader.[108] Chapters 9 and 10 will provide additional application cases of the methods described in this chapter to the real world systems Joint Direct Attack Munition (JDAM) and Terrestrial Planet Finder (TPF).

8.1 Overview

As motivated by prior chapters, the following is a high level overview of the dynamic MATE analysis process:

Classic MATE

- Identify problem, constraints, and decision makers
- Define attribute-space: $\{X^M\}$
- Define tradespace: $\{DV^N\}$
- Develop simulation/models: $F_{XM} : \{DV^N\} \rightarrow \{X^M\}$
- Develop cost models: $f_c : \{DV^N\} \rightarrow C$
- Develop utility models: $f_u : \{X^M\} \rightarrow U$

Tradespace Network Analysis

- Define transition rule set: $\{R^K\}$, where $R^k \in \{R^K\}, R^k : DV_i \rightarrow DV_j$
- Develop tradespace network: $\boldsymbol{T}:T_{ijk}$

Temporal Strategy

- Codify system dynamic context
- Specify baseline (start) design (including empty set if designing from scratch)
- Find min cost/time or max utility path from baseline to all other designs in tradespace

In order to organize and focus the key parameters for dynamic MATE analysis, a Design-Value Matrix can be used. Figure 85 below shows a high level view of the Design-Value Matrix, or DVM. While at first a bit overwhelming in terms of amount of information, the DVM can provide useful insights to the designer and help to track design-space to value-space mappings. Along the rows of the matrix are three categories: Decision Makers, Design Variables, and Path Enabling Variables. Across the columns of the matrix are three categories: Value-space Parameters, Design-space Parameters, and Resources. The value-space parameters are broken down into separate columns for each attribute within each class of value. The design-space parameters include the design and path-enabling variables. The resource parameters include cost, time or whatever other resource needs to be tracked. Two types of relationships can be tracked in the DVM: existence, and change type. Existence can take three values: present, potential, or absent. Change type can take on six values: increase/decrease, increase, decrease, add/subtract,

[108] The X-TOS project, a low altitude atmospheric science mission, was conducted in Spring 2002 in the MIT graduate space system design course and is described in Ross 2003. The validated X-TOS model calculated the science user attributes and used a CER-based cost model.

add, or subtract. The increase/decrease scale relates to scalability type changes, while add/subtract relates to modifiability type changes. The process of filling in the DVM will be discussed in the following sections.

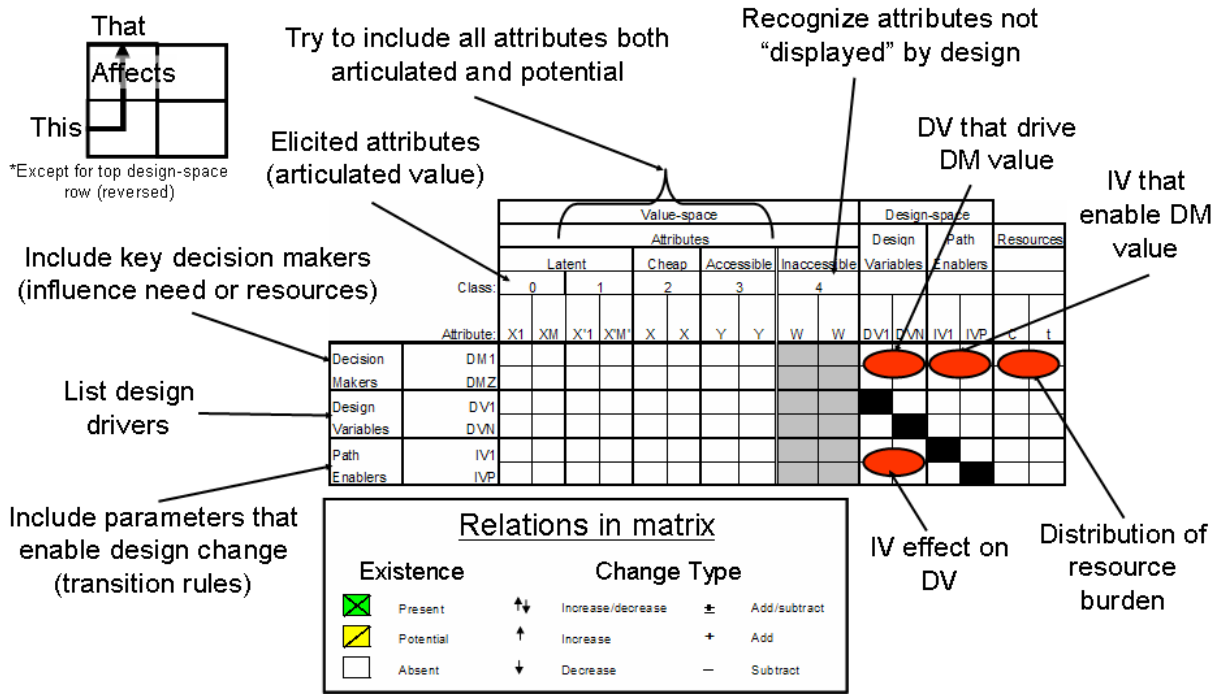


Figure 85 The Design-Value Matrix

8.2 Thinking and Deciding: Defining the Dilemma

Revisiting the concepts discussed in section 4.1, "Thinking and Deciding," the beginning of any dynamic MATE analysis process requires the analyst to recognize the driving question, problem, or dilemma. Inherent in finding the dilemma is the need to identify the important decision makers for the to-be analyzed system. Discovering the dilemma may require discussions with the key decision maker(s), or at least a proxy representative. The analyst must recognize that any goals derived for solving the dilemma may change with time, as the decision maker's thinking changes. Those changing goals, and their associated possibilities are the attributes and design concepts of the MATE process.

A key artifact to create at this stage is the mission statement, including an overall description of the stakeholders and the driving problem to be addressed by the system design. The scope of the problem should be explicitly stated, as this document will provide the foundation for the problem-solving endeavor and will be used as a basis for design and process decision-making.

8.2.1 Additions to DVM

The first row category should be filled out, including present and potential decision makers for the system. Figure 86 below shows the entries on the matrix.

Design-Value Matrix		Value-space										Design-space					
		Attributes										Design		Path		Resources	
		Latent				Cheap		Accessible		Inaccessible		Variables		Enablers			
	Class:	0		1		2		3		4							
	Attribute:	X1	XM	X'1	X'M'	X	X	Y	Y	W	W	DV1	DVN	IV1	IVP	C	t
Decision Makers	DM1																
	DMZ																
Design Variables	DV1																
	DVN																
Path Enablers	IV1																
	IVP																

Figure 86 DVM with Decision Maker set entered

8.2.2 Expected Output

Problem/Dilemma in the context of a mission statement
Set of key decision makers {DM}

8.2.3 Application to X-TOS

For the X-TOS mission, the key dilemma was the need to fly an already designed payload in low earth orbit, penetrating the atmosphere. The payload was designed to take in-situ atmospheric density measurements. The principal decision maker was the payload designer, who was identified as the system User. The mission statement, as stated in (Ross 2003), was:

> *"design a conceptual space-based space system to characterize the upper atmosphere, with specific emphasis on the thermosphere and ionosphere. Building upon lessons learned from A-TOS and B-TOS, develop an architecture for the space system by March 22, 2002; building upon lessons learned from C-TOS, complete a preliminary design of this architecture by May 15th, and link this preliminary design back to the process used for the architectural study. Learn about engineering design process and space systems."*

The A-TOS, B-TOS, and C-TOS projects were satellite systems, for ionospheric sampling, designed by graduate student teams over the course of Summer 2000 to Summer 2001.[109] The actual dilemma being solved by the mission statement reflects the multiple decision maker context of the project. Firstly, the science user, embodied by the payload scientist, was in the role of key decision maker for the project. The design team itself was in the role of Designer and clearly had preferences that shaped the mission statement in terms of educational goals and limited temporal resources. Implicit in the statement are fidelity statements reflecting the limited resources available to the class (the reference to the level of output from the B-TOS and C-TOS projects reflected an output expectation on amount of time and effort required for the project). An additional decision maker not explicitly included in the mission statement is that of the

[109] For a detailed discussion of the A-, B-, and C-TOS missions and their relation to MATE, see Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design.

faculty, which have desires on student effort and achievement for the project. The class did, in fact, explicitly discuss these three categories of decision makers, but decided to make the class and faculty value propositions into constraints on the class process and products (schedule, effort, and expected deliverables).

The DVM with X-TOS decision makers is shown in Figure 87.

Design-Value Matrix			Articulated						Already present					Almost present				Modifiably present																DV to value									IV to value				Resource impact			
X-TOS			Attributes																															Design Variables									Path Enablers				Resources			
			Latent											Cheap				Accessible					Inaccessible																											
		Class:	0						1					2				3					4																												
		Attribute:	X1	X2	X3	X4	X5	XM	X6	X7	X8	X9	XL	X	X	…	X	Y	Y	Y	…	Y	W	W	W	W	…	W	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DVN	IV1	IV2	IV3	IVP	C	t		
Decision Makers	User	DM1																																																
	Customer	DM2																																																
		DMZ																																																	
Design Variables		DV1																																																	
		DV2																																																	
		DV3																																																	
		DV4																																																	
		DV5																																																	
		DV6																																																	
		DV7																																																	
		DV8																																																	
		DVN																																																	
Path Enablers		IV1																																																	
		IV2																																																	
		IV3																																																	
		IVP																																																	

Figure 87 X-TOS DVM with DMs added

8.3 Setting the Boundaries: Context and Constraints

Once the decision makers and dilemma have been defined, the next step is to consider the context in which the decision makers and potential system reside, and any constraints that will shape the solutions created by the design effort. Constraints are usually more explicit and easier to characterize, so begin with those. Constraints, as defined in the optimization literature are requirements that a problem must satisfy in order to be feasible. These limitations are concrete boundaries on resources used, designs considered, or demand met. Constraints can take the form of physical or functional, and can be nature-defined, or human-defined. Constraints may be static, or dynamic. The nature of identified constraints must be carefully tracked, since movement of a "binding" constraint can significantly change the "best" outcome for a particular problem.[110]

It is important to note that often a designer will consider some design parameters as "constants" since they do not greatly affect a particular analysis. It is important to keep track of which constants are really constant, and which are only assumed to be so. A useful dichotomy to consider is the distinction between designer controllable constants and designer uncontrollable constants.

[110] A binding, or active, constraint is one that is actively limiting a particular problem solution. Non-binding, or inactive, constraints do not affect a particular problem solution. For example, if a person were at a fast food restaurant and was trying to pick an item from the menu, all options may be open since the person has plenty of money. On the other hand, if the same person were at a fancy restaurant, some of the pricier fares may not be feasible due to their expense. The amount of money available for food choice is a non-binding constraint in the first example, and a binding one in the second.

The context of a system is technically everything outside of a system's boundary. The context includes the operating environment, as well as the origin of inputs and the destination of outputs. Since the context can affect the nature of the inputs and the interpretation of the outputs, designers need to be cognizant of contexts that may affect the value of the system being designed. Since the context is by definition outside of the designer's control, it can be a source of tremendous uncertainty for the system. Understanding how the system value changes in relation to the context will be a key part of the dynamic MATE process defined later.

Potential contexts to define include market, policy, technology, physical and operations environment. The market context includes consideration of economic competitors, funding issues, and relationship of system to other systems within the client organization, among others. The policy context includes consideration of rules, regulations, laws, and policies, both national and international, public and private, that may constrain or enhance development or operation of the system. The technology context includes both current and future technology possibilities and their relationship to current and future system capabilities, as well as system interactions with external systems. The physical context relates to the actual physical interactions of the world with the system, both in development and operations, including issues such as manufacturing, testing, and launch. The operations environment context includes informational flows between the system and the users and operators, including issues such as interface standards, radiation environments, and availability of system oversight and repair.

8.3.1 Additions to DVM

While no place currently exists on the DVM for constants and constraints, it is possible that some design variables are deemed "constant" for the particular design due to lack of effect on present attributes. Their inclusion might relate to effects on potential attributes, however, and should be tracked if the designer wishes to understand how a system can deliver potential value as well as present value.

8.3.2 Expected Output

List of active constraints
Description of expected context, including market, policy, technology, physical and operations environment

8.3.3 Application to X-TOS

The active constraints for X-TOS included constraints both on the design itself and the process of designing. The design constraints related to proper physical and environmental interactions with the already-designed payload (including the requirement to sample in-situ). The design process constraints related to the limitations on time, effort, and knowledge available to the class for the project. One semester was allocated to the project, with a fixed class size of approximately 16 students. No additional funding beyond student personal resources were allocated, though the students did have access to a computer lab with needed analysis software, as well as access to several domain experts.

The expected context for the system itself included the constraint of being a U.S. government payload, requiring a U.S. launch vehicle. The launch vehicle constraint was initially found to be a binding constraint, reducing the availability of higher value solutions at higher cost.[111]

8.4 Value Accessibility: Classifying the Attributes

Given the decision makers identified, and the expected context for the system, the next step in the analysis is to determine the attribute set. (Ross 2003) discusses the process of attribute elicitation from decision makers. (Keeney 1992) also discusses the process of value articulation and eliciting value objective hierarchies at length. The dynamic MATE analyst, however, does not stop at the articulation of attributes.

Recognizing that attributes could change, it may be useful for the analyst to discuss possible future scenarios that may result in new or changed attributes. The current articulated attribute set, if realizable through a system design, are classified as class 0 attributes. Potential attributes uncovered through scenario-change discussions can be placed into class 1 or class 2 attributes for consideration during concept generation.

Once the analyst feels that he has a complete set of attributes, those attributes should be analyzed for decomposability. Identification of fundamental attributes increases the likelihood of developing a changeable, or at least value-enhancing system.

8.4.1 Additions to DVM

The first column category should be filled out, including placement of attributes into their possible class. Without the design specified, however, exact classification is impossible. Marks can at least be placed in each decision maker row indicating which attributes that decision maker has in his attribute set. Figure 88 shows the DVM locations of the new additions.

Design-Value Matrix		Value-space										Design-space					
		Attributes										Design		Path		Resources	
		Latent				Cheap		Accessible		Inaccessible		Variables		Enablers			
	Class:	0		1		2		3		4							
	Attribute:	X1	XM	X'1	X'M'	X	X	Y	Y	W	W	DV1	DVN	IV1	IVP	C	t
Decision Makers	DM1																
	DMZ																
Design Variables	DV1																
	DVN																
Path Enablers	IV1																
	IVP																

Figure 88 DVM with Value-space (attributes) added into columns, and DM interest marked in proper row

[111] According to the initial user preferences, a clear "Best" solution was shown to exist (highest utility and lowest cost in the tradespace). Analysis of the data revealed the launcher constraint prevented better designs from being considered. (See pp. 98 of (Ross 2003) for discussion of the constraint.)

8.4.2 Expected Output

Definition of attribute set (for each decision maker) $\{X^M\}$
Classification of attributes, including potential strategy for expanding class 0 and/or 1.

8.4.3 Application to X-TOS

The attributes from the X-TOS mission were {Data Lifespan, Latitude Diversity, Equator Time, Latency, and Sample Altitude}. The attribute best (most acceptable) and worst (least acceptable) values and units are given in Table 8. These attributes are the class 0, or articulated value, attributes for the mission. No other attributes were initially considered by the original design team. Further dynamic MATE analysis, however, added the following attributes: {Satellite Mass, Initial Operating Capability Cost, Development Time, and Satellite Lifetime}. These attributes are class 1, or free latent value, and are listed in Table 9.

Table 8 X-TOS User Attributes (class 0: articulated value)

Attribute	Best	Worst	Units
Data Lifespan	132	0	Months
Latitude Diversity	180	0	Degrees
Equator Time	24	0	Hours
Latency	1	120	Hours
Sample Altitude	150	1000	Kilometers

Table 9 X-TOS Customer Attributes (class 1: latent unarticulated value)

Attribute	Best	Worst	Units
Satellite Mass	100	1000	Kg
Initial Operating Cap Cost	0	100	$M
Development Time	0	3	years
Satellite Lifetime	20	0.5	years

The DVM has been filled in with these values and is shown in Figure 89.

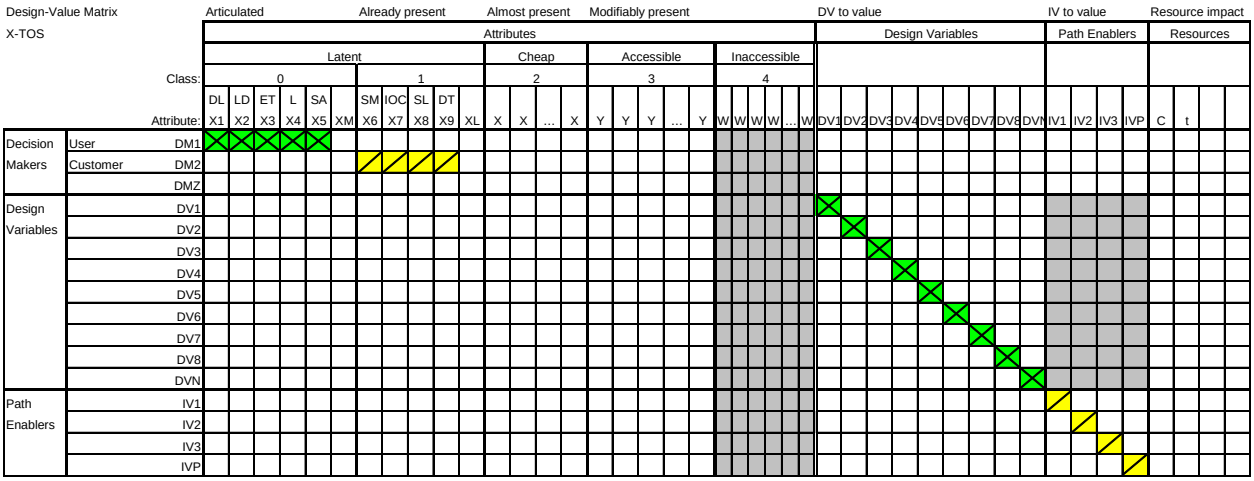


Figure 89 X-TOS DVM with attributes added

8.5 Creativity : The Science and Art of Design

The traditional MATE focus on concepts generated through consideration of the attributes now has an expanded scope. While the designer should focus on the currently articulated value for generating the primary system concepts, potential attributes should also be considered, as long as the cost associated with doing so is communicated to the decision maker[112]. Generating design solutions that deliver value both expressed and unexpressed is not a scientific or deterministic process. Engineering expertise, experience, and creativity guide the genesis of solutions. Focusing the effort within a guiding framework may make the process more efficient and accessible to designers.[113] The non-unique mapping of capability to physical systems means that no unique solution exists to the problem of design. Focused creative processes, such as TRIZ can be used, however no one process can ensure the "best" design creation, hence the "art" of design.

8.5.1 Additions to DVM

Brainstorming of relationships from the attributes to design variables should be started in this stage, including from potential attributes as well.

8.5.2 Expected Output

Structured plan for attribute-driven design process

8.5.3 Application to X-TOS

The process followed by the initial X-TOS project involved a brainstorming session using the user attributes as drivers. Various concepts were proposed, including ballistic payload carriers, tethered payloads, satellites, and high-flying aircraft. Two main constraints limited the class's ability to create concepts to carry forward in the analysis: the first was the requirement to fly the user payload in-situ through the atmosphere, precluding any concepts that do not actually fly through the atmosphere. The second was the resource constraint on the class's available time and expertise: non-mainstream concepts, such as ballistic payloads, would require too much time and effort to analyze in the amount of time available and were thus deemed infeasible for the mission.

8.6 Concepts: Design Variables

The design variables are the designer-controlled quantitative parameters that reflect some aspect of a concept, which taken together as a set define a system design or architecture. The design variable set represents the actually tradable parameters within the purview of the designer. Factors that cannot be changed do not belong within the design variable set. Likewise, factors beyond the control of the designer (or the decision makers) should not be included in the design variable set. At this time the designer can consider possible mechanisms that would allow one instantiation of the design variable set to change into another. For example, suppose the design variable set includes the following: {orbit altitude, orbit inclination, amount on-board fuel for delta_v}. If a particular design has the value: {800 km, 23 deg, 300 m/s} and a different one has

[112] The costs for increasing the scope of design include the time and resources required for analysis of more design options, as well as the potential accusation of designing a system for needs not yet (or possibly ever) expressed. Most people do not want to pay for unused capabilities. The cost of "carrying" unused options is a common dilemma for real options analysts.

[113] Chapter 6, Concept Generation, of Ulrich and Eppinger. Product Design and Development. gives good suggestions on mechanisms for focusing creativity during design concept generation.

{1100 km, 23 deg, 100 m/s}, what is the mechanism to allow the first system to turn into the second one? Transition rules, R^k, are proposed by looking at the design variables and considering how one, or a combination, can vary, including the resulting costs for the change.

Derivation of the design variables follows from explicit consideration of how a system can be created to "display" the attributes desired. The word "display" attempts to reflect the idea that attributes can be on either form or function. If the system incorporates the form attributes and does the function attributes, then it is said to "display" those attributes. It is entirely possible, in fact likely, that a system will "display" attributes that are not in the decision maker(s)' articulated attribute set. Those "displayed" attributes that are not class 0 attributes are now classified as class 1 attributes. The MATE analyst should attempt to capture the class 0 and class 1 attributes and brainstorm possible class 2 attributes, which can be "displayed" by the system through some translation engine. Identification of class 0, 1, and 2 attributes will occur most naturally at this stage, though other class 1 and 2 attributes will most likely be added at a later time as well.

Utilizing a *DV-X* QFD, as described in (Ross 2003), helps to focus consideration on design variables that most strongly result in the "display" of class 0 attributes. An expanded QFD incorporating class 1 and 2 attributes could be used, but design variables that do not directly affect the class 0 attributes should not be kept in the design variable set. The expanded QFD is actually a part of the Design-Value Matrix as depicted in Figure 85.

Once the design variable set and attribute sets are defined, the mapping of design variables to attributes can be developed. The model, or simulation, necessary for the mapping can range from simple, low fidelity relations to complex, time-based simulations requiring many hours to run. The appropriate fidelity chosen for the mapping must consider carefully the resources available for the analysis, and the mechanisms available for proper model validation.

Once the mapping relation has been completed, the tradespace can be run and data generated over a large range of design vector instantiations and their attribute levels. The resulting data will form the basis for the following changeability analysis. It is assumed that the generated tradespace contains the universe of possible designs[114]. The tradespace has the ability to compare vastly different concepts on the same terms: utility and cost[115].

8.6.1 Additions to DVM

At this stage, the design variable row category should be filled in. Various concepts, which include different design variables, can be included in the same or different matrix, depending on the designer's tastes. Attributes that can be "displayed" by the current set of design variables can now be placed into class 0 or 1, depending on whether present decision makers have them in their attribute sets. Other class 2 and 3 attributes can be brainstormed and classified based on the proposed design variables. Figure 90 shows the DVM with the design variable section highlighted. Additionally, the design-variable columns can be added to the right side of the matrix, in the "Design-space" section as indicated.

[114] If additional designs were to be considered, they can readily be added to the dataset and do not affect the logic of the following analysis. The changeability analysis, however, will have to be rerun with the new tradespace.

[115] Elicitation of utility functions and development of cost functions is not discussed here. See (Ross 2003) for descriptions of these processes.

Design-Value Matrix		Value-space										Design-space					
		Attributes										Design		Path		Resources	
		Latent				Cheap		Accessible		Inaccessible		Variables		Enablers			
	Class:	0		1		2		3		4							
	Attribute:	X1	XM	X'1	X'M'	X	X	Y	Y	W	W	DV1	DVN	IV1	IVP	C	t
Decision Makers	DM1																
	DMZ																
Design Variables	DV1																
	DVN																
Path Enablers	IV1																
	IVP																

Figure 90 DVM with design variables rows and columns added and design variable-attribute relationships added in proper columns

8.6.2 Expected Output

Definition of concepts, including design variable set $\{DV^N\}$
DV-X QFD capturing *DV* generation rationale
Mapping of design concepts to attributes, $F_{XM}: \{DV^N\} \rightarrow \{X^M\}$
Cost and Utility mappings, $f_C: \{DV^N\} \rightarrow C$, $f_U: \{X^M\} \rightarrow U$
Preliminary transition rules describing connectivity of $\{DV^N\}$, $\{R^K\}$, $R^k: DV_i \rightarrow DV_j$

8.6.3 Application to X-TOS

The design variables considered by the X-TOS mission included {Inclination, Apogee Altitude, Perigee Altitude, Communication Architecture, Total On-board Delta-V, Propulsion Type, Power Type, and Antenna Gain}. Additionally, several mission design variables were considered, however, analysis revealed they added additional cost without improving the utility. The design variable set and their enumerated values are shown in Table 10 below. The valid number refers to the total number of designs out of the explored designs that were deemed "feasible" by the expert code screen.[116]

[116] An example of an infeasible design is one which has its apogee altitude less than is perigee. Dumb enumeration of all combinations of the design variables will result in some combinations that do not make physical sense. X-TOS designers created an expert screening code that flags infeasible designs and does not include them in the further analysis, saving precious computational time.

Table 10 X-TOS Design Variables

X-TOS DESIGN VARIABLES	RANGE
Orbital Parameters	
Inclination (degrees)	0, 30, 60, 90
Apogee Altitude (km)	200-2000
Perigee Altitude (km)	150-350
Physical Spacecraft Parameters	
Communication Architecture	TDRSS/AFSCN
Total Delta-V	200-1200
Propulsion Type	Electric/Chemical
Power Type	Fuel cell/Solar array
Antenna Gain	High/Low
Total # of Explored Designs = 7840 (3384 valid)	

The DVM with the X-TOS design variables is shown in Figure 91 below. The mapping of design variable influences on attributes is indicated by "present" marks, showing actual influences of currently considered design variables. "Potential" effects of design variables on the class 1 attributes are also indicated. If the class 1 attributes become articulated (move to class 0), the "potential" marks will change to "present" marks. The "present" versus "potential" categorization helps the designer keep the current value-added work separate from consideration of possible future value states.

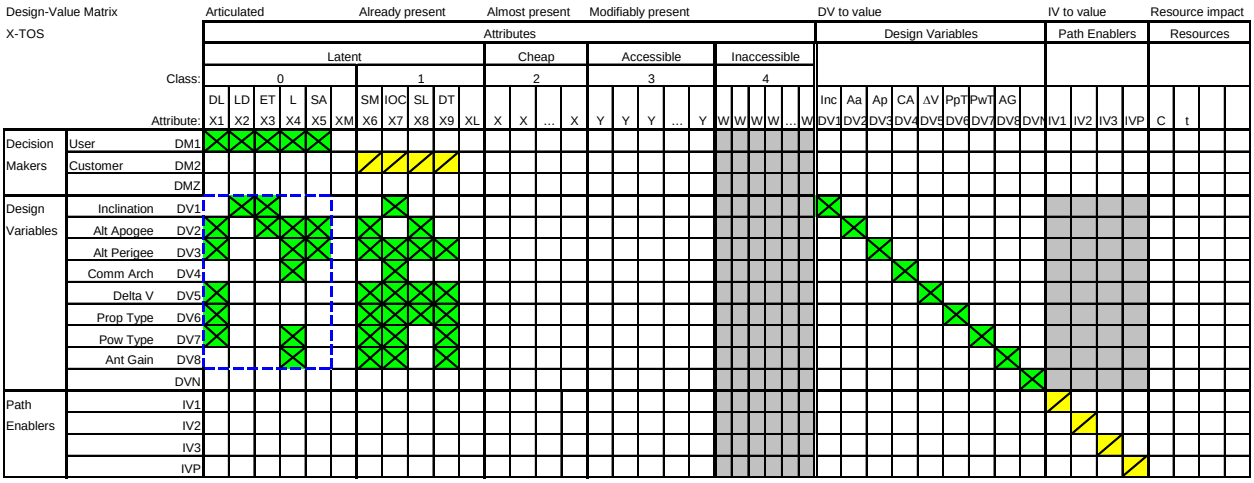


Figure 91 X-TOS DVM with design variables and their relationship to attributes added.[117]

The X-TOS model, including cost and utility functions, were developed in Matlab by the class over a two month period. (Ross 2003) discusses the details of the code.

[117] Blue dotted area encloses information included in MATE Design-Attribute QFD

8.7 Changeable Designs: Transition Rules and "Path-enabling" Variables

After the design variables are proposed, the next step is to propose mechanisms for design change. Consideration of how individual or groups of design variables could change is another act of design, similar in vein to initial concept creation. Change mechanisms can include present variables, as well as "enabling" variables that create the opportunity for change mechanisms. The transition rules are the specification of how one design can be changed into another.[118] Each transition rule takes into account a subset of the design variables, potentially including the enabling variables as well, specifying the "cost," or resources needed, for the transition. An example of a transition path from one state to another includes "spending" down one variable in order to get an increase in another, or "spending" down an enabling variable.

In order to help visualize and generate each rule, a Rule-Effects matrix can be created, with rows as proposed rules, and columns as the design and path-enabling variables. An entry in row *i*, column *j* means that for rule *i*, the corresponding change in design variable *j* will occur, with the presence of the appropriately marked path-enabling variable, *IV*. An example Rules-Effects Matrix (REM) is shown in Figure 92.[119] Both scalable and modifiable changes (variable level and existence) can be represented in the REM. Summation of effects by path-enabling variable will be captured in the DVM path-enabling to design variable submatrix. For modeling and design purposes, path-enabling variables should be treated similar to design variables. Instead of driving the "display" of attributes, however, path-enabling variables drive the "ability" to change. The effect on design variables by the existence of path-enabling variables will be dependent on the system architecture, just as the effect the existence of current design variables have on other design variables. Switching path-enabling variables "on" may have a discontinuous effect on the non-enabled design (e.g., turning "on" tugability for a satellite may entail the addition of grapple points and advanced attitude determination and control subsystems, unnecessary in the non-tugability enabled satellite system.)

Rule-Effects Matrix		Design Variables				Path Enablers				Change Origin	
		DV1	DV2	…	DVN	IV1	IV2	…	IVP	Flex	Adapt
Rules	R1										
	R2										
	…										
	RK										

Scalability

↑↓	Increase/decrease
↓	Decrease
↑	Increase

Modifiability

±	Add/subtract
+	Add
–	Subtract

Figure 92 The Rules-Effects Matrix (potential relationships: scalable or modifiable, origin: flexible or adaptable)

8.7.1 Additions to DVM

The Path-Enabling Variable row category can now be filled in, marking the change type relationship to each design variable as indicated in Figure 93.

[118] For an example of transition rules applied to the Space-Based Radar (SBR) system, see section 7.6 of Roberts. Architecting Strategies Using Spiral Development for Space Based Radar.

[119] Additional REM examples are given in the X-TOS application section and Chapters Chapter 9: and Chapter 10:.

Design-Value Matrix		Value-space										Design-space					
		Attributes										Design		Path		Resources	
		Latent				Cheap		Accessible		Inaccessible		Variables		Enablers			
	Class:	0		1		2		3		4							
	Attribute:	X1	XM	X'1	X'M'	X	X	Y	Y	W	W	DV1	DVN	IV1	IVP	C	t
Decision	DM1																
Makers	DMZ																
Design	DV1																
Variables	DVN																
Path	IV1																
Enablers	IVP																

Figure 93 DVM with path-enabling variables entered into rows and columns, with appropriate relation ship to design variables entered

8.7.2 Expected Output

Proposed list of path enabling variables $\{IV^P\}$
Expanded design tradespace $\{DV^N|IV^P\}$
Additional transition rules incorporating enabling variables, $\{R^L\}$
Expanded rule set $\{R^K|R^L\} = \{R^{K+L}\}$

8.7.3 Application to X-TOS

Eight transition rules were proposed for the X-TOS mission based on analysis of the design variable set. Three rules were internally motivated, thus adaptable. Five rules were externally motivated, thus flexible. The rules are listed in Table 11 below. These rules then suggested "path-enabling" variables that allowed the rules to occur. In particular the path-enablers were used to allow for the flexible changes. These path-enablers were {refuelable, tugable, upgradeable}. Figure 94 below shows the transition rules in a REM for the X-TOS example, including both the eight actual and three potential. (It was assumed for this analysis that existence of the path-enabling variables did not increase system cost. For more accuracy, the costs of the path-enablers should be considered, as well as their effect ("on/off") on the design.)

Table 11 X-TOS Used transition rules

Rule	Description	Change agent origin
R1: Plane Change	Increase/decrease inclination, decrease ΔV	Internal (Adaptable)
R2: Apogee Burn	Increase/decrease apogee, decrease ΔV	Internal (Adaptable)
R3: Perigee Burn	Increase/decrease perigee, decrease ΔV	Internal (Adaptable)
R4: Plane Tug	Increase/decrease inclination, requires “tugable”	External (Flexible)
R5: Apogee Tug	Increase/decrease apogee, requires “tugable”	External (Flexible)
R6: Perigee Tug	Increase/decrease perigee, requires “tugable”	External (Flexible)
R7: Space Refuel	Increase ΔV, requires “refuelable”	External (Flexible)
R8: Add Sat	Change all orbit, ΔV	External (Flexible)

Rule-Effects Matrix			Design Variables								Path Enablers			Change Origin	
X-TOS			Inc	Aa	Ap	CA	ΔV	PpT	PwT	AG	Rf	Tg	Up		
			DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	IV1	IV2	IV3	Flx	Adp
Rule	Plane change	R1	↑↓				↓								X
	Apogee burn	R2		↑↓			↓								X
	Perigee burn	R3			↑↓		↓								X
	Plane tug	R4	↑↓									X		X	
	Apogee tug	R5		↑↓								X		X	
	Perigee tug	R6			↑↓							X		X	
	Space refuel	R7					↑				X			X	
	Add sat	R8	↑↓	↑↓	↑↓	↑↓	↑↓							X	
Potential Rules	Sat Up: Power	R9							↑↓				/	/	
	Sat Up: Prop	R10						↑↓					/	/	
	Sat Up: Ant Gn	R11								↑↓			/	/	

Figure 94 X-TOS REM listing both actual and potential rules for the analysis. Requirement for enabling variables indicated, as is change type by origin

The X-TOS DVM with path-enabling variables is shown in Figure 95 below. Included in this step is marking the nature of the relationship between the path-enablers and the design variables. Relationships include adding or deleting design variables, or changing the level in a design variable (modification or scaling of the design variable set, respectively). Once the “path-enabler to design variable” relationship is captured, the “path-enabler to attribute” relationship can be inferred based on the “design variable to attribute” relationship (see bottom left of DVM showing “path-enabler to attribute” relationship). Additionally, decision maker interest in design variables and path enablers can be inferred by the latter’s connection to attributes of interest.

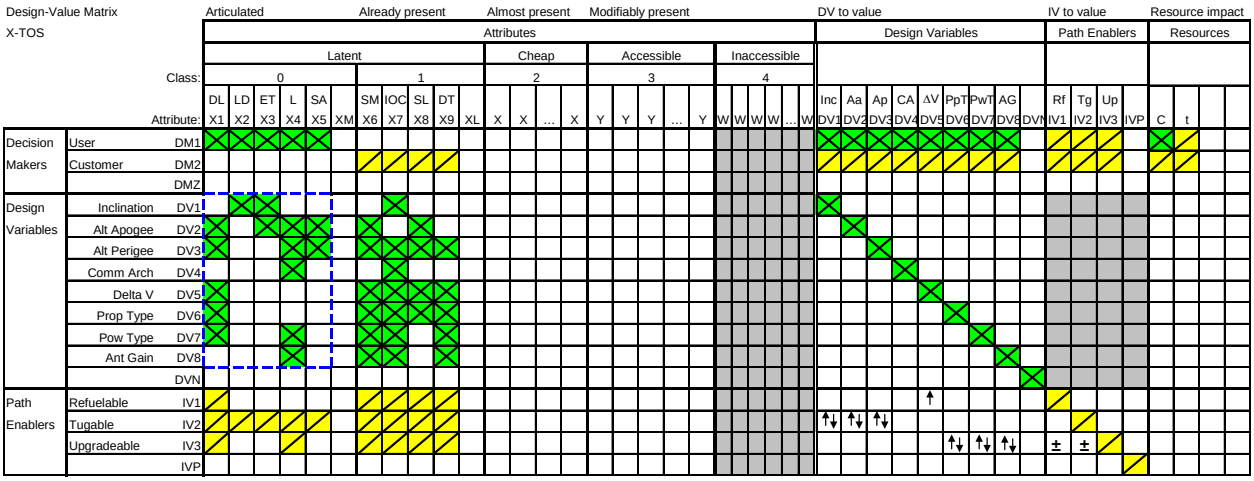


Figure 95 X-TOS DVM with path enabling variables added to rows and columns. Additional mappings of path-enablers to design variables capture REM relationships

8.8 Applying Transition Rules and Paths: The Accessibility Matrix and the Tradespace Network

After the design-space, value-space, and transition rules have been defined, the rules can be applied to the design-space in order to determine the connectivity of the space. The accessibility matrix, T_{ijk}, contains the "cost" for transitioning from design i to design j using rule k. The matrix is actually a tensor of dimension n x n x K, where n is the number of designs in the tradespace and K is the number of rules. In practice, "cost" is often taken to mean dollars and time. In this case, two T_{ijk} tensors are needed: $T_{ijk}^{(cost)}$, and $T_{ijk}^{(time)}$. For "free" transitions, a "small number" should be used since values of zero indicate inaccessibility. For reasons of computational efficiency, sparse matrices should be used when possible since the size of the matrix can grow very large (e.g. the X-TOS tradespace of 3384 designs and 8 rules has a 9.2×10^7 element T_{ijk}.)

The creation of the transition matrix must follow the application of an algorithm that looks at all elements of the tradespace and determines if a particular transition rule applies. Judicious use of code loops must be considered to keep runtime to a reasonable bound. Dynamic creation of a sparse matrix, while only following calculations if a rule is possible can keep the algorithm to $O(Kn^2)$ and memory requirements at a minimum. In practice the accessibility matrix is often sparse to the order of 1% full, which reduces the computational burden by two orders of magnitude.

An important distinction of this method over typical network analyses is the existence of heterogeneous links. The nodes in the network are the design points, while the directed arcs are the allowed transition paths. Note that the maximum number of arcs is $m=Kn^2$. Each arc has both a cost and time associated with it, as well as rule number. All of the arcs need to be tracked because the cost and time of a rule may change over time (due to technology improvements, for example), and because the strategic goals for a decision maker can vary from minimizing time for transitions, to minimizing cost for transitions, to some combination of the two.

In fact, using a network algorithm, such as the modified correcting algorithm, it is possible to specify paths from any node to all other nodes in the tradespace while adhering to a strategy of

the decision maker's choice.[120] Example strategies include finding the minimum cost, maximum utility, minimum time, or some combination of the three, path between any two nodes in the tradespace. In this way the designer can determine how to transition from a baseline design to another goal design in the tradespace, and evaluate that path in terms of utility, cost, and time.

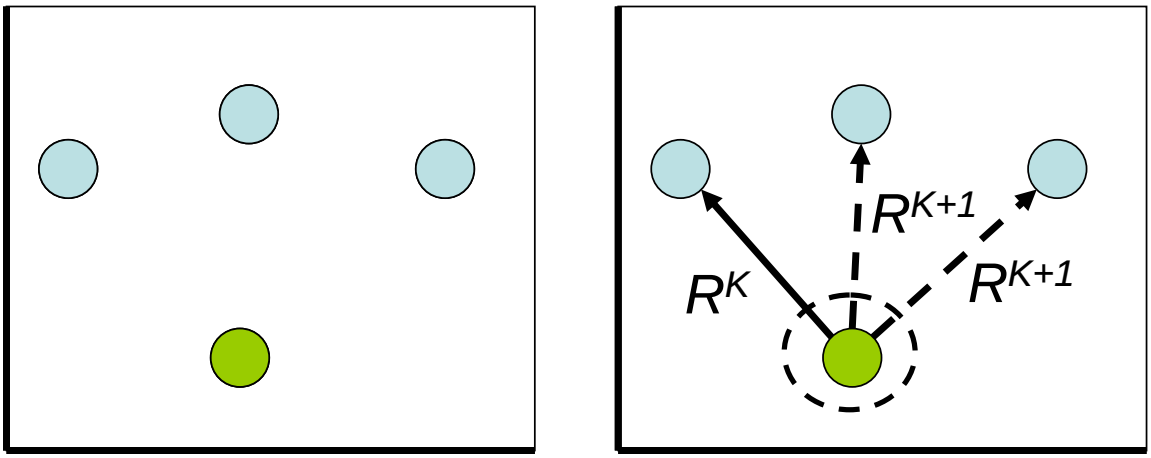


Figure 96 Tradespace (l) and Tradespace with Transition Paths (r)

As transition rules are applied to a tradespace, connecting arcs link designs that obey the rules. Figure 96 shows notionally the traditional tradespace with a tradespace connected by transition rules. Multiple rules can link the same two nodes, thereby increasing the potential change mechanisms to move from one design to a different design. The accessibility matrix captures all of the arcs connecting the design nodes for each rule.

8.8.1 Expected Output

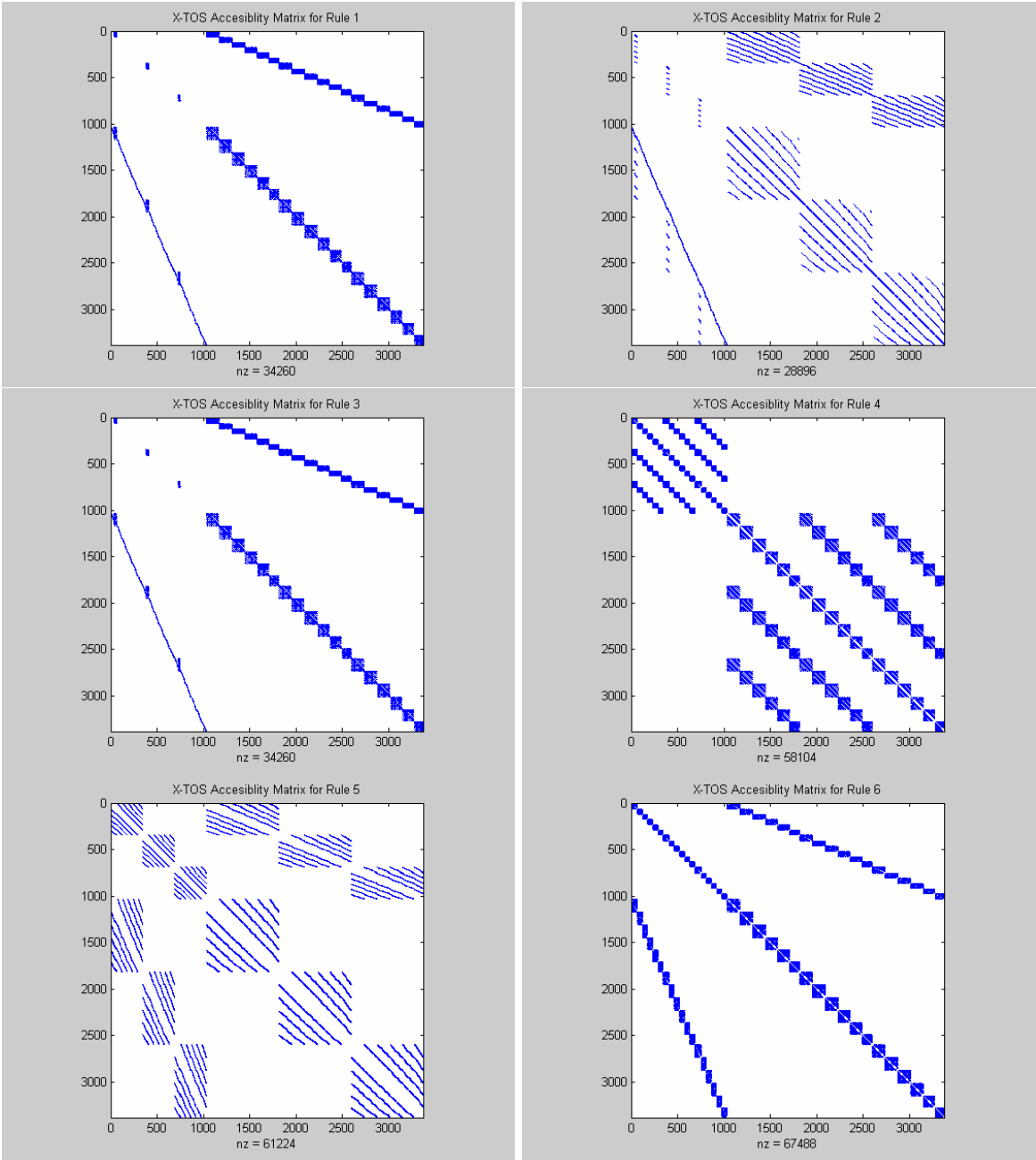
Algorithm for applying rule set to tradespace
Generation of accessibility matrix, T_{ijk}, $i,j = 1...n$, $k = 1..K+L$

8.8.2 Application to X-TOS

The eight X-TOS transition rules, mentioned in 8.7.2, were applied using a sequential logic algorithm that looked at all Kn^2 possible paths. Efficiency was achieved by using sparse matrices and rule exit conditions that prevented unnecessary computations if a rule was determined to be infeasible for a particular path between design i and design j. During each rule applicability step, an entry in $T_{ijk}^{(cost)}$ is made equal to the cost of the transition from i to j using rule k. A "free" transition is assigned the value of 10^{-6}. Likewise, an entry in $T_{ijk}^{(time)}$ is made equal to the time of the transition from i to j using rule k. A "spy_k" plot depicts the accessibility matrix T_{ij} for rule k, with a dark mark representing the existence of a connection between design i and design j. Figure 97 below shows the spy plots for $T_{ijk}^{(cost)}$ for rules 1 to 8. Recall rules 1 to 3 are adaptable changes, while rules 4-8 are flexible changes. The value nz is the number of nonzero entries in the matrix. Table 12 below gives the density fraction for each of the rules (fraction of tradespace connected). Two instances of rule 8 were investigated: rule 8 allowed only replacement of identical satellites in the same orbit (in essence, an expensive refueling option); rule 8b allowed

[120] See example algorithms, including the modified label correcting algorithm in Ahuja, Ravindra K., Thomas L. Magnanti, et al. (1993). Network Flows--Theory, Algorithms, and Applications. Upper Saddle River, NJ, Prentice Hall.

only replacement of identical satellites, but allowed orbit changes (in essence, a satellite replacement option, enabling mission change). Both rules assumed the replacement satellite to be identical to the original (including the ability to reproduce the original satellite within 6 months).



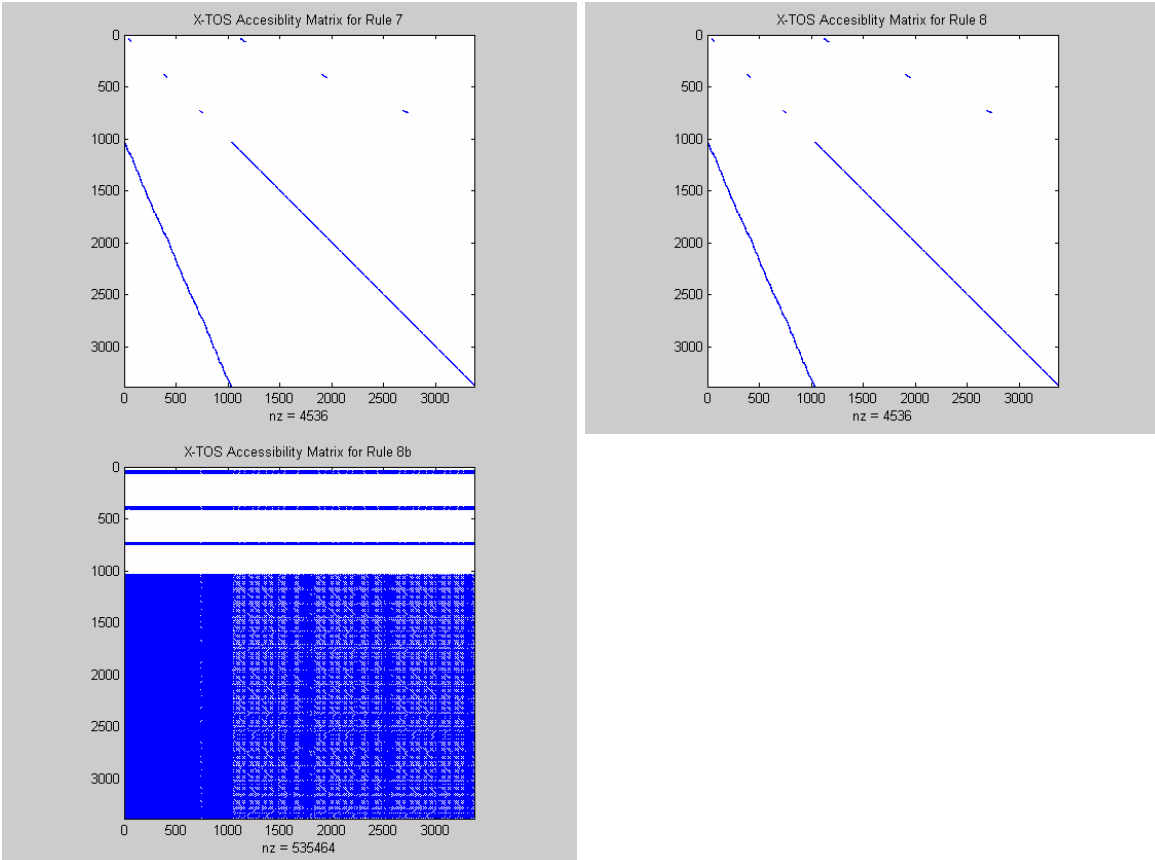


Figure 97 X-TOS Accessibility Matrix sparsity plots

Table 12 X-TOS Accessibility Density

Rule	Fraction Tradespace Connected
R1: Plane Change	0.30%
R2: Apogee Burn	0.25%
R3: Perigee Burn	0.30%
R4: Plane Tug	0.51%
R5: Apogee Tug	0.53%
R6: Perigee Tug	0.59%
R7: Space Refuel	0.04%
R8: Add Sat (identical sat, same orbit)	0.04%
R8b: Add Sat (identical sat, any orbit)	4.68%

8.9 System Timeline: Epochs and Eras

Tying in the concepts of context and time, and borrowing from economics, the system change scenario can be defined in terms of Epochs. An Epoch is a time period that bounds the change scenario, during which utility functions, constraints, design concepts, available technologies, and articulated attributes are defined. The purpose of the Epoch is similar to the purpose of short run analysis in Economics: to parse a complex problem into a series of simpler ones. Similar to Economics short and long run analyses, many system aspects and constraints are “fixed” in the

short run (Epoch), but variable in the long run (Era). For each Epoch *i*, the duration of the Epoch, as well as the beginning state, $S_{i,b}$, and ending state, $S_{i,e}$, must be defined. (If no change occurs, the two design states are the same.) Continuity of states means that the ending state of Epoch *i* is equal to the beginning state of Epoch *i+1*. Figure 98 shows a qualitative picture of a string of Epochs, which together form the system Era.

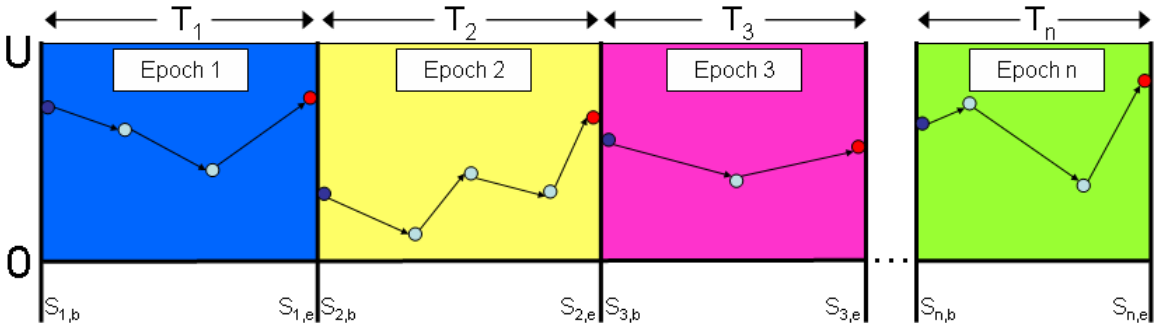


Figure 98 Example Epoch string, forming System Era

An example system Era for a satellite system with serviceability is shown in Figure 99.

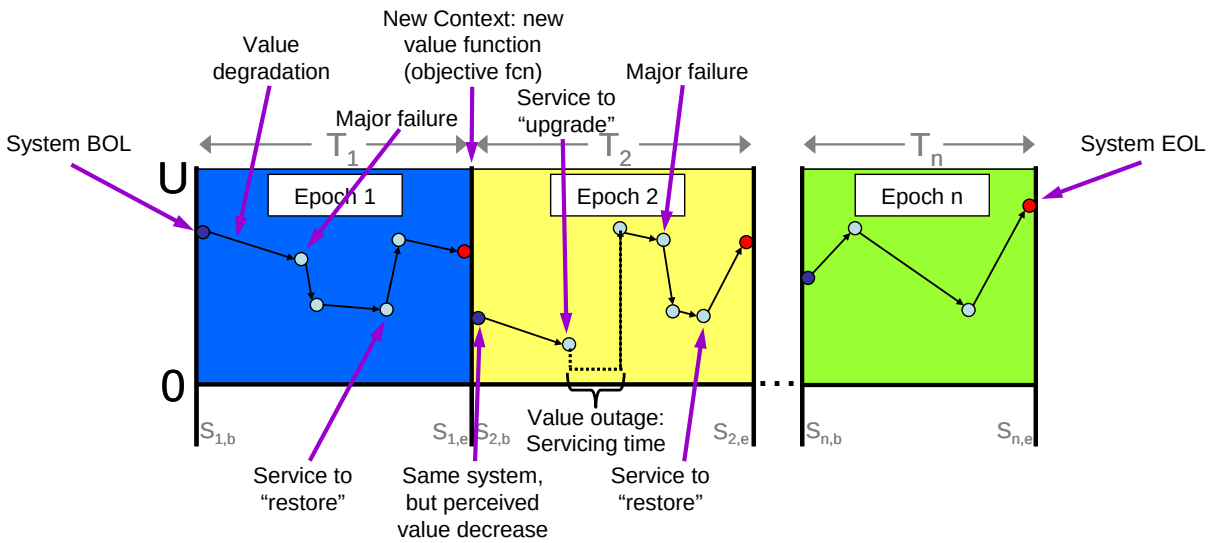


Figure 99 Example Era for satellite with serviceability

During each Epoch in the Era, path analysis can be conducted, utilizing the accessibility matrix. A goal design can be specified, and paths from the baseline to the goal can be derived using any specified transition strategy. An example is in Figure 100 below for a single Epoch. In this case, the strategy is to find the minimum cost path from the starting state to the ending high utility state. The beginning design state $S_{1,b}$ is specified, along with the preferences, the design concepts, constraints, and Epoch duration. The accessibility matrix is calculated using available transition rules. Allowable paths are investigated and the "best" path is determined according to the specified minimum cost strategy in order to reach the goal state $S_{1,e}$.

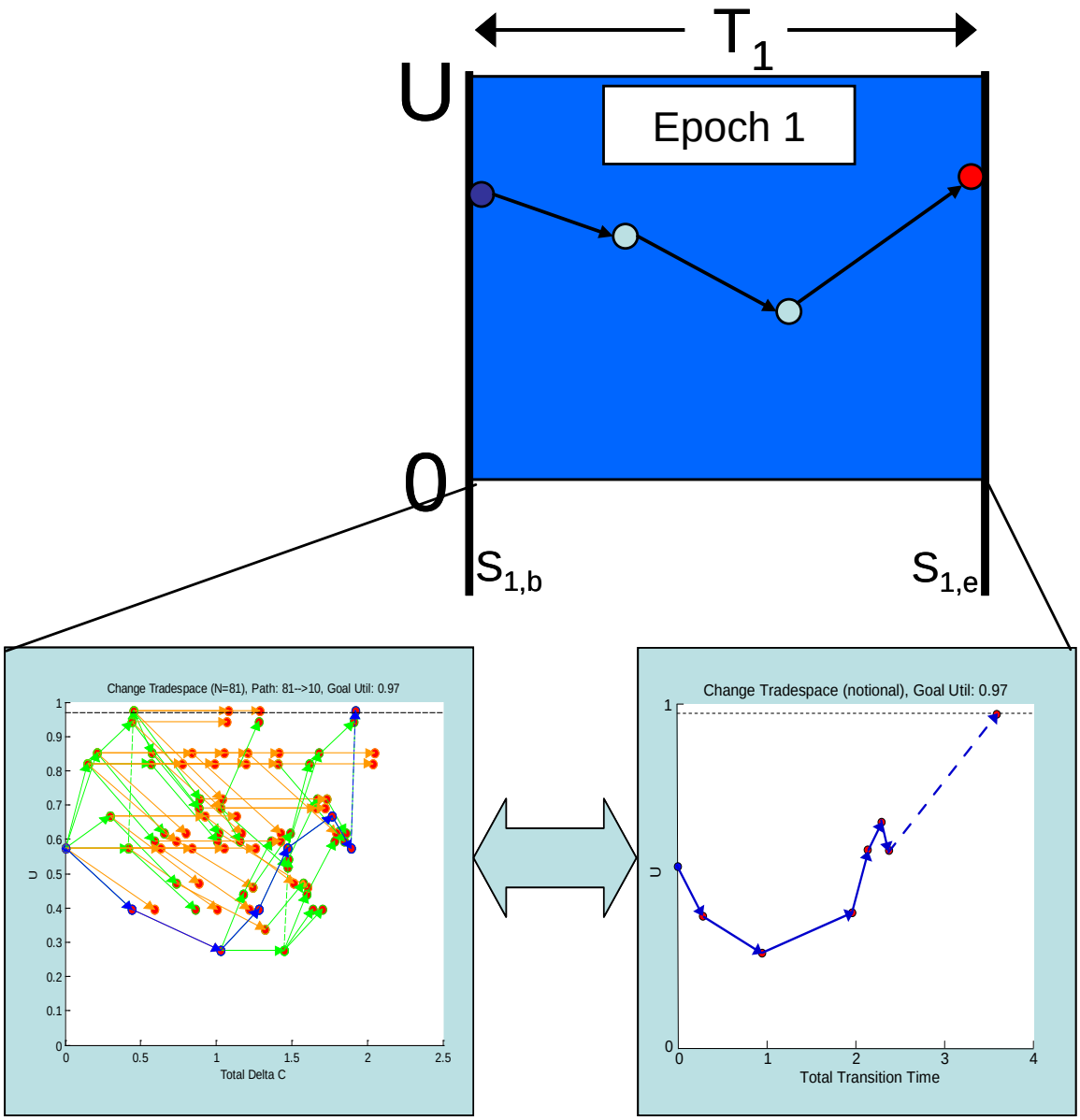


Figure 100 Example notional one Epoch path analysis

Suppose a new context for the system arises, necessitating the addition of a second Epoch. The beginning state for Epoch two continues the ending state of the previous Epoch. Even though the system is physically and functionally the same, the system is perceived to have lower value due to perception shift in the new Epoch. Figure 101 below shows the adjustment of utility in the same system under the new context. The designer now tries to find another path in the new Epoch in order to increase the value of the system. Again, path analysis can be readily applied to the tradespace. In this example, a new technology enables the addition of a new design variable. Additionally, a new decision maker enters the mix, affecting the total value perception of the system.

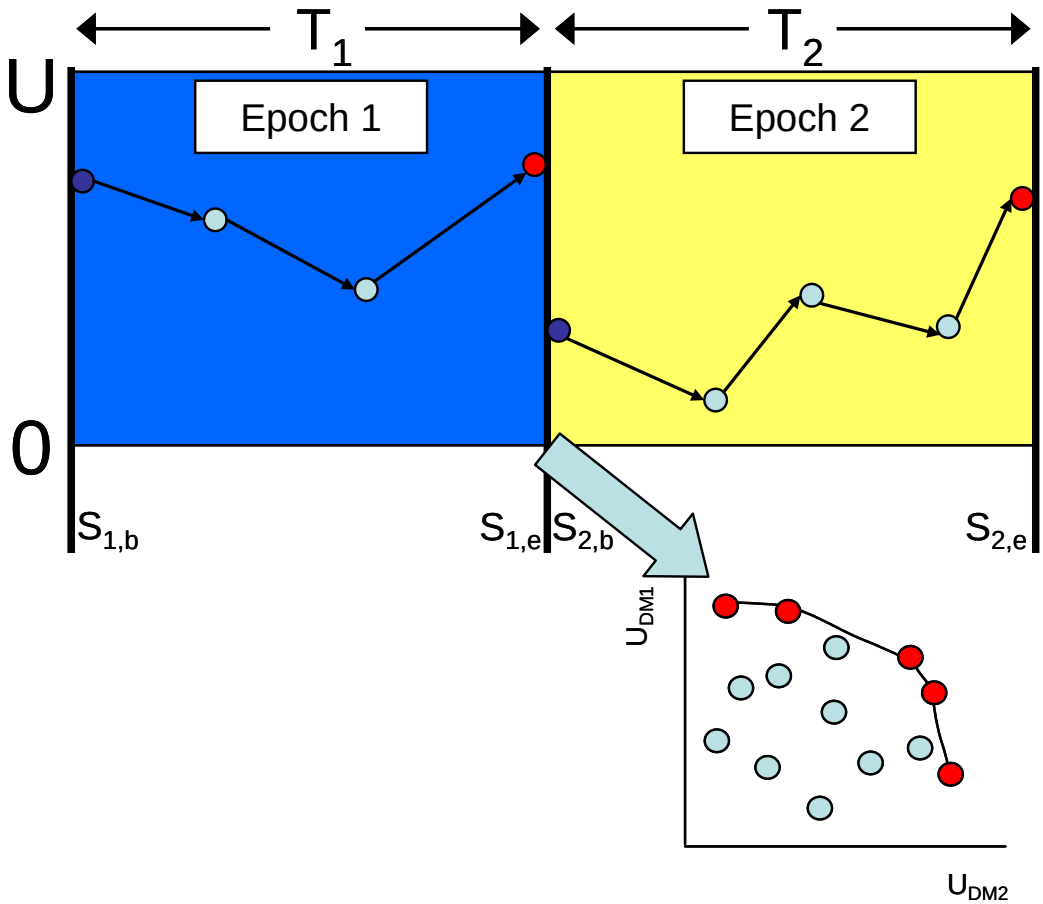


Figure 101 Example notional two Epoch path analysis with utility discontinuity

Several issues must be considered in the usage of Epochs and system Era analysis. First, the Epoch timeline can be assessed at any point during system lifecycle, not only during early conceptual design. Second, Epochs can be known in advance, or in the moment, deterministic, or probabilistic. The mathematical treatment of the paths, costs, utilities, and times must appropriately match the uncertainty level of the data. Third, value (utility) is determined during each Epoch since perception is context dependent and varies with time. Fourth, selection of the system Epoch end state is dependent on strategy for the Epoch. No absolute correct, or "best" design exists without subjectively specifying the "best" strategy. Strategies can include maximum utility, minimum cost, minimum time, minimum risk, or any combination, among others. Fifth, strategies themselves can be predictive, adaptive, or static. The system analyst can use the Epoch analysis while the system is in operation, continuously updating probabilities and value data to determine the "best" path to other designs, as well as the "best" goal design to pursue in each Epoch. Sixth, the Epoch is a mechanism for stringing together short runs into the long run (System Era), and as such, it may make sense to sometimes "take the longer view" rather than only seek the best Epoch solution. It is possible, due to the path-dependence of design transitions, that some future "best" state may only be accessible by taking the "bad" designs in the short run. Such insight can be gained using this analysis approach.

Since a "full" tradespace is generated in each Epoch, and the costs and utilities plotted are independent of design alternatives, the Epoch tradespace network is not dependent on the starting, or baseline design chosen for that Epoch. As such, system Era timeline analysis is modular by design. Various Epochs can be specified in advance and strung together in various orders. Paths within and across these timelines can be calculated according to arbitrary strategies. In this way, system Era timeline analysis is reusable, with the analyst able to update calculations and strategies as new information becomes available.

As a technical implementation consideration, the total transition times of paths within an Epoch cannot exceed the Epoch duration (such example of "taking too long" should be used as a filter to remove infeasible transition paths).

Very different goals for achieving value over time can be pursued using the Epoch or system Era analysis. Figure 102 below shows these goals, which include:

Minimizing the need for changeability: choose $S_{n,e}$ that is most "passive value robust"

Maximizing the changeability: choose $S_{n,e}$ that is most "active value robust"

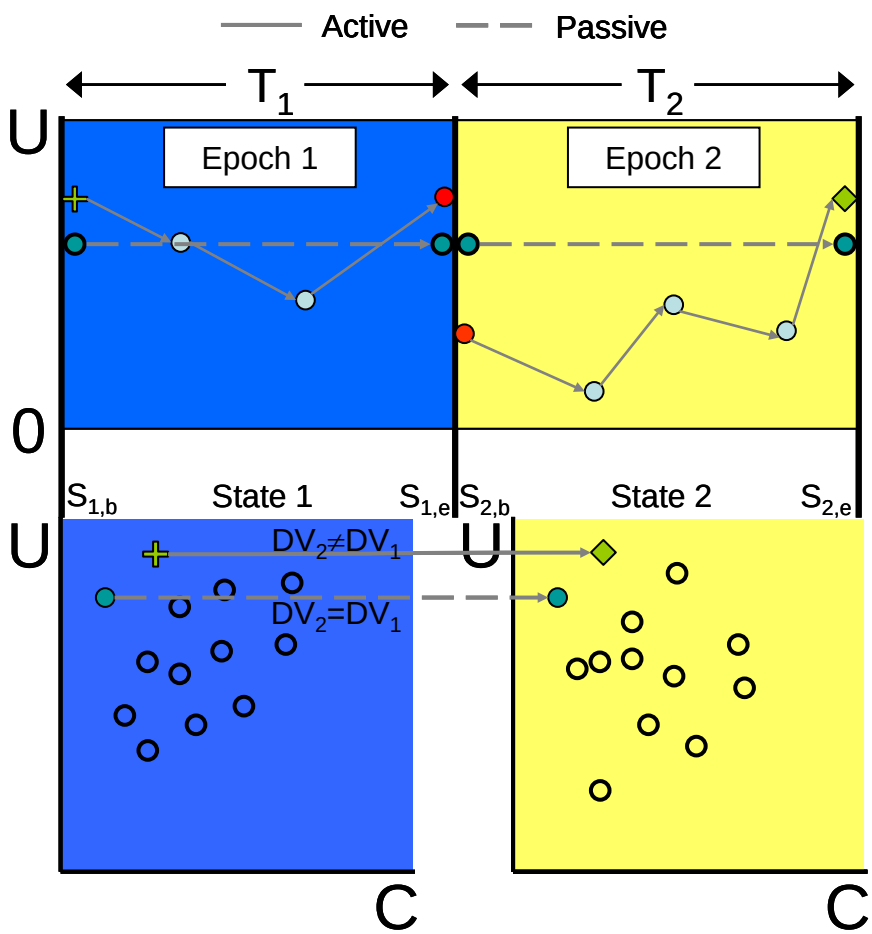


Figure 102 Active versus passive value robustness across two Epochs

8.9.1 Expected Output

Definition of various epochs
Definition of possible system eras
Proposed strategies for system timeline, min(C), min(t), max(U), other

8.9.2 Application to X-TOS

For the X-TOS dynamic MATE analysis, the Epochs that were considered were the preference experiments described in Section 7.1. Using a template, such as the one depicted in Appendix C: Epoch Template, the analyst attempted to determine various scenarios where the value of the system may be perceived differently. Families of Epochs correspond to changes in articulated attributes, attribute priorities, attribute perceptions, and value aggregation techniques.

The following is an example Epoch template filled in for the X-TOS baseline scenario (initial operating scenario). Subsequent Epochs only have to define their differences from the baseline. The baseline design, DV_{base}, is equivalent to the $S_{i,b}$ design mentioned above.

Epoch name:	X-TOS Initial operating scenario	Modified: 10.04.05
Similar to:	N/A	
Epoch duration:	Five years, or until system context change	
Epoch goal:	Find maximum utility design at $S_{i,e}$	

Constraints

Resource: Must spend less than $100M over 5 years
Political: Must not use foreign launch vehicle
Market: N/A
Physical: Must use
Operational: Must provide less than 5 Gbps downlink data rate
Other: Must have a catchy acronym

Constants

Constant variable set, {*CON*}:
Controllable:
Uncontrollable:

Preference-space

Decision Maker set, {DM)}: User
Number of DM, size({DM}): 1
For Decision Maker *i*
Attribute set$_i$, {X^{Mi}}: {Data Lifespan, Latitude Diversity, Equator Time, Latency, Sample Altitude}
Attribute Priorities, {k^{Mi}}: [0.3,0.125,0.175,0.1,0.425]

Single att utility curves, $U^j(X^j)$: See attached
Multi-att utility function, $f_U(k_j,U^j)$: MAUF
Changeability Cost threshold, $\hat{C}$: 50$M
Changeability Time threshold, $\hat{t}$: Depends 30 min short term, 6 mos long term

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Design-space

Design variable set, $\{DV^N\}$: {Inclination, Apogee Altitude, Perigee Altitude, Communication Arch, Total DeltaV, Propulsion Type, Power Type, Antenna Gain}
Baseline design, DV_{base}: None; new design
Path-enabling variable set, $\{IV^P\}$: None; changeability not considered
Transition rule set, $\{R^K\}$: R1: Plane Change (Adapt), R2: Apogee Burn (Adapt), R3: Perigee Burn (Adapt), R8: Add New Sat (Flex)
Cost function, $f_C(CON,DV,IV)$: SMAD CERs

Model-space

Model to be used, $F_{XM}(CON,DV,X)$: 16.89 developed X-TOS code version 1.1

For the original X-TOS study, the decision maker actually did change his preferences during the course of the design process. The original preferences of the decision maker were captured in Exp1b32, and can be read off of Figure 103. The revised preferences are shown in Exp1b31. An example path analysis is shown on the following pages, applied to movement from the best design ending Epoch(Exp1b32) to the best design in Epoch(Exp1b31), with the goal of reaching the highest utility design in the new Epoch. The starting point from Exp1b32 is the "obvious" best solution, which has the highest utility and lowest cost for that Epoch (design id 1).

Expb3:	1	2	3	4	5	6	7	8	9	10	11	12	13
DL	0.3	0.1	0.2	0.1	0.4	0.5	0.425	0.4	0.1	0.2	0.1	0.2	0.4
LD	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175
L	0.1	0.05	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.3	0.2	0.3	0.2	0.4	0.1	0.1	0.1	0.3	0.2	0.2
SM													

Figure 103 Epoch variations defined by changes in priorities for two attributes.[121]

[121] Of particular interest is transition from Epoch Expb32 to Epoch Expb31 representing the shift in preferences experienced by X-TOS

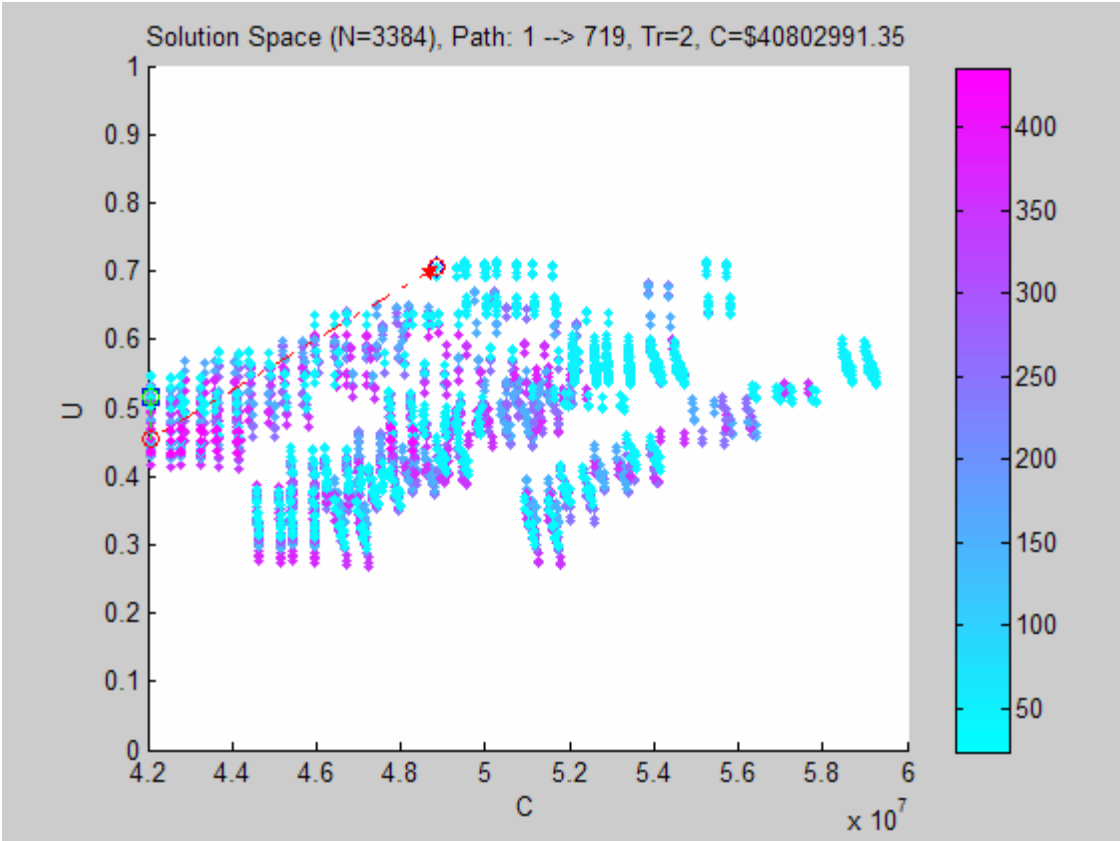

Figure 104 Epoch Expb31 minimum cost path from "best" previous Epoch design

Figure 104 depicts a minimum cost path strategy for transitioning from the "best" design in the previous Epoch to a determined "best" design in the current Epoch (Expb31). Design id 1 was determined to the beginning design. The sequence of transitions, including design id node, followed transition rule, and transition "costs" are listed in Table 13 below.[122] For this example, the "best" current design (design 719) was selected because it is a "low cost, high utility" Pareto Set design. Ultimately for this path, the minimum cost strategy is to use a replacement satellite to reach the desired end state (transition rule 8). Recognizing the potential high cost for this option may inspire designers to develop additional lower cost transition rules for future analyses.

Table 13 Minimum-cost path transitions in Epoch Expb31

Transition Number	Path			Tradespace Coord		Transition "cost"	
	Node1	Rule	Node2	C	U	ΔC ($M)	Δt
1	1	3	39	42.0 42.1	0.52, 0.45	free	~1 hr
2	39	8	719	42.1 48.8	0.45 0.71	40.8	~6 mos
Total	1	→	719	42.0 48.8	0.52 0.71	40.8	~6 mos

[122] The X-TOS transition rules used are listed in Table 11 and are R1: Plane Change, R2: Apogee Burn, R3: Perigee Burn, R4: Plane Tug, R5: Apogee Tug, R6: Perigee Tug, R7: Space Refuel, R8: Add Sat.

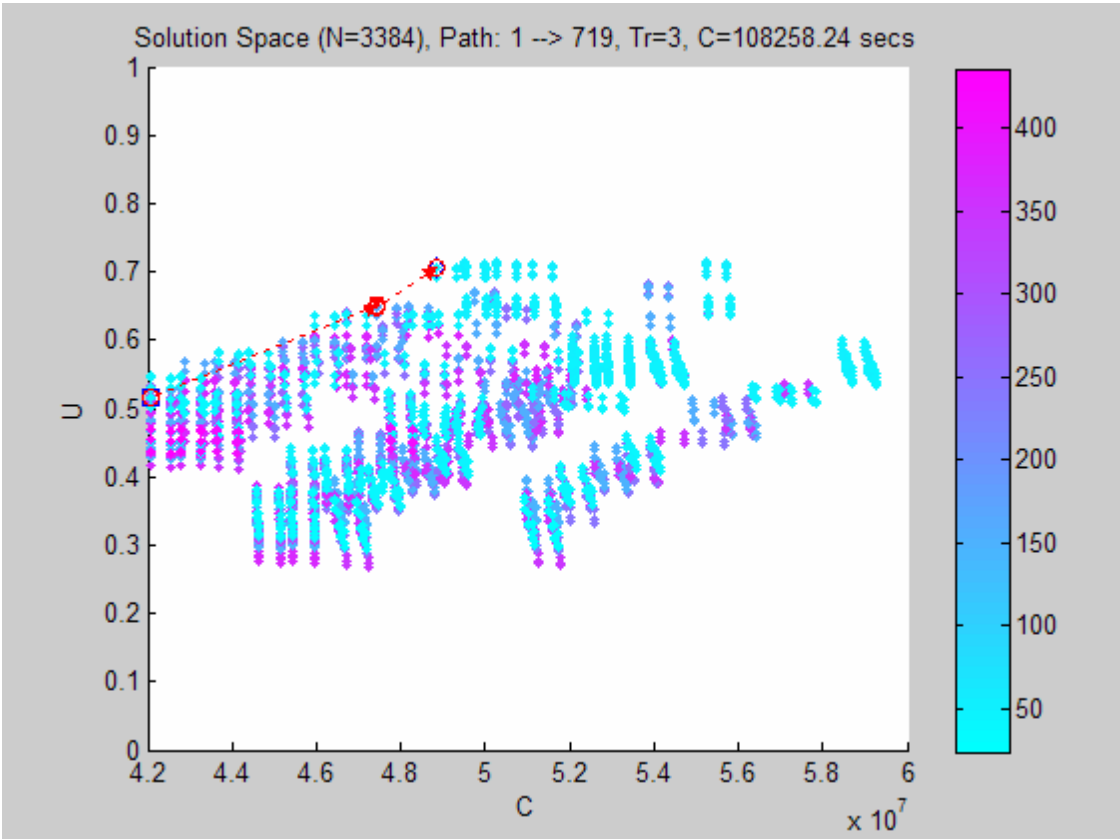

Figure 105 Epoch Expb31 minimum time path from "best" previous Epoch design

Figure 105 depicts a minimum time path strategy for transitioning from the "best" design in the previous Epoch to a determined "best" design in the current Epoch (Expb31). Design id 1 was determined to the beginning design. The sequence of transitions, including design id node, followed transition rule, and transition "costs" are listed in Table 14 below. The minimum time path as shown has an incredibly high price tag (due to the high cost of a plane-change space tug, which charges per imparted m/s velocity change on target vehicle). Decision makers and analysts can use this type of analysis to determine the cost of accessibility for various designs of interest. Some designs may be highly accessible from a temporal perspective, but monetarily too costly.

Table 14 Minimum-time path transitions in Epoch Expb31

Transition Number	Node1	Path Rule	Node2	Tradespace Coord C	Tradespace Coord U	Transition "cost" ΔC ($M)	Transition "cost" Δt
1	1	3	1107	42.0 47.4	0.52, 0.65	free	~1 hr
2	1107	4	2675	47.4 47.4	0.65 0.65	751.9	~ 1 day
3	2675	7	719	47.4 48.8	0.65 0.71	19.8	~3 hr
Total	1	→	719	42.0 48.8	0.52 0.71	771.7	~30 hr

8.10 Quantifying Changeability: Decision Metrics for a Dynamic Context

In order to truly leverage design insights into changeability, a quantified decision metric should be used for comparing designs. Since changeability is a superset concept of flexibility, adaptability, scalability, and modifiability, as described in Chapter 6, defining a quantified changeability metric will reflect the subconcepts as well. As discussed in section 6.5, "Asking the Question," there are two principal components to determining changeability: whether a design can change, and whether the "cost" for change is acceptable. The first part is an objective concept, while the second is subjective. Counting the number of ways that a design can change will answer the whether question in a more detailed and quantitative fashion; surely a design that has more possible end states is somehow more changeable than a different design.

Formulating the tradespace as a network is a natural model for considering state transitions, which in effect is the same as the concept of change. The tradespace network is defined by the design options under consideration (the nodes) and the transition rules connecting the designs (the arcs).

8.10.1 Deriving Changeability

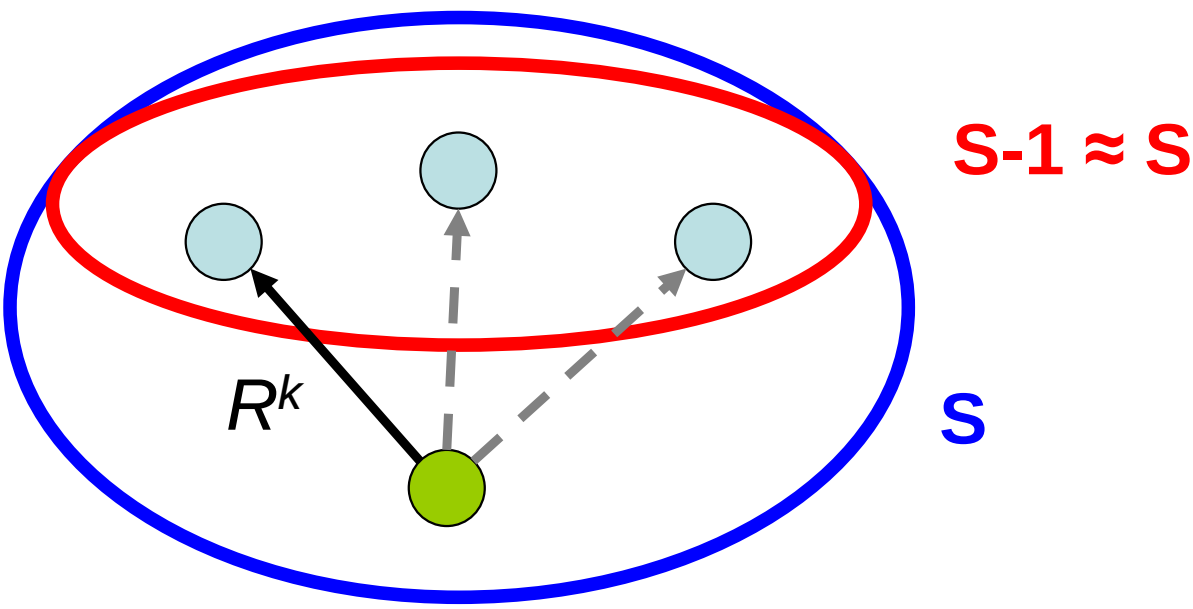

Figure 106 Design (node) connections determined by rule^k, leading to maximum connectivity to full space S

Figure 106 shows an illustration of the base node and other nodes that may be connected through rule R^k. The maximum number of nodes accessible to the base node is S, with the maximum number of paths being $S \times K$.

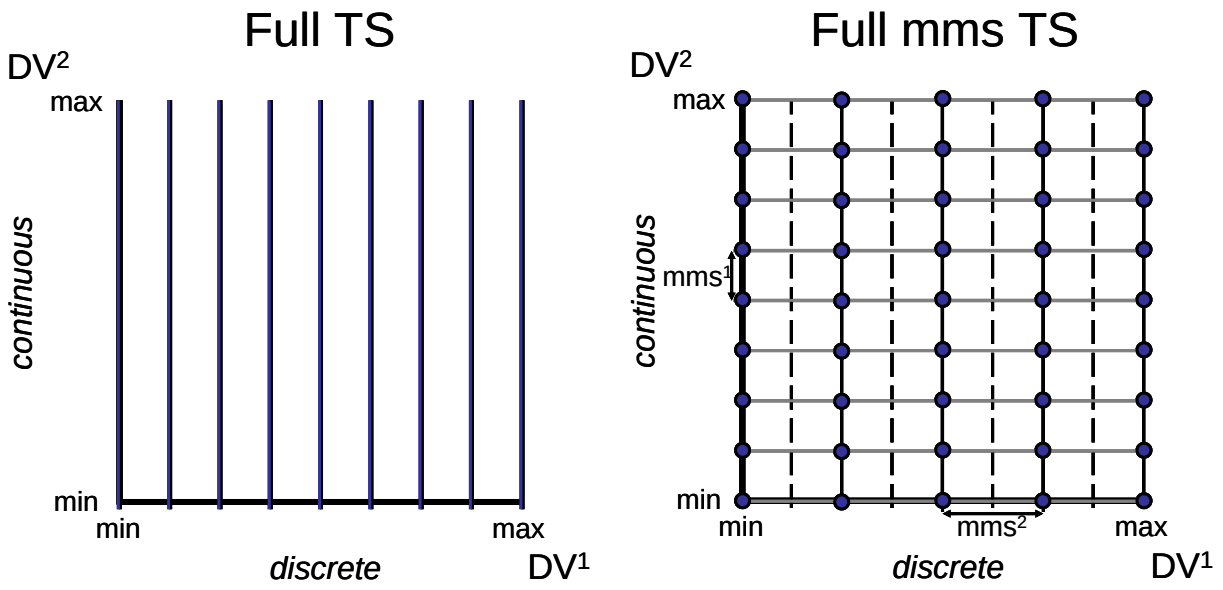

Figure 107 Discretizing design space with minimum meaningful scale

In order to describe the enumeration of DV^i, which is the set of all possible values for DV^i, as a countable set, it will be necessary to define the concept of the *minimum meaningful scale*, *mms*. Even though in reality many design variables will be continuous in nature, actual continuous variation in its value will not be value-perceived by a decision maker. Take for example satellite orbital altitude. The altitude can take any value between zero and infinity (an uncountably infinite set of possibilities). In practice, however, the difference between 100 and 110 km may make no difference. The minimum meaningful scale defines the resolution of meaningfulness for the design variable. Defining the mms^i has the effect of discretizing the possible values of a design variable, creating a countable set (either finite or infinite). Figure 107 shows a notional two-dimensional design space with the discretizing effect of a minimum meaningful scale. In practice the set will be finite due to constraints both in physical and value-space.

The notion of changeability, as discussed in section 6.2, is the ability to alter the system from state 1 to state 2 for less than a subjective "cost." In terms of the network formulation of the tradespace, the ability to change from state 1 to state 2 corresponds to a path linking state 1 and state 2. The "cost" of the path is the "cost" of the change. The subjective "cost" threshold set by the decision maker determines whether a path should be counted as possible. The number of possible paths from a given node is called its outdegree. The "cost" threshold acts as a filter, allowing only those paths that cost less, in terms of dollars or time, to count toward the outdegree of the node. In this way, changeability can be quantified as a filtered outdegree of a given node, or design. Figure 108 below shows the derivation of filtered outdegree from the network formulation of the tradespace. The subjectivity of the changeability of a design is caused by the subjective nature of the cost threshold. The existence of outgoing paths from a design is not subjective, however.

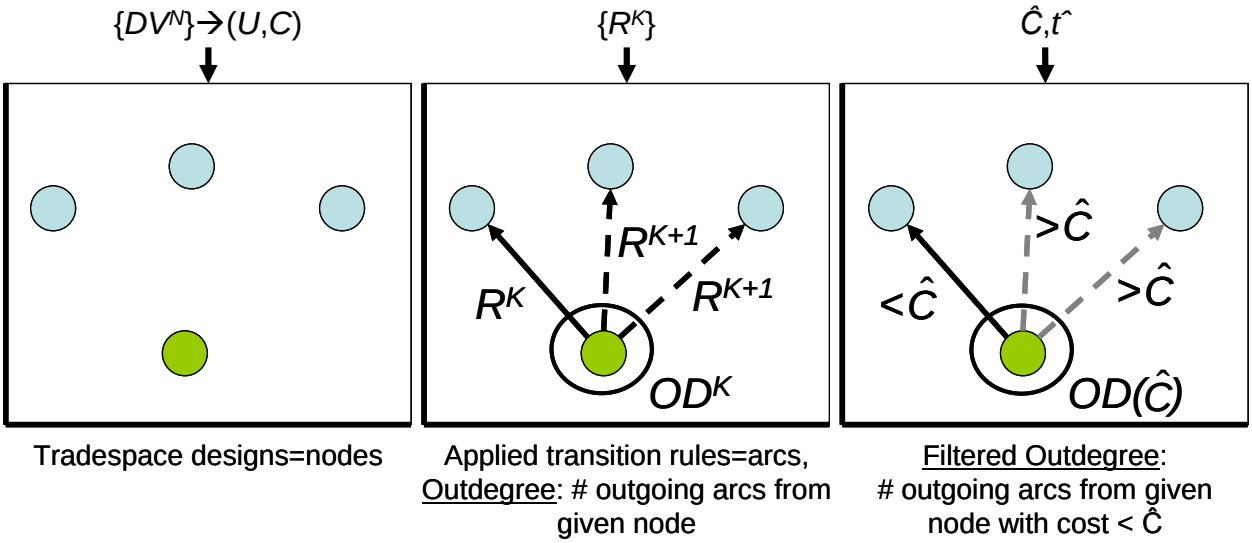

Figure 108 Tradespace network formulation with filtered outdegree[123]

An important aside is the realization that more than one path may exist connecting the same two nodes. The calculation of outdegree will count each path separately since they represent multiple mechanisms for achieving change. One path may be followed in one case, while a different path may be followed in a different case. Explicit attention to path heterogeneity will embolden designers to develop even more path mechanisms, further increasing the changeability of designs.

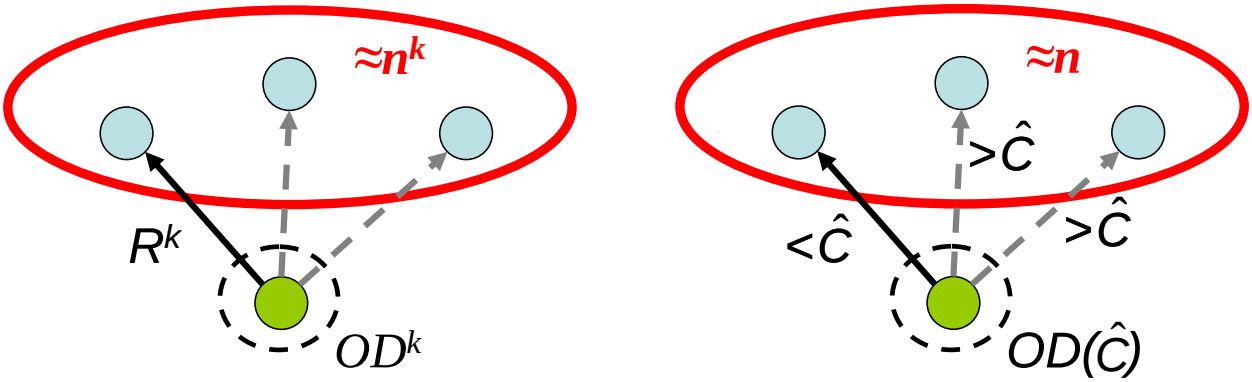

Figure 109 Outdegree^k from node due to rule^k and Outdegree(Ĉ) for arcs costing less than Ĉ

In addition to determining connectivity through the design rules, a cost filter must be applied to each arc to determine acceptability to a decision maker (see Figure 109). As mentioned in Section 6.5, to determine changeability, the subjective cost threshold must be met. That cost threshold, Ĉ, is the cost filter, above which arcs are no longer counted. An outdegree function of cost threshold can be derived, giving insight into the subjective nature of changeability (see Figure 110 below). In the prior example, the cost filter was assumed to be infinite. In practice, the connectivity, or "infinite outdegree" is calculated first. Next the filter is applied, which reduces the number of allowed outgoing arcs from a given node. Thus, the infinite outdegree provides an upper bound to the changeability of a design. The calculated outdegree is affected by

[123] Steps include: generate tradespace nodes, apply transition rule arcs, calculate outdegree and filtered outdegree given subjective acceptability threshold

the number of rules, design variables, and minimum meaningful scale for each design variable. Changes in any of these three parameters will change the outdegree. Causes of change include new technology or creative solutions for transition rules, new concepts for design variables, and new perceptions for minimum meaningful scales. Clearly if a designer wants to make a design more changeable, he would seek more applicable design rules, or increase the number of possible destination states given current rules.

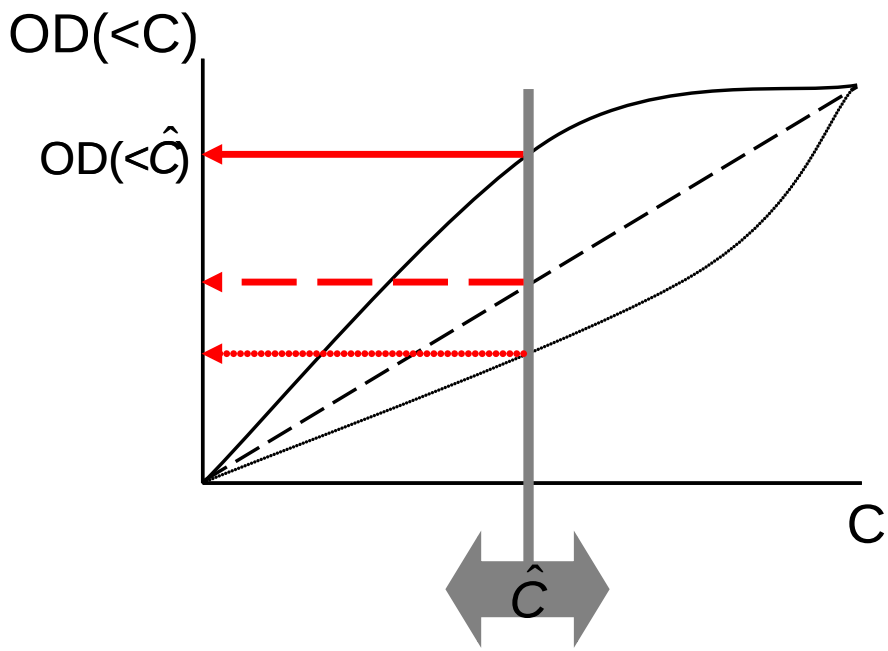

Figure 110 Outdegree function reflecting changeability as a function of subjective cost threshold

The effect of the filtering is a reduction of the number of allowable arcs in the accessibility matrix T_{ijk}:

$$T_{ijk}^{(allowed)} = \text{AllowedTransition}(T_{ijk}^{(cost)}, T_{ijk}^{(time)}, \hat{C}, \hat{t})$$

The filtered outdegree for node i can be calculated by summing $T_{ijk}^{(allowed)}$ across dimensions j and k.

8.10.2 Sampling and Granularity

The effect of sampling and granularity on tradespace enumeration was investigated with a sample problem. Four levels of enumeration were tested, with n=81, 256, 625, and 1296, shown in Figure 111 below. The outdegree for the initial 81 designs were tracked across the levels of tradespace sizes. Figure 112 below shows that more changeable designs remained at higher outdegrees than other designs, suggesting stability of α^k for the example.[124] It is important to realize that the tradespace must be converged (unbiased) in order for the filtered outdegree to give an accurate measure, i.e., not contain enumeration strategy artifacts.[125]

[124] α^k, is the fraction of tradespace accessible through rule k; its stability is a measure of the sampling bias of the tradespace. See Appendix E for a discussion of sampling strategies and stability of the outdegree measure.

[125] A biased tradespace can suggest erroneous patterns to the human decision maker, especially when arbitrary enumeration steps are used; the discretization of the steps could suggest structure in the tradespace that is the result

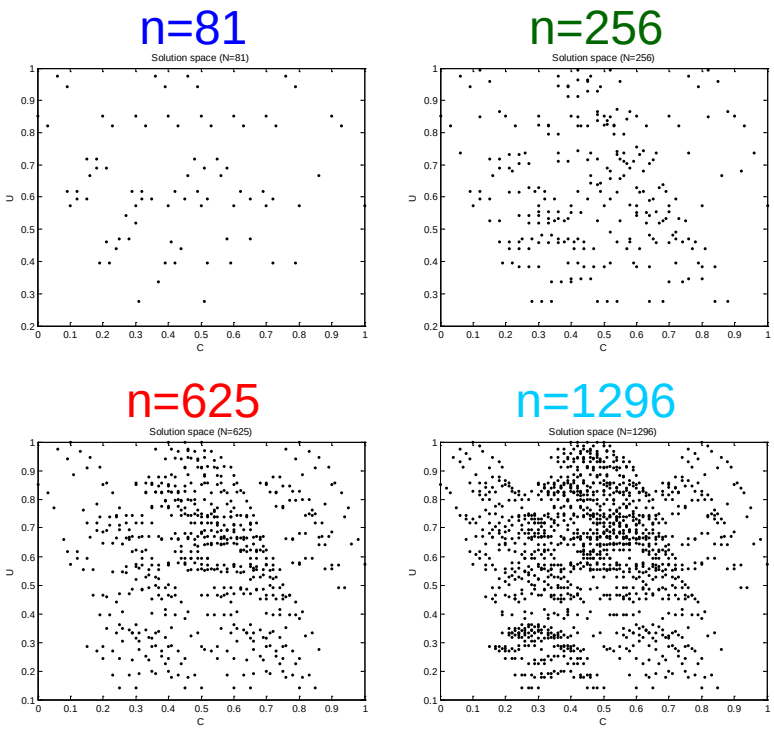

Figure 111 Example sub-sampling levels of tradespace

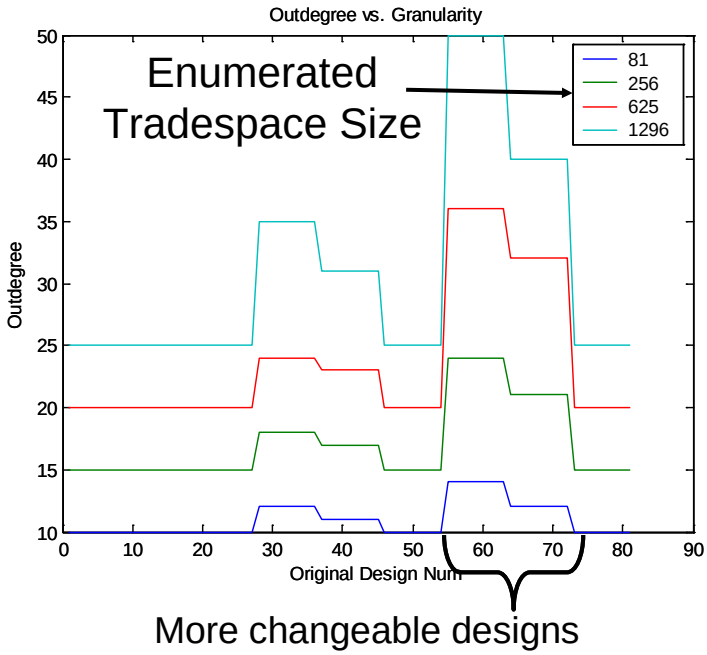

Figure 112 Outdegree number for designs at differing enumeration levels

of the structure in the enumeration. Design of Experiment (DOE) techniques or random enumeration strategies should be used to reduce the sampling and inference bias on the results.

Since the analyst is interested in the structure of the tradespace without enumeration sampling bias, the best strategy is to pursue random sampling of each design variable. Enumeration through random sampling will remove the bias introduced through arbitrary ranges. (Lotov, Bushenkov et al. 2004) discusses the use of random sampling as the best way to approximate nonconvex, multidimensional pareto surfaces. In general, MATE analysis is a superset of that problem (the analyst is dealing with multi-dimensional nonconvex data, but is interested in not only the pareto surface, but the interior structure as well). Lotov suggests sampling from a uniform distribution over each variable range.[126].

Coupled with the need for appropriate sampling is the need to create an algorithm to "snap" to the mms-defined design vector grid. "Snapping" to the grid ensures consistency in comparing a random-sampled tradespace (or any other enumeration strategy) to the complete tradespace.

8.10.3 Quantifying "Value Robustness"

Since "value robustness" relates to delivery of constant value in the face of change, both constancy and change must be defined. Thus robustness only has meaning when describing the system in the context of some set of changes. According to the definition given in 6.2.1, robustness is:

$$robustness_{ij}: \left| U_{t2}(F_{XM,t2}(DV_j)) - U_{t1}(F_{XM,t1}(DV_i)) \right| \approx 0, \text{ for } T_{ijk} < \hat{C}, \ \forall j \text{ in TS},$$

where U_{t1} and U_{t2} are the value interpretations of the system at time 1 and time 2 respectively. Likewise DV_i and DV_j are the before and after states of the design. F_{XMt1} and F_{XMt2} are the design-to-attribute model mappings of the system at time 1 and time 2. $F_{XM,t1}(DV_i)$ is the set of attributes at time 1 of design i, while $F_{XM,t2}(DV_j)$ is the set of attributes at time 2 of design j.

Since direct comparison of utility across time periods is akin to direct comparison of distinct utility functions, the numeric difference has no absolute meaning. Instead, either rank, or value-efficiency must be considered. Determining rank entails transforming an iso-cost listing of designs, sorted in terms of decreasing utility. The most valued designs per cost level would form the preferred set of designs (Pareto Set). Membership in the set can be readily expanded to include designs with rank greater than 1, allowing for "good" as well as "best" designs to be included (Fuzzy Pareto Set).[127] Drawing upon the results in Chapter 7, the concept of "value robustness" can be quantified as "the magnitude of a design's Pareto Tracing," or its Pareto Trace Number, where the tracing occurs over tradespaces reflecting the change pressures under consideration.

As mentioned earlier, achieving value robustness can occur by choosing designs that remain valuable without change (high Pareto Trace Number) or by choosing designs that can be changed over time, attempting to dynamically join a changing Pareto Set. For dynamic MATE analysis, the defined Epochs span the potential change scenarios for consideration.

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[126] Further research should be conducted on the best distribution to use in order to minimize the time to remove sampling bias. Application of Design of Experiments (DOE) could be a fruitful path as well for study.

[127] For a discussion of "Fuzzy Pareto Optimality" see Smaling, Rudolf. (2005). System Architecture Analysis and Selection Under Uncertainty. PhD thesis in ESD. Massachusetts Institute of Technology. Cambridge, MA: 214.

The static design approach, incorporating the traditional notions of robustness, leads to the following observation:

> *Passive "value robust" designs are those that have a high Pareto Trace Number over the Epochs of a system Era*

The dynamic design approach, incorporating a more changeable notion of robustness, leads to the following observation:

> *Active "value robust" strategy is one that seeks designs that are of high "then" value, which is accessible through many paths over the Epochs of a system Era*

The strategic interpretation incorporates both the static high Pareto Trace Number design, as well as looking for Pareto options in each Epoch that have a high indegree measure. These designs could then become the goal design for that Epoch and methods of changing the Epoch-entering design to the goal design can be sought through changeability analysis.

8.10.4 Quantifying "Flexibility/Adaptability" to get "Scalability/Modifiability"

As mentioned in Chapter 6, changeability is the concept that ties together flexibility, adaptability, scalability, and modifiability. Flexibility and adaptability relate to the location of the change agent: external (flexible) or internal (adaptable) to the system boundary. These changes are in terms of design, or real-space change. Scalability and modifiability relate to how the attributes for the system change: the level of an attribute (scalable), or the membership of the attribute set (modifiable). When determining if a system is "X"-able, both the origin of the change agent and the type of attribute change need to be specified.

As mentioned earlier in this section, the flexibility/adaptability is the number of potential change paths available to a design costing less than the subjective cost threshold determined by a decision maker. Flexibility and adaptability are subset concepts of changeability and thus can be quantified in the same terms. This leads to the following observation:

> *A "flexible" design is one that has a high outdegree measure of externally generated change paths, as filtered by a decision maker's acceptable cost threshold*

Likewise, adaptability can be defined:

> *An "adaptable" design is one that has a high outdegree measure of internally generated change paths, as filtered by a decision maker's acceptable cost threshold*

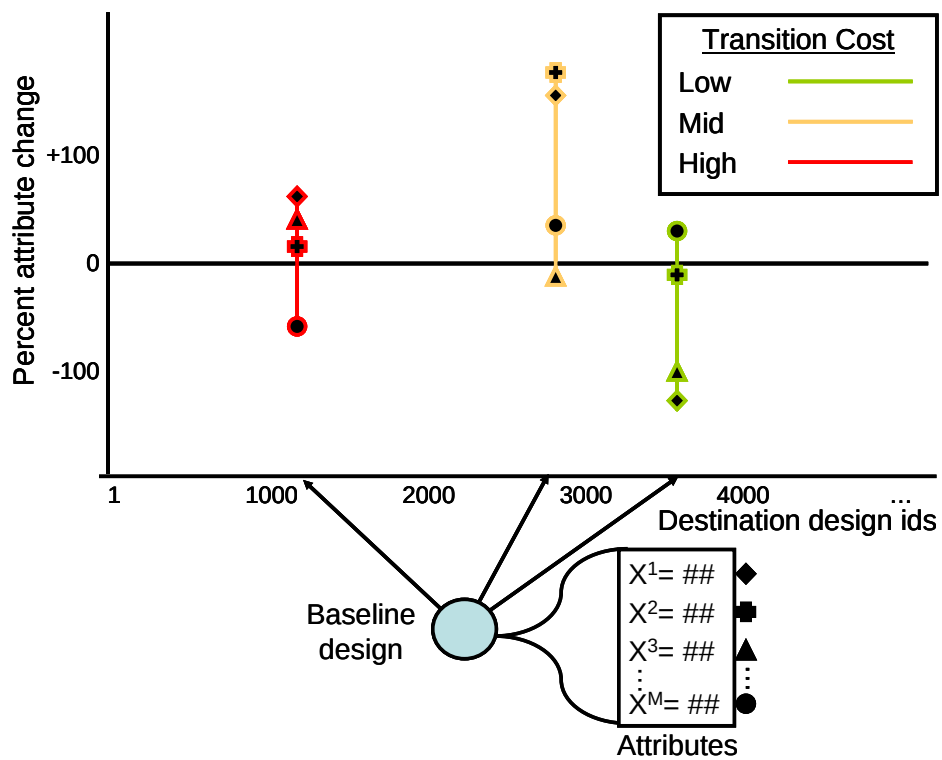
Turning attention to attribute-space, a change in levels of "displayed" attributes is a scalable change and according to the definition given in 6.2.1, scalability is:

$$\text{scalability}_i^{l}\text{: } [F_{XM}(DV_i) \rightarrow F_{XM}(DV_j)]^{l} \text{ for } T_{ijk} < \hat{C},\ \forall j \text{ in TS,}$$

where T_{ijk} is the transition tensor, specifying the "cost" of transitioning from design i to design j using rule k. As a concrete quantifiable, a scalable design in X^i has a large number of paths from i to all other designs in the tradespace that result in a change in the value of X^i. Thus scalability can be defined:

> *A "scalable" design is one that has a high outdegree measure of change paths that result in the change in level of "displayed" attributes, as filtered by a decision maker's acceptable cost threshold*

Of course what usually interests a decision maker is not the quantity of options, but rather the attribute value of the destination designs. A difficulty in the analysis arises if one only looks at one attribute at a time. Unless the design is uncoupled (a one-to-one mapping between design variables and attributes exists), any change in a design variable will result in the scaling of multiple attributes. Curves of X^i versus DV can be determined, however, for complex systems, a simple relation will probably not exist, precluding such useful measures as partial derivatives and functional forms. A design that is scalable in X^i, most likely will be scalable in X^j as well and deciding the best final design state must take into consideration the destination attribute levels and their effect on a decision maker's utility.[128] Figure 113 below shows the multi-dimensional tension inherent in scalability depiction, including percent attribute change at destination nodes from a baseline design.



[128] In fact, prescriptively a decision maker may be better off specifying his time-varying utility function instead of specifying desired scalability. It is easier for the analyst to explore multi-attribute tradespaces in terms of the aggregate utility metric than it is to compare multi-dimensional data such as attribute scaling tradeoffs.

Figure 113 Notional scalability showing multi-dimensional attribute tradeoffs

Modifiability relates to the number of ways and cost of adding or subtracting attributes from a "displayed" attribute set. According to the definition given in 6.2.1, modifiability is:

$$modifiiability_i^l: F_{XM}(DV_i) \cap F_{XM}(DV_j) = X^l \text{ for } T_{ijk} < \hat{C}, \forall j \text{ in TS},$$

where X^i is the added or deleted attribute. Modifiability can be quantified as the filtered outdegree of a design, counting only paths that add or subtract attributes, leading to the following

> *A "modifiable" design is one that has a high outdegree measure of change paths that result in the addition or subtraction of "displayed" attributes, as filtered by a decision maker's acceptable cost threshold*

Each of these changeability definitions can be quantified by the filtered outdegree derived above. Figure 114 below reviews the filtered outdegree definition.

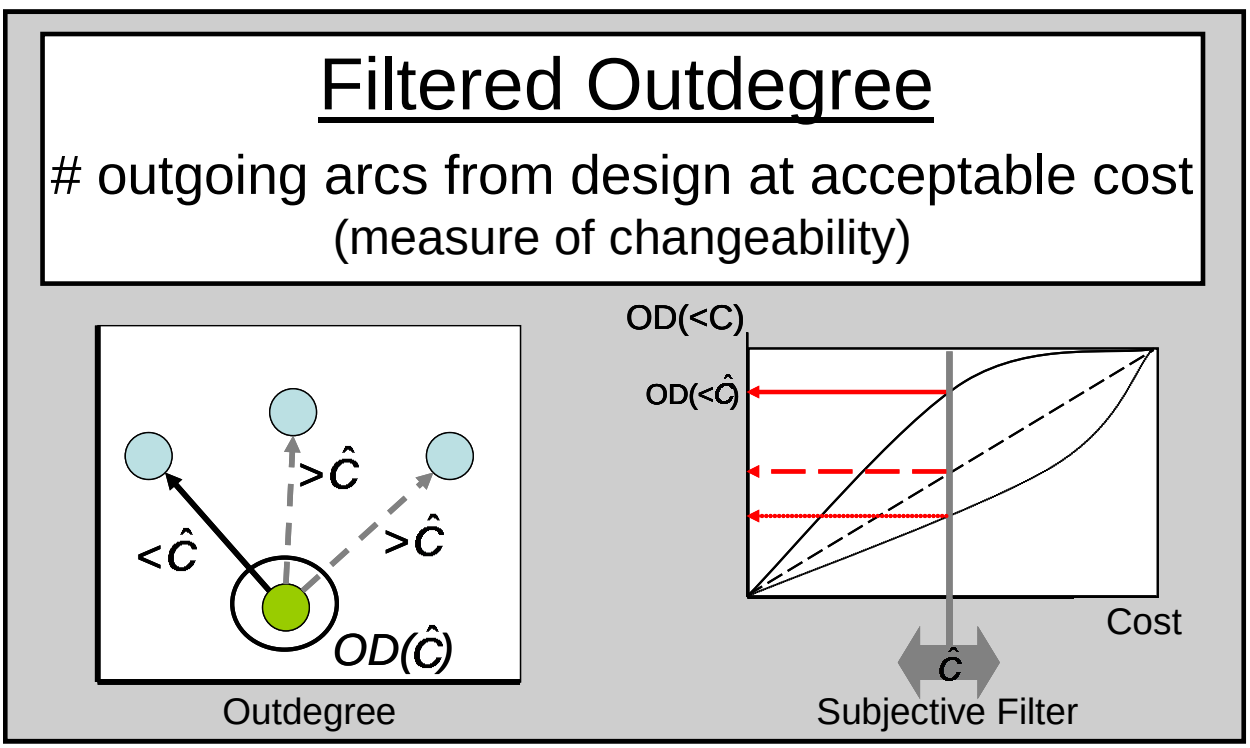


Figure 114 Filtered Outdegree definition

Example applications of these changeability definitions are given in the "Application to X-TOS" section below.

8.10.5 Expected Output

Definition of $\hat{C}$ and $\hat{t}$ for each decision maker
Calculation of $OD(<C.<t)$ function

8.10.6 Application to X-TOS

Investigating value robustness of X-TOS requires definition of Epochs, or context change scenarios. Suppose a series of Epochs are defined that correspond to the preference experiments in Section 7.1. These preference experiments correspond to changes in attribute set, k_i levels, linearization of single attribute utilities, and multi-attribute utility functional form. The analogical situation is that of articulation of unarticulated value (adding new attributes), changes in priorities (k_i levels), miscommunication of preference curves (linearization of SAU), and misapplication of preference aggregation functions (MAU functional form). Additionally, including the two-decision maker static experiment represents the case of the addition of a new decision maker into the mix. Altogether, these represent 60 Epochs of preference variations. Pareto Tracing across these Epochs will give insight into "value robust" designs that can withstand quite a variety of value-interpretive shifts. Figure 115 shows the Pareto Trace Number for five designs, which were the most "value robust" to the tested Epochs. Figure 116 below shows the distribution of value robustness in terms of Pareto Trace Number frequencies.

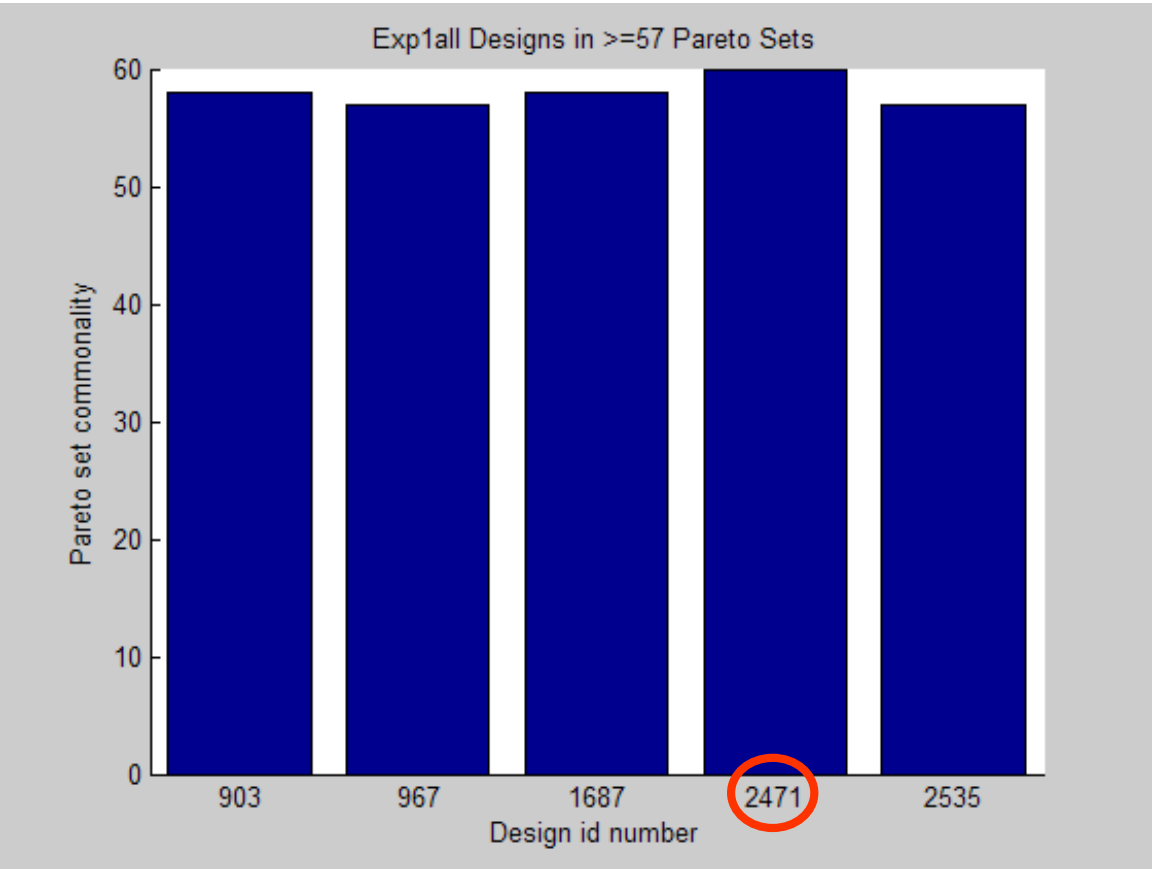


Figure 115 X-TOS "Value Robust" designs for tested preference variations in Exp1

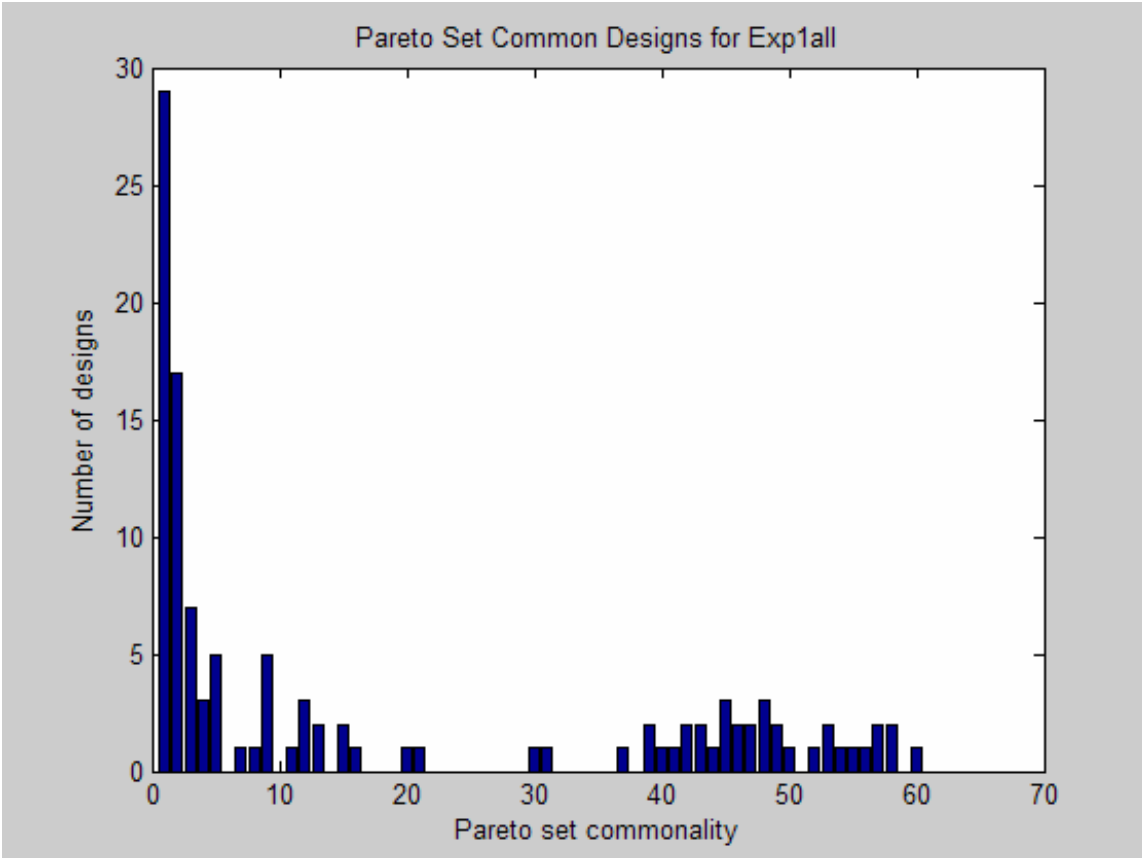


Figure 116 X-TOS "Value Robustness" distribution (Pareto Trace Number versus frequency) for Exp1

Choosing design 2471 would be a static "value robust" strategy to delivering value across these epochs. Choosing any of the 5 designs 2471, 903, 967, 1687, or 2535 as goal designs can be part of a dynamic strategy to achieve value robustness across these Epochs. Seeking ways to change to these designs would be part of the strategy (following the in-paths to these designs is one way). Highly changeable designs are more likely to find a path to the robust designs. A dynamic strategy to move a design into high value regions of the tradespace, even if Epochs are not well-defined, can likewise be a "value robust" strategy.

An example of the X-TOS OD(<C,t) function is given in Figure 117 below. Seven designs are plotted, showing their filtered outdegree as a function of cost threshold. As the cost threshold increases, the outdegree increases, to a point. The cost above which no outdegree increase occurs is C_∞, and represents the point which all paths are counted and no new transition mechanisms are enabled. Notice that design 7156 changes from being the third least changeable to the second most changeable design as the cost threshold increases. The maximum changeability for a system occurs when the decision maker's cost threshold is above C_∞. Designs 903, 1687, 2471, and 2535 will show up again in further analysis below. The design variables and their values are given in Figure 118 below.

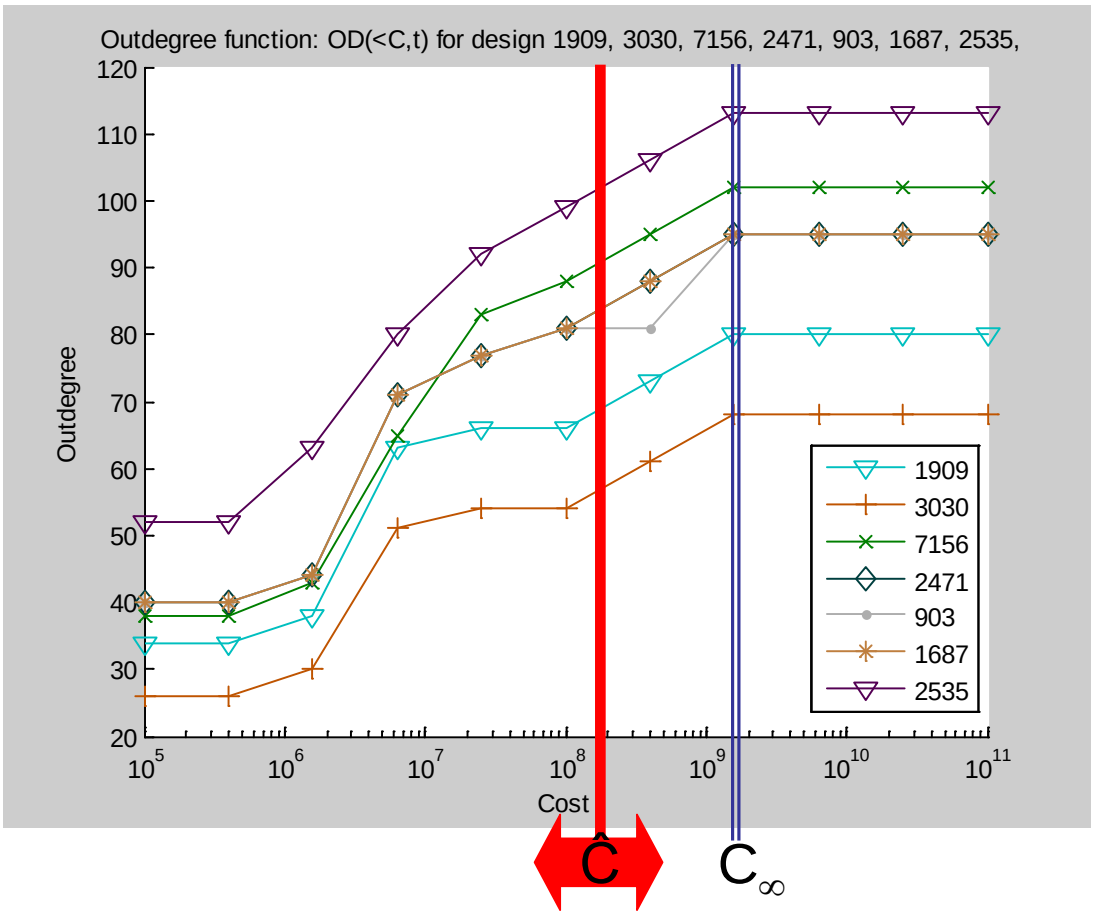


Figure 117 X-TOS OD(<C,t) for several designs

DV	2471	903	1687	2535	1909	3030	7156
Inclination	90	30	70	90	70	90	90
Apogee	460	460	460	460	1075	2000	770
Perigee	150	150	150	290	150	150	350
Com Arch	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS
Delta V	1200	1200	1200	1200	1200	1200	1000
Prop Type	Chem	Chem	Chem	Chem	Elec	Elec	Chem
Pwr Type	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Solar Array	Solar Array
Ant Gain	Low	Low	Low	Low	Low	Low	Low
Data Life	0.51	0.51	0.51	10.05	0.52	0.61	11
Lat Div	180	60	140	180	140	180	180
Eq Time	5	11	6	5	2	2	5
Latency	2.27	2.27	2.27	2.30	2.42	2.67	2.40
Sample Alt	150	150	150	290	150	150	350
Cost ($10M)	4.21	4.21	4.21	4.88	4.52	4.99	4.15

Figure 118 Design variable values for designs in OD(<C,t) plot

Figure 119 depicts the outdegree tradespace showing design number versus outdegree as colored by cost threshold. As the cost threshold increases, the outdegree of the designs increase *differentially*. The differential nature of the outdegree function shows that designs that are perceived as more changeable will vary depending on the subjective cost threshold (what is changeable to decision maker one may not be changeable to decision maker two, even if they have the same attribute set and utility curves). For a given cost threshold, a traditional tradespace plot can be shown, colored by outdegree, depicting the utility-cost location of the most changeable designs. Figure 120 below shows the X-TOS tradespace colored by outdegree when the cost threshold is greater than C_∞.

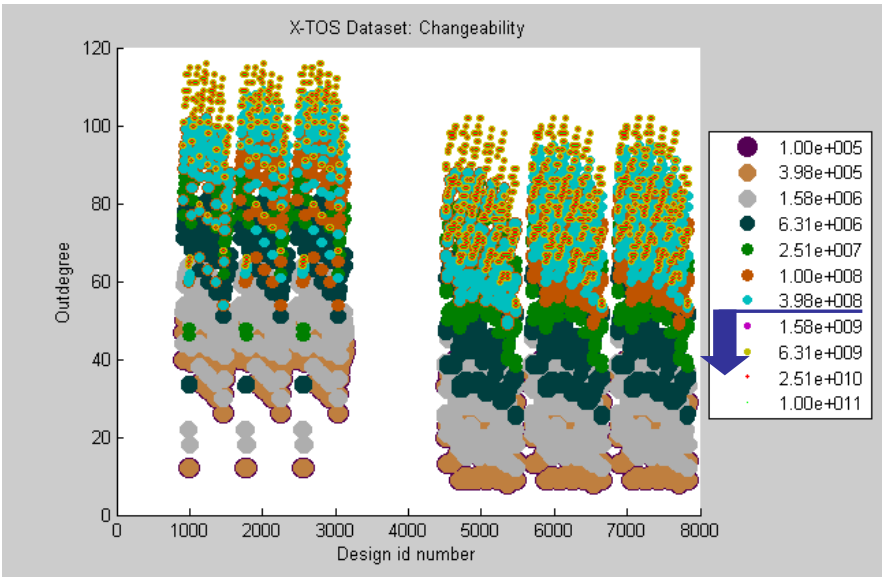


Figure 119 OD tradespace of OD versus Design ID number

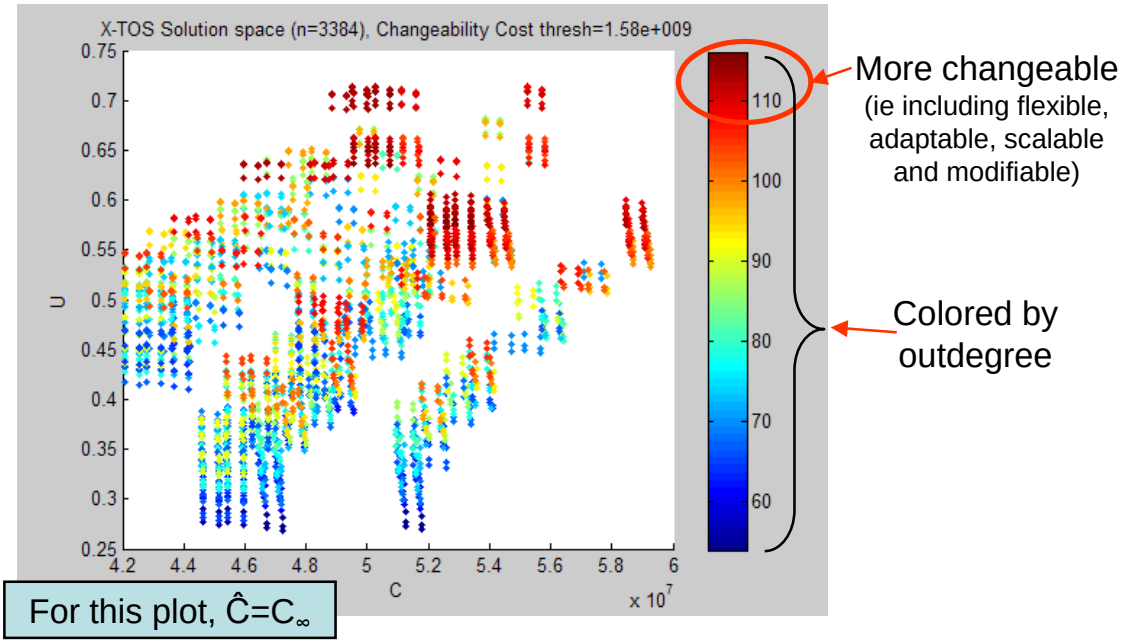
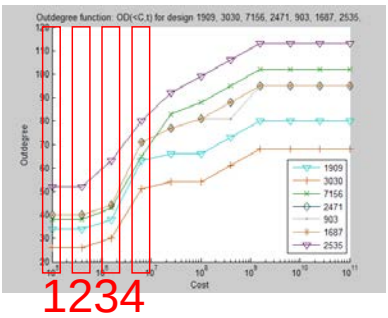


Figure 120 X-TOS tradespace colored by OD

Figure 122 and Figure 122 on the following pages show the progression of the colored utility-cost tradespace as the cost threshold increases. Some designs remain highly changeable and should be considered favorably by designers desiring changeable designs independent of cost threshold.



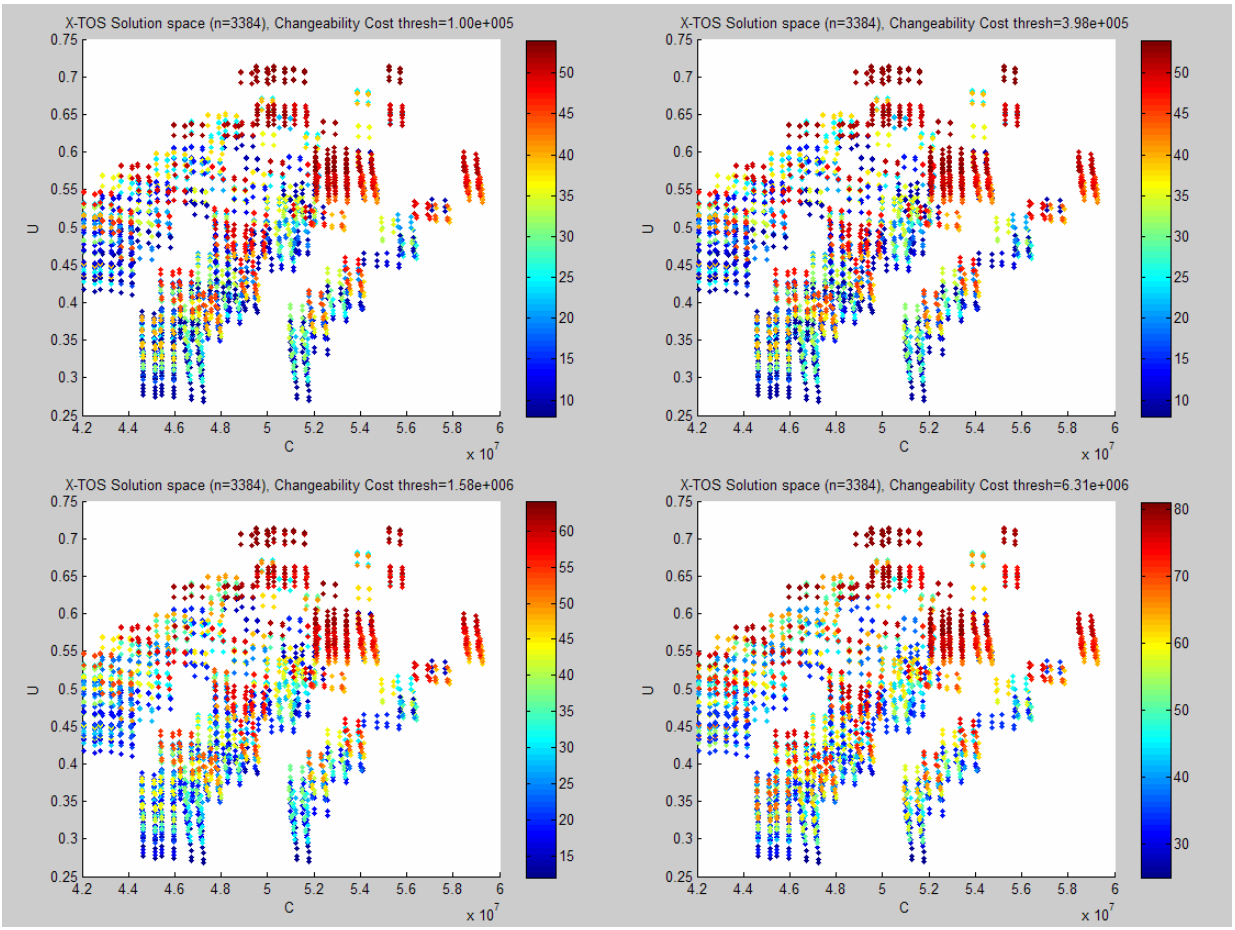


Figure 121 X-TOS tradespace colored by OD with increasing cost threshold (from 1 to 4)

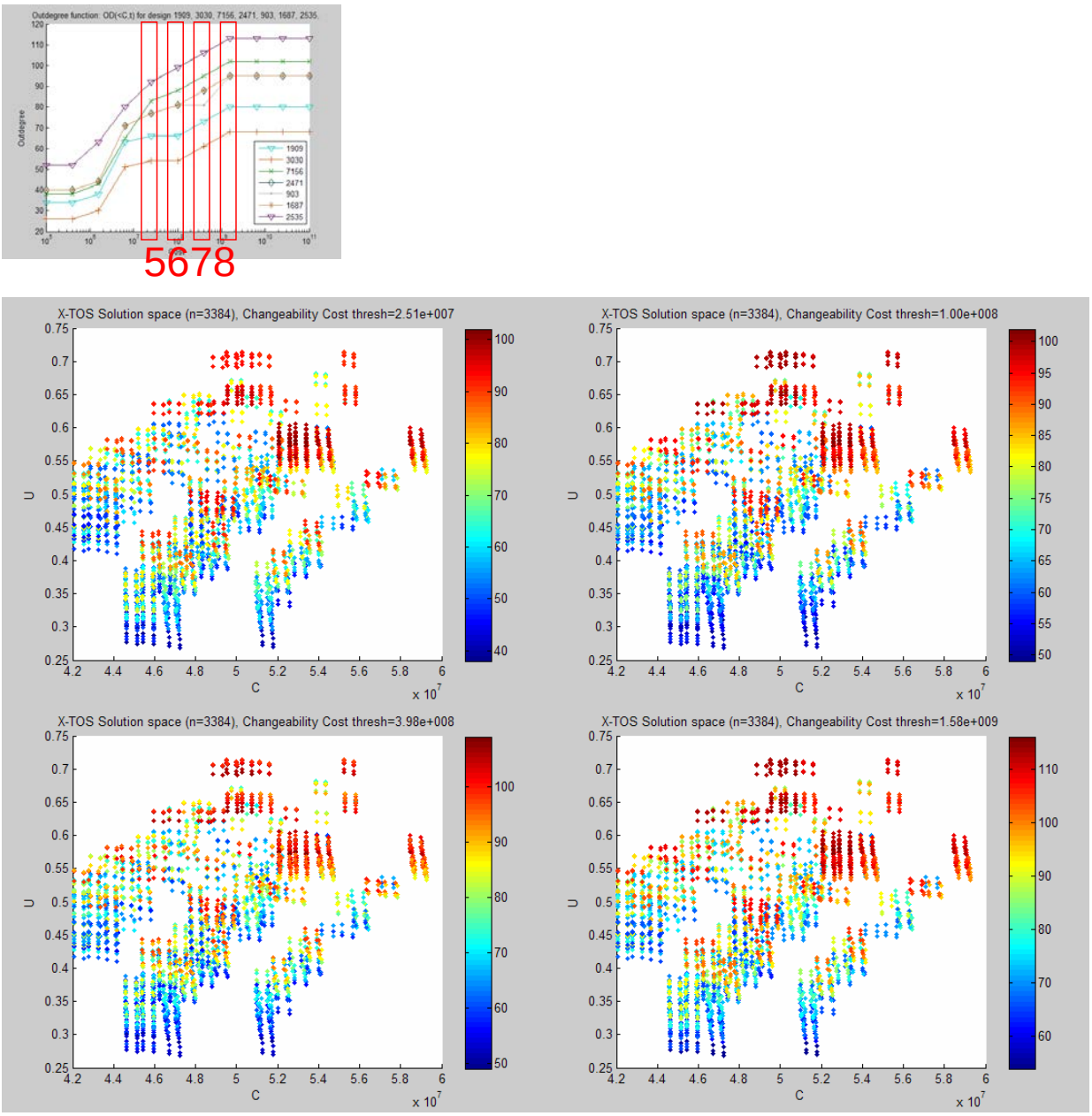


Figure 122 X-TOS tradespace colored by OD with increasing cost threshold (from 5 to 8)

Adaptability and flexibility can be decomposed out of the more general changeability by considering the nature of the transition rules being employed. Rules 1-3 are internally motivated and are thus adaptable, while rules 4-8 are externally motivated and are thus flexible. The outdegree calculated only counting rules 1-3 is the adaptable outdegree, while the outdegree

calculated only counting rules 4-8 is the flexible outdegree. Figure 123 and Figure 124 show the adaptable and flexible outdegree functions for the same 7 designs as Figure 117.

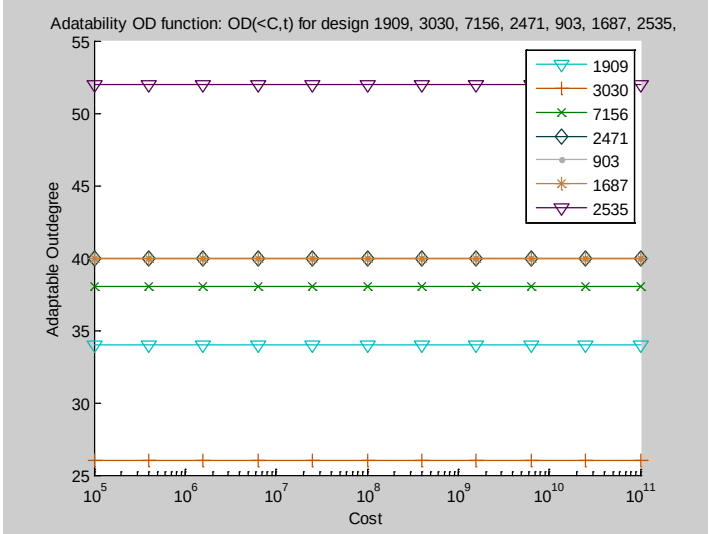


Figure 123 X-TOS Adaptability OD function for selected designs

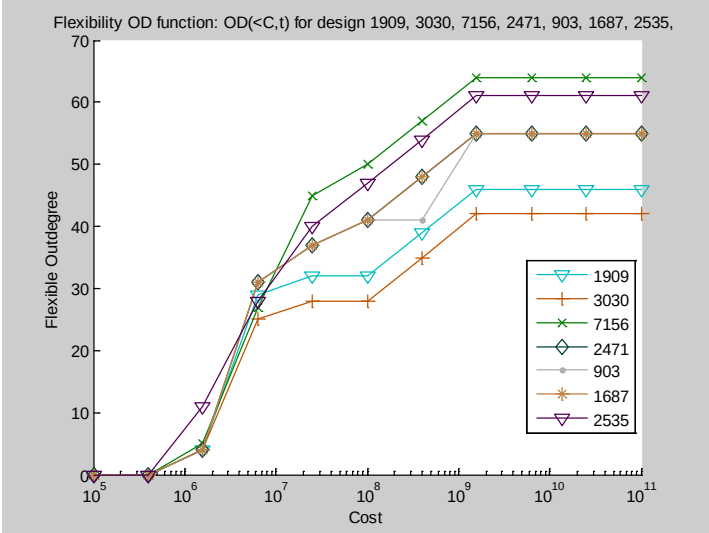


Figure 124 X-TOS Flexibility OD function for selected designs

Turning attention to scalability requires looking at particular designs. Design 2535 was chosen for consideration due to its high changeability performance seen in Figure 117. Looking at designs accessible from design 2535, as determined by T_{ijk}, and comparing the resulting attribute values allows the computation of Figure 125. The relative change in attribute value is shown on the y-axis, while destination design number is on the x-axis. All attributes value changes are on the same line, with different symbols marking the height of the change. The color of the lines represents the minimum cost path from the baseline node to that destination node. As can be seen, all attribute values scale with a change in design, suggesting a highly coupled design, and one that requires tradeoff losses for gains in particular attributes.

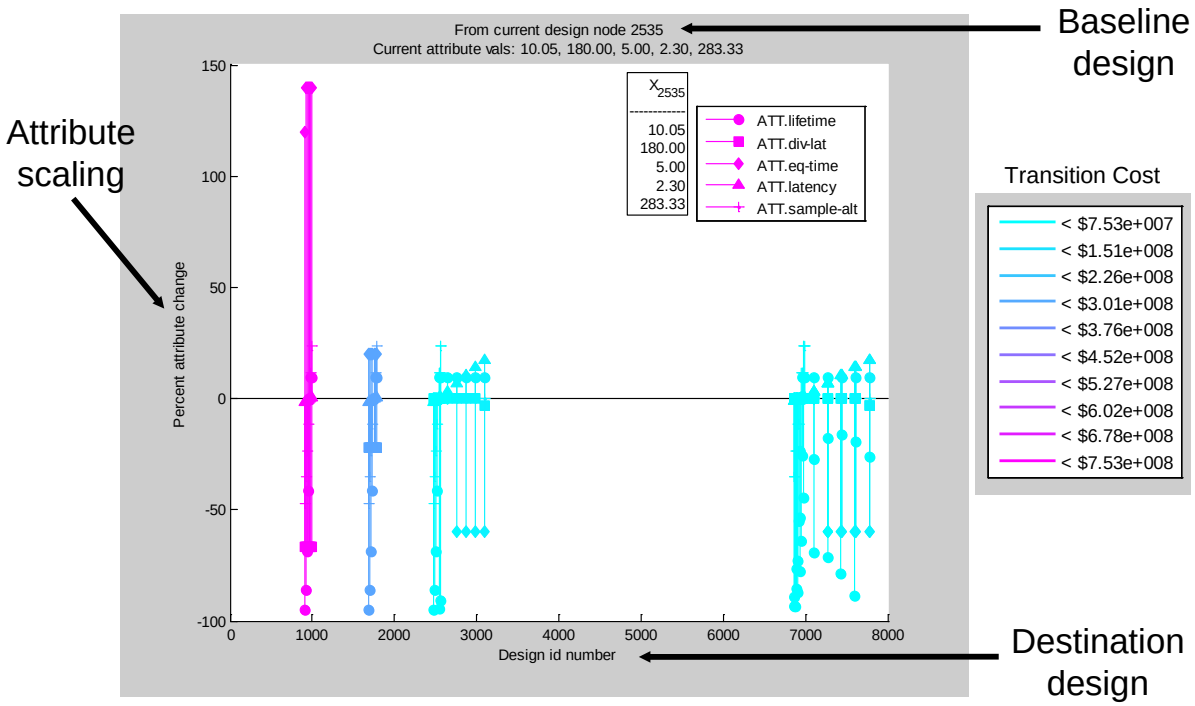


Figure 125 Scalability for X-TOS design 2535

Further insight can be gained when comparing the scalability plot colored by cost to the scalability plot colored by change type. These plots for design 2471 are in Figure 126 below. Notice the adaptable, and inexpensive, scalability to gain an increase in almost all attributes near design 7000.

Since the addition or deletion of attributes considered in the dynamic X-TOS study incurred no cost, all designs were considered equally modifiable. (The "deletion" of attributes such as diversity of latitude, or equatorial time, did not lead the analyst to consider new designs, which may have resulted in a cost change.) In theory, deletion of attributes can lead to vestigial design variables that are no longer necessary. Removal of these design aspects can result in savings, though the change itself most likely incurs cost. Likewise, addition of attributes that are not latent, will incur some cost as new design variables are added. The X-TOS study only had latent attributes, so no cost was incurred for adding design variables.[129]

[129] Path-enabling variables, such as refuelability, and tugability, were assumed for all designs for simplicity. In an actual study these path-enabling variables would be treated as additional design variables that incur system cost. The ability to follow transition paths that rely upon these variables can be turned on or off depending on the enumerated value of the variables. For example, tugability can be treated as a binary existence variable, either 'yes' or 'no.' Tugable designs and untugable designs are analyzed in the same tradespace, with the former able to follow the "tugging" rules, and the latter unable.

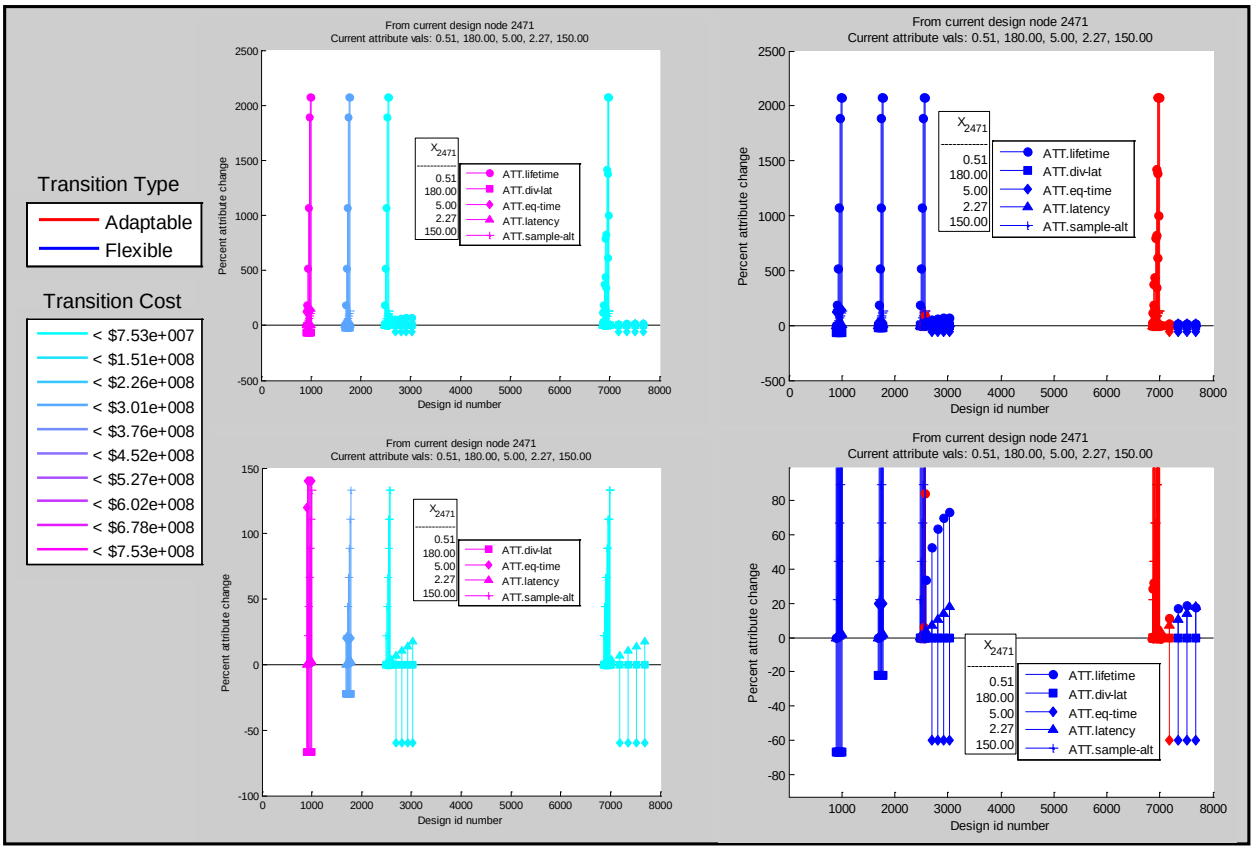


Figure 126 Scalability for X-TOS design 2471, colored by cost and flexibility/adaptability

8.11 Visualization and Communication

A key theme that should be apparent from prior discussions is that of visualization and communication. The strength of the human mind is its ability to recognize patterns and make "leaps" of intuition. The goal of dynamic MATE analysis is to take a complicated dynamic problem and move it into a tractable medium. Use of graphics to represent designs in as few, meaningful dimensions as possible, helps to convey key concepts. Human cognitive limitations require the minimization of distractions, while maximizing content and access to patterns. Humans are better at recognition over recall, so minimize loads placed on memory.[130]

Goals for visualization include representing multidimensional data simply, as well as spatially separating data, instead of temporally.

As guidelines for generating displays, according to (Tufte 2001), graphs should[131]:

- Show the data
- Not get in way of message
- Avoid distortion

[130] For a discussion of human cognitive limitations in relation to data processing and interaction, see Golub, Evan. (2005). An Introduction to Human-Computer Interaction. 22nd Annual Human-Computer Interface Laboratory Symposium and Open House, University of Maryland.

[131] pp. 13, Tufte, Edward R. (2001). The Visual Display of Quantitative Information. Cheshire, CT, Graphics Press.. The book discusses and displays visualization and graphical techniques for effectively communicating data.

- Present many numbers in a small space
- Make large data sets coherent
- Encourage comparison between data
- Supply both broad overview and fine detail
- Serve a clear purpose

Graphics are often more memorable than words and often defy the jargon that frequently trap many conversations and cloud communication. Prudent usage of visual displays can transcend linguistic barriers and focus discussions on data pattern discovery.

8.11.1 Learning

One of the key goals in the dynamic MATE process is to promote learning among the key design participants. Designers learn about the values of the decision makers, as well as the "physics" of the problem relating the design to the attributes. Decision makers learn about how their preferences, including subjective thresholds and arbitrary requirements, affect design options. Both parties can explore how creative solutions and flexible needs can coincide to deliver value over time. The articulation of needs can be focused through the process, and tracked to changing contexts. The world is dynamic, and learning is the dynamic reflection of information and understanding in a system or organization. Visualization and graphical communication can transcend domain barriers, facilitating learning among and between designers and decision makers. Without learning, a system cannot hope to dynamically deliver value.

8.12 Implementation Issues

The key implementation barriers to the dynamic MATE process are access to appropriate domain expertise, and sufficient computational resources.

8.12.1 Expertise Needed

In order to apply the dynamic MATE process, the following expertise is needed:

First, the analyst or designer should have the ability to communicate effectively, especially with the decision makers. The ability to elicit preferences from a decision maker is both a formal and a social process.

Second, the designer should have domain expertise in the appropriate field of interest in order to credibly develop a feasible concept. Likewise, the analyst should have the appropriate domain expertise in order to credibly develop a feasible model of the concept.

Third, the analyst should have some experience with network analysis techniques, as well as algorithm development to ensure efficient code development. The analysis approach described above can be very computationally intensive. If the proper scaling is not developed within the algorithms, the approach will become intractable. Advances in computation will alleviate the need for clever algorithms, however it is anticipated that the complexity of the analysis will grow to match, negating any advantage.

Fourth, the analyst or designer should have some expertise in decision theory, especially to understand the underlying assumptions and limitations of utility theory. Knowledge of actual

decision-making processes will help the analyst or designer both elicit and model decision maker's preferences and biases.

Fifth, it is very useful for the analyst or designer to have access to domain expertise of the decision maker to better understand his value-perspective. One of the roles of the MATE analyst is boundary spanner: providing an effective communication channel across domains.

8.12.2 Fidelity

The fidelity of the models, mapping design-space to value-space, is a key determinant of quality information. Just as any system will provide incorrect answers with incorrect inputs, so too will a system with incorrect innards. Determining the appropriate fidelity for a model is more of an art, than a science. To first order, the fidelity of a model determines the uncertainty of its output. Previous MATE work has suggested an iterative process of model development, where verification and validation at later steps feeds back to inform earlier models. A good rule of thumb for determining fidelity: the more important an output variable, the higher (more detailed) should be the fidelity of the model deriving it.

8.13 Problems with Method

When possible, the derivation of the dynamic MATE process attempts to rely on basic principles and methods, minimizing unnecessary assumptions. One key limitation, however, is the subtle complexity inherent in transition rules and paths. Actual field implementation of the method may require over simplification of costs and times for change. Additionally, the infinite permutations of some path types may make the problem intractable. Application of real analysis to continue the work above will alleviate some of that problem.

Another problem is the development of appropriate schedule models, including relationship to the budget process. Actual systems are strongly constrained by real budget profiles, which are not readily captured in the current MATE models.[132]

Simplification of designs to a relatively small set of design variables may overly simplify the design problem and underestimate the true differences between systems. It may be the case that opportunities for changeability, such as software design, are not included in hardware-centric design thinking, especially when software is not seen as attribute drivers.

A problem of particular note mentioned in section 8.10.2 is that of tradespace sampling. Sampling biases are readily introduced in arbitrary enumeration strategies short of full enumeration. Design of Experiment techniques or random sampling should be used to test convergence of the tradespace before the generated outdegree calculations will become accurate. Along these same lines, the calculation of changeability must be recalculated any time the minimum meaningful scale, transition rule set, or design variable set changes. The outdegree for a particular design will change accordingly. (This fact is both a problem and a benefit: knowing what changes the outdegree can provide motivation for designers or decision makers to intentionally change the parameters to increase the perceived changeability of a design.)

[132] 🖇🕮 potential research could incorporate schedule modeling work such as in Browning, Tyson R. (1998). Modeling and Analyzing Cost, Schedule, and Performance in Complex System Product Development. PhD thesis in Technology, Management, and Policy. Massachusetts Institute of Technology. Cambridge, MA: 299.

8.14 Examples

More detailed examples of dynamic MATE implementation can be found in the following two chapters. A smaller scale example application of the dynamic MATE process is to the distribution of costs and benefits for a system. Utilizing the DVM, each design and path-enabling variable can be traced to attributes, both current and potential, across the spectrum of articulated to unarticulated value. Figure 127 and Figure 128 show how the DVM can be used to visualize the current and potential value of design variables and path enablers. Design variables that directly promote attributes of interest to a decision maker are directly relevant to "willingness to pay." The same applies to path enablers and their affect on design variables that promote attributes of interest. This type of analysis can bring to light important interpersonal value trades, especially when new capabilities or decision makers are contemplated for a system. Of course, the benefit of more open and explicit communication is also a drawback, as value free riders become apparent. No one enjoys losing a free lunch. Additionally, power is lost when information is shared, so the analyst should be aware that some information will come at too high a cost to justify its inclusion. A policy-savvy analyst should be able to incorporate the necessary information while maintaining credibility and support of the appropriate decision makers.

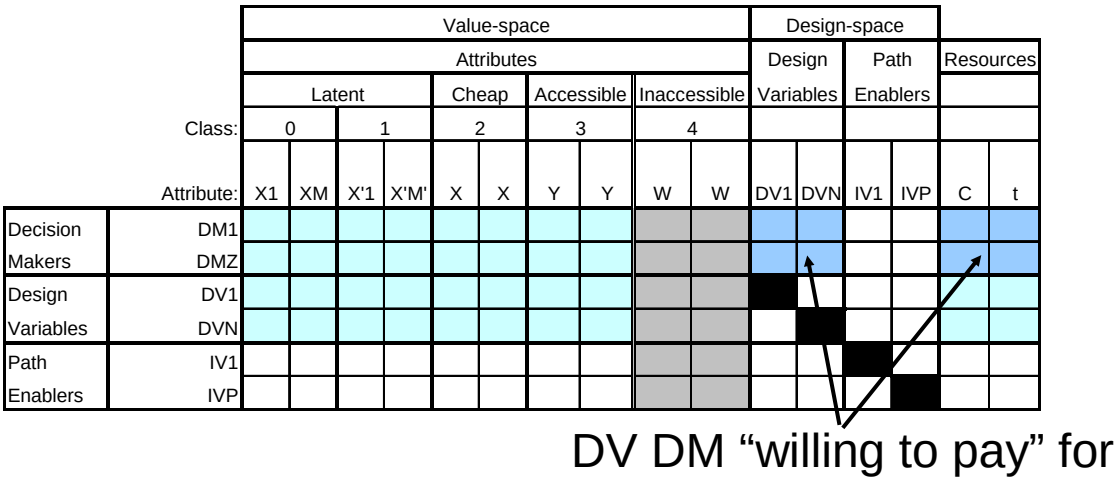


Figure 127 DVM with resource allocation indicated from design variables

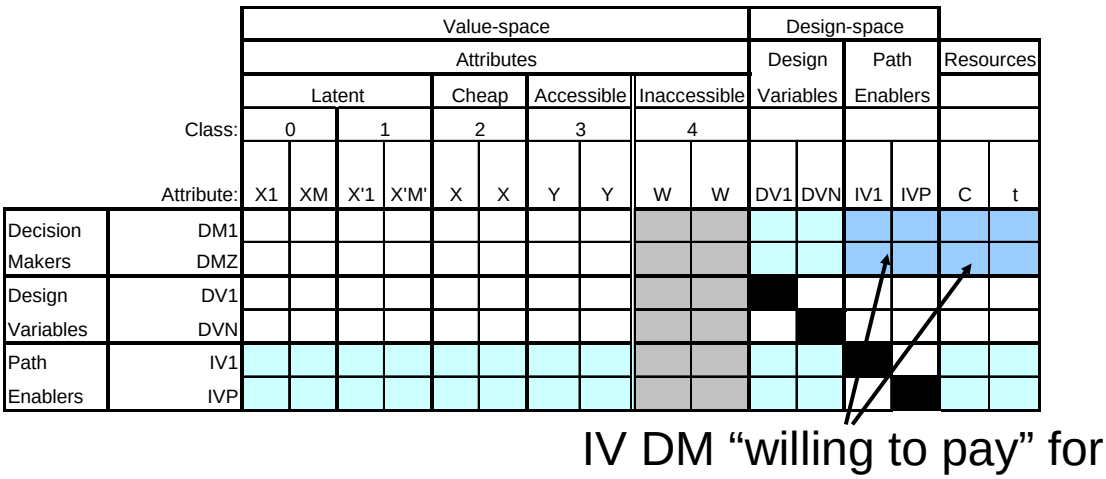


Figure 128 DVM with resource allocation indicated from path-enablers

8.15 Analysis Method Summary

Dynamic MATE analysis can be viewed in terms of a layered approach: construct tradespace, determine families of change scenarios (Epochs), construct system timelines to define the ilities (Era). (See Figure 129 below.)

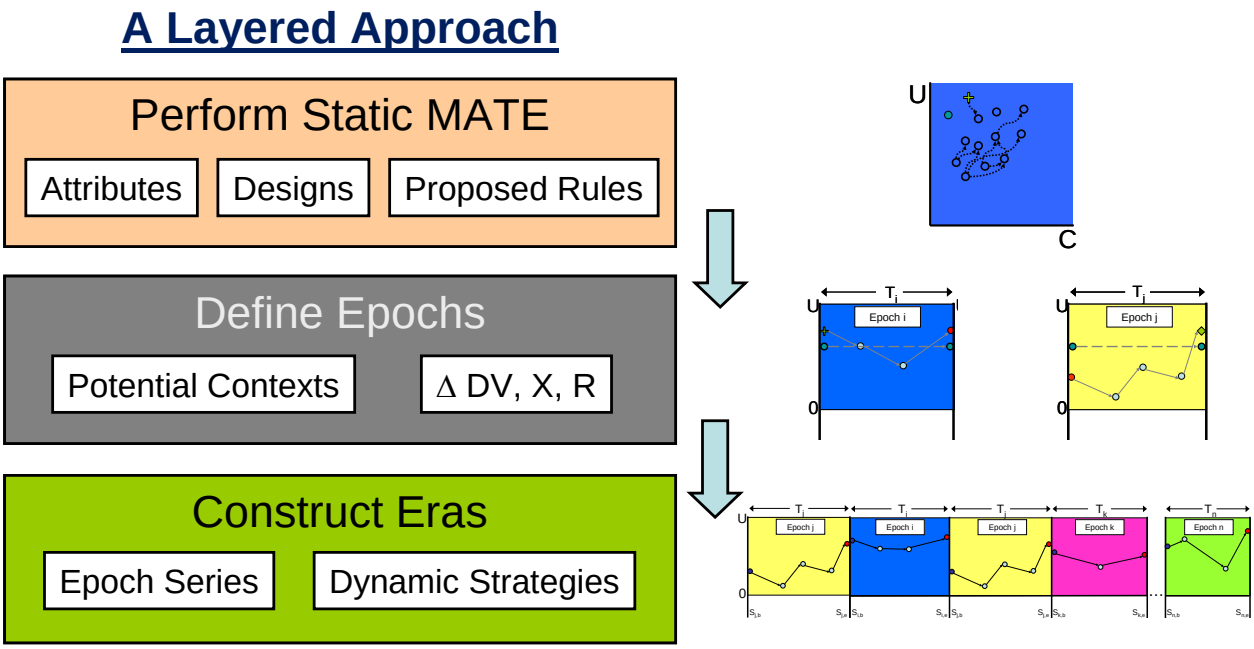


Figure 129 Dynamic MATE summary

In order to perform dynamic MATE, the following stages must be addressed:

Define the Mission and Decision Makers
Perform Static MATE (Construct the Tradespace)

- Preference elicitation (X, X→U)
- Concept formulation (DV)
- Models/simulations (C, DV→X)
- Preliminary transition rules (R)

Define Epochs

- Preference changes (from individual requirements to new decision makers)
- Policy or market context changes
- Technology changes (new concepts or transitions)
- New transition "rules" (R)

Construct Eras

- Define and calculate design-space ilities: flexibility, adaptability, rigidity
- Define and calculate value-space ilities: scalability, modifiability, robustness

Changeability (Flexibility, adaptability, modifiability, and scalability) is quantified as the filtered outdegree from a given design, as determined by the subjective cost threshold of a decision maker.

"**Passive value robustness**" is quantified as the Pareto Trace number for a given design, as determined by a set of change scenarios.

The Design-Value Matrix (DVM) can be used to track both articulated and unarticulated value, motivating the creation of transition paths that can be used to change designs in order to dynamically increase value to decision makers at low "cost."

The following two chapters provide detailed case applications of dynamic MATE to real world systems: the Joint Direct Attack Munition (JDAM) and the Terrestrial Planet Finder (TPF) systems.

Chapter 9: Case #1: Previously Designed System (Joint Direct Attack Munition, JDAM)

"Flex targeting" includes "real-time imagery and target location…against mobile targets" using "complete integration… of sensors" in order to "reduce the time from target identification to target destruction from hours and days to minutes" –Gen John Jumper 26 Oct 1999[133].

Figure 130 The Joint Direct Attack Munition variant GBU-31[134]

9.1 Overview

The Joint Direct Attack Munition (JDAM) system is a modification kit designed to transform a simple free-falling, "dumb" bomb into a precision guided "smart" bomb at low cost (see Figure 130). Motivated by combat needs during the first Gulf War (circa 1991), JDAM was proposed to solve the adverse weather problem that hampered bombing runs during dust storms and oil fires. The highly accurate laser-guided bombs, frequently touted on television, were expensive and too environmentally constrained in actual use.

Laser-guidance requires clear line-of-sight to the laser illuminated target. During the Gulf War, Iraqi air defense realized the limitations of laser-guided munitions and sought to obfuscate the targets. Oil fires, with thick black smoke, prevented lasers from being useful from a distance. Likewise, significant cloud cover necessitated bombers to fly lower in order to "see" their target, putting both aircraft and pilot at risk from air defenses. The weather restrictions, and short-supply and expense of the laser-guided munitions led "Air Force Chief Merrill McPeak [to call] for development of a bomb launched from 35,000 feet or higher hitting a target with precision but without the high price tag."[135]

The initial need specified by then Air Force Chief of Staff General Merrill McPeak was to create an "autonomous weapon" that can "attack a broad spectrum of fixed and relocatable targets," which can perform in "all weather," is highly "accurate" and is "low cost."[136] The Air Force and Navy developed programs to create tail kits in order to modify the large arsenal of "dumb" bombs in storage into guided munitions. In 1991 the two programs were joined to form the

[133] From Northrop Grumman Analysis presentation called "The B2-A Spirit: Kosovo and Beyond" on JDAM usage in Kosovo, 16 Feb, 2000. http://www.analysiscenter.northropgrumman.com/files/bk.pdf Cited 3/7/06.
[134] From Wikipedia "Joint Direct Attack Munition" entry http://en.wikipedia.org/wiki/Image:GBU-31_xxl.jpg Cited on 3/10/06.
[135] Sloyan, Patrick J. "The Bargain Basement Bomb." Long Island Newsday. November 14, 1999.
[136] pp 42. Ingols, Cynthia and Lisa Brem (1998). "Implementing Acquisition Reform: A Case Study on Joint Direct Attack Munitions." Case study. Fort Belvior, VA, Defense Systems College Management: 60.

JDAM program. Out of studies conducted at the Naval Air Weapons Station China Lake, a kit with a dual navigation system utilizing inertial and Global Positioning System (GPS) data was selected as the concept to pursue.[137] An initial contract award went to two prime contractors in 1994: Marin Marietta (now Lockheed Martin) and McDonnell Douglas (now Boeing). "The first phase of development, EMD-1, could be compared to the Demonstration and Validation phase of traditional acquisition processes."[138,139]

9.2 Static Analysis

The following section is a partitioning of the design problem, utilizing the classic MATE perspective.

9.2.1 Decision Makers, Requirements and Attributes

The key decision makers for JDAM were the following:

Air Force/Navy: As users, these divisions of the armed services were the initial motivators for the need, as personified by Chief of Staff General McPeak (and his later successors, including General John Jumper.)

JDAM System Program Office (SPO): Representatives from the SPO acted as proxies for the Air Force/Navy stakeholders, determining the system design acceptability on an on-going basis.

McDonnell Douglas: At the time of the project bidding and Phase I, McDonnell Douglas lost major contracts and faced large workforce reductions. The primary goal was to attain a long term, lucrative contract with the government.

McDonnell Douglas team: As designers, these people were primarily concerned with successful bidding to the government and passing into Phase II development of the system.

Due to overlapping preferences, these decision makers can be grouped into two key decision maker sets to be considered: **"Government"** (Air Force/Navy and JDAM SPO) and **"Prime"** (McDonnell Douglas and McDonnell Douglas design team).

The following seven objectives were defined by the government as "key performance parameters" that had to be met in order to achieve minimum acceptability standards:

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[137] According to the JDAM Chief Systems Engineer during development (private conversations). The GPS navigation enabled high precision targeting, while the inertial navigation system (INS) provided relatively accurate back-up in case of GPS-jamming or otherwise unavailability.

[138] pp 56. Lucas, Malee V. (1996). Supplier Management Practices of the Joint Direct Attack Munition Program. SM thesis in Aero/Astro. Massachusetts Institute of Technology. Cambridge, MA: 174.

[139] Notice that the first phase of development did NOT include concept exploration. As mentioned above by the Chief Systems Engineer and Proposal Manager for the McDonnell Douglas team, the concept of INS/GPS guidance with maneuverable tail kit for dumb bombs was already decided by the Government.

"Untradeable" Requirements set by Government[140]

1. Average Unit Procurement Price, AUPP = $40,000 / unit ($1991)
2. Ability to perform in adverse weather, WX = "yes"
3. Accuracy = 13m Circular Error Probable CEP
4. Aircraft compatibility = {B-1, B-2, B-52,F-22,FA-18C/D}=threshold, {F-16,F-15,F-117,FA-18E/F,AV-8,F-14,P-3,S-3}=objective
5. Aircraft carrier operability = "yes"
6. captive carriage in-flight retargeting = "yes"
7. Warhead compatibility = {MK-84, BLU-109, MK-83, BLU-110}

Transforming the requirements into attributes necessitates considering values beyond the "required" levels for the above seven quantities. These required levels will become the "minimum acceptable level" for the derived attributes. Since both poor-weather and good-weather accuracies may be assessed, the weather "requirement" will be folded into the accuracy requirement and split into "good weather accuracy" and "poor weather accuracy." Also, the captive carriage requirement has been expanded into "Retargeting Time," in order to address the ability to retarget as a continuum from not at all to instantaneous and continuous. Direction of increasing utility can be readily inferred from the definitions for the requirements. Additional attributes are proposed based on Prime being the other key decision maker in addition to the government. The proposed Government attributes with ranges are included in Table 15.

Table 15 Proposed JDAM Government Attributes

Name	Short Name	Units	"Best" level	"Worst" level	Direction of increasing utility	Definition
Average Unit Procurement Price	PU	$/unit	0	40000	lower	Average unit procurement price to Gov't
Adverse Weather Accuracy	WA	m CEP	0.01	30	lower	Maximum likely radial miss distance (poor weather)
Aircraft Compatibility[141]	AC	User-defined	1	0	higher	Aircraft in compatibility set[142]
Aircraft carrier operability	CS	binary	1	0	higher	Suitability to use on aircraft carrier

[140] pp 51. Ingols and Brem "Implementing Acquisition Reform: A Case Study on Joint Direct Attack Munitions." and conversations with JDAM Proposal Manager. These were the JDAM "Key Performance Parameters," or KPP.

[141] Aircraft Compatibility includes compatible aircraft *beyond* the minimally acceptable set ("threshold" above).

[142] The Aircraft Compatibility attribute can be defined as a multi-attribute utility function (MAUF) in order to reflect the varying value for including various aircraft in the set. Eight aircraft are in the "optional" set: F-16, F-15, F-117, FA-18E/F, AV-8, F-14, P-3, S-3. Let X^i = 1 or 0 ("yes" or "no") if aircraft *i* is included in the compatibility set. The decision maker can rank order from most to least important the aircraft for compatibility consideration. Based upon the work of Spaulding 2003, a normalized set of k_i value can be determined from the ranked list that should result in an isomorphic ordering with a fully-elicited k_i value set for a MAUF with these attributes. The resulting Aircraft Compatibility MAUF will range from 0 to 1 (none of these to all of these included) with values reflecting the combined value of having differing aircraft in the set. Conversations with the Prime clearly indicated different value for particular aircraft over others.

Name	Short Name	Units	"Best" level	"Worst" level	Direction of increasing utility	Definition
Retargeting Time	RT	minutes	0	infinite	lower	Minimum time before impacting target to set target position
Warhead Compatibility	WC	User-defined	1	0	higher	Warheads in compatibility set

As an example for creating the Aircraft Compatibility attribute see Table 16 and Figure 131. Table 16 lists aircraft ranked from most to least important to include in the compatible set. The normalized k_i value is derived based on the ranking (1st = 0.5, 2nd=0.4375, 3rd=0.375, etc. rounded to the nearest 0.05). Each aircraft *i* has the listed k_i value associated with it, and the X^i=1 or 0 ("yes" or "no") if JDAM is compatible with aircraft *i*. The Aircraft Compatibility value for a particular design of JDAM will range from 0 to 1 and be calculated using a multi-attribute utility function[143]. (In effect, the Aircraft Compatibility attribute is the decision maker's happiness with compatibility based on which aircraft are in the set.)

Table 16 Proposed Rank Listing of Desired Aircraft Compatibility

Rank of Importance	Aircraft	Normalized k_i
1	F-16	0.5
1	F-15	0.5
1	F-18E/F	0.5
4	F-14	0.3
5	F-117	0.25
5	AV-8	0.25
7	S-3	0.15
8	P-3	0.05

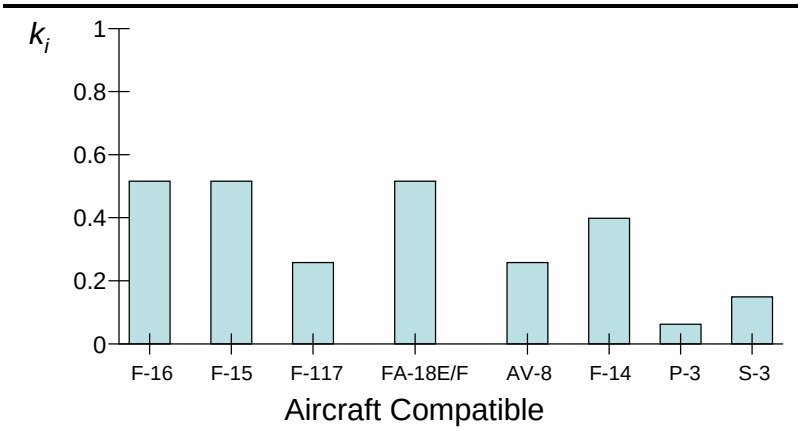


Figure 131 Example k_i Weights for Inclusion of Aircraft in Compatibility Set

[143] The "single attribute utility" is the same as X^i since inclusion is binary (either in the set or not). Thus, substituting X^i for $U^i(X^i)$ in the MAUF gives $U = \frac{\left(\prod_{i=1}^{8}\left(Kk_i X^i + 1\right)\right) - 1}{K}$, and *K* is the solution to $K + 1 = \prod_{i=1}^{8}\left(Kk_i + 1\right)$, for the case of k= [0.5, 0.5, 0.25, 0.5, 0.25, 0.3, 0.05, 0.15], K=-0.9511

The Warhead Compatibility attribute can be similarly constructed. For the sake of this study, however, compatibility with all required warheads ({MK-84, BLU-109, MK-83, BLU-110}) will be treated as a binary 0 or 1 ("yes" or "no") for full compatibility.

In addition to the Government attributes, Table 17 lists additional proposed Prime attributes.

Table 17 Proposed JDAM Prime Attributes

Name	Short Name	Units	"Best" level	"Worst" level	Direction of increasing utility	Definition
Average Unit Cost	CU	$/unit	0	40000	lower	Expected average unit cost to Prime at desired level of production

Based on conversations with the JDAM Proposal Manager, and thoughts about the intended uses for the system, additional potential attributes are listed in Table 18 below. The decision makers and attributes are captured in the Design-Value Matrix (DVM) in Figure 132 below, including both actual and potential attributes.

Table 18 Potential JDAM Attributes

Name	Short Name	Units	"Best" level	"Worst" level	Direction of increasing utility	Definition
Standoff Distance	SD	nmi	50	1	higher	Stand-off weapon release distance at 20,000 ft
Shelf Life	SL	years	30	1	higher	Mean time to failure for system in storage
Return on Investment	ROI	fraction	100	0	higher	Profit/cost for system
Clear weather enhanced accuracy	CA	m CEP	0.01	30	lower	Maximum likely radial miss distance (clear weather)

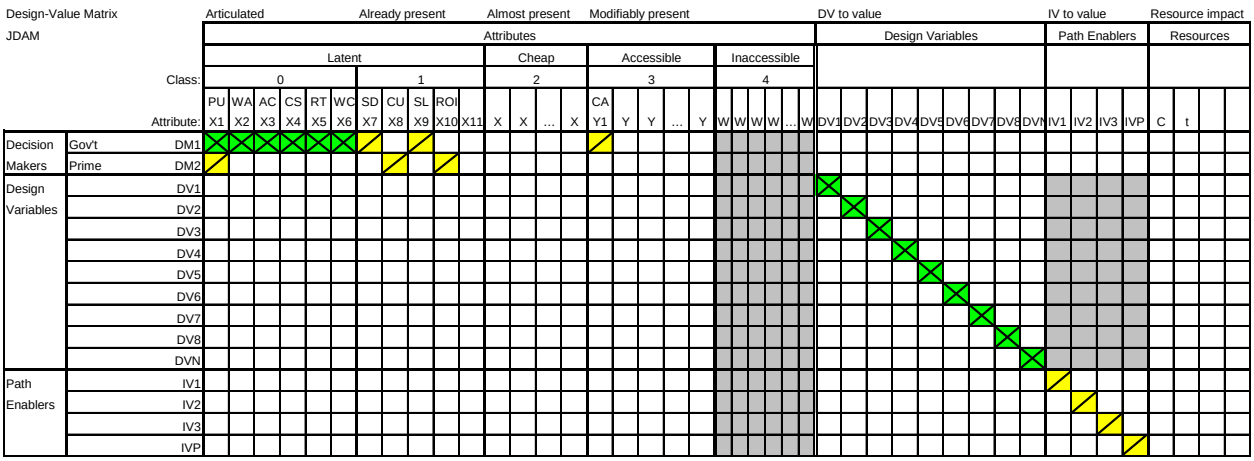


Figure 132 Design-Value Matrix for JDAM with Decision Makers and Attributes added

The utility functions for Government and Prime, including their k_i weights—their "priorities"—are shown in Figure 133 below. Linear utility functions were used for this case, as interview data was unavailable. The set shown in this figure correspond to the "original" Epoch for JDAM, meaning the initial set of expectations and constraints. In addition to the articulated average unit cost (CU) for Prime's attribute set, unit price (PU) and return on investment (ROI) were included to address the larger concerns of the firm (McDonnell Douglas). The lower the unit price, the higher the quantity demanded, or at least the better the firm would look to the government customer. On the other hand, the firm desires financial reward, captured in the ROI, for undertaking the endeavor.

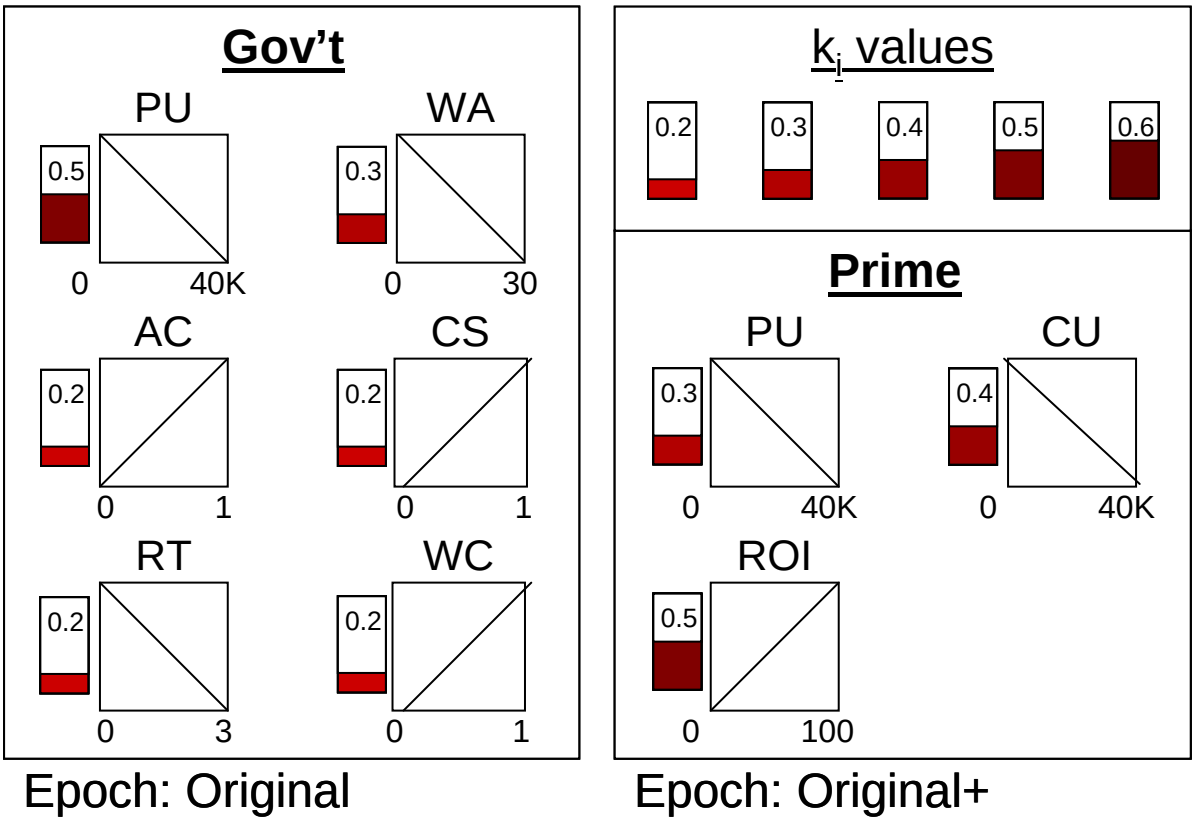


Figure 133 Government and Prime utility functions

9.2.2 Context and Constraints

The particular context for JDAM was one of an acquisition reform experiment. "The JDAM program was designated as a Defense Acquisition Pilot Program to implement the reform initiatives of the Federal Acquisition Streamlining Act of 1994."[144] Along with the focus on reducing cost came the new paradigm of "cost as an independent variable" or CAIV. CAIV allowed for "rational trade-offs between cost and performance with the full agreement of the

[144] pp 53. Lucas. Supplier Management Practices of the Joint Direct Attack Munition Program.

requirements officers."[145] As a part of this focus came an emphasis on teamwork and reduction of unit cost through innovation.[146]

The development schedule for Phase I (EMD-1) was 18 months, and the government did not want the typical reams of paperwork associated with a proposal. The development teams were encouraged to adopt commercial practices when possible, eliminating unnecessary military specifications and bureaucracy in order to reduce cost and development time. In particular, the design team was given class 2 change authority, enabling them to make system changes without paperwork justification before the fact. Additionally, Prime was able to retain ownership of the design specifications, as opposed to the usual mode of business where the government pays for and retains the design specifications.

The principal constraints placed on the development efforts were: 1) the concept of an INS/GPS tail kit for existing bombs, 2) the average unit procurement price must not exceed $40,000, and 3) the accuracy must not be worse than 30 m CEP (w/o GPS) or 13 m CEP (with GPS).

9.2.3 Concepts

Considering the mission concept and objectives for the system, the basic functions that the system has to perform are the following:

1. Know position of self relative to target
2. Decide how to get to target
3. Get self to target
4. Interface with aircraft
5. Interface with warhead
6. Operate on aircraft carrier without negative effects
7. Be "cheap" to procure by the government

Function 1 can be broken into two parts if absolute knowledge is possible:
1a. Know self position
1b. Know target position

Given the concept constraint of an INS/GPS tail kit modification on existing warheads, the following design-space variables can be created:

The Navigation System performs function 1a, while the Targeting System performs function 1b. (In a relative position system, these two functions are combined into a "difference" function.)

The Control System (software) performs the differencing function to determine the path to take to get from current position to target position, function 2.

[145] pp 151. Lucas. Supplier Management Practices of the Joint Direct Attack Munition Program.
[146] Lucas. Supplier Management Practices of the Joint Direct Attack Munition Program. for an extensive discussion on the stimulation of architectural innovation due to teamwork in a cost-cutting, but open-communication environment.

The Maneuvering System performs function 3 (since the weapon is "thrown" from the aircraft, it does not have to impart its own velocity to get to target, but rather only alter its velocity and orientation).

The "shape" of the JDAM affects its ability to fit in an aircraft and is the principal determinant of aircraft compatibility and warhead compatibility, functions 4 and 5.[147]

The overall environmental robustness and inertness determines the JDAM aircraft carrier suitability, function 6.[148]

Lastly, the price charged by McDonnell Douglas determines the Average Procurement Price to the government, "function" 7. Even though the price is under the designer's control, profitability goals, namely the return on investment, dictate the unit price exceed the unit cost by some amount. By varying the price, McDonnell Douglas can also potentially increase the quantity demanded, leveraging the market forces of supply and demand, possibly increasing net revenues.

Table 19 Proposed JDAM Design Variables

Name	Short Name	Units	Range	Type	Definition
Planform	Plf	user-defined	{None, strakes/tail fins, canard/wing, etc.}	current	"Aeroshape" including controls for maneuverability
Navigation System	NS	user-defined	{None, INS, INS/GPS, GPS, INS/GPS/aircraft updating, INS/GPS/aircraft updating/diff GPS}	current	Type of system for determining self position
Targeting System	TS	user-defined	{None, fixed data, remote comm.}	current	Type of system for determining target position
Goal AC	GA	user-defined	Same as AC	current	Goal aircraft compatibility
Software	Sfw	user-defined	{simple to complex}	current	Type of software for determining best "path" from current to target
Aircraft Carrier Compatibility	Acom	binary	yes-(no)	fixed	Constraint for hardware/software to meet aircraft carrier environment
Unit Price Charged	PC	$/unit	0-40000	current	Dollars charged per unit
Inflight Comm	IC	user-defined	yes-no	potential add to GS	Type of onboard remote communication capability for inflight target/position updating
Laser Sensor	LS	user-defined	yes-no	potential add to GS	Type of laser sensor for target tracking

[147] According to JDAM Chief Systems Engineer (private communication). The "shape" includes the planform.

[148] The aircraft carrier suitability requirement derives principally from 1) EMI constraints with the carrier's ubiquitous radiation environment (radars, radios, etc), 2) G-load constraints regarding catapult-assisted take-off and capture, 3) corrosive environment constraints (salt water), and 4) sizing constraints (kit must fit through doorways and in standard storage containers

Name	Short Name	Units	Range	Type	Definition
Wings	Wng	user-defined	yes-no	potential add to Plf	Type of wings for increased range
Terminal Guidance	TG	user-defined	yes-no	potential add to GS	Type of terminal guidance for close-range target tracking

Table 19 shows the list of proposed design variables that reflect these considerations. The Maneuvering System is considered to be the "airframe" for JDAM, including the planform (shape and movable control surfaces).[149] Together, the Navigation and Targeting Systems along with the Control System can be considered the Guidance System (GS). The Control System will be traded through the "software" design variable. The Aircraft Carrier Compatibility design variable will be treated as a fixed constraint to be applied to all other design considerations, driving system architecture and component selection to perform in the carrier environment. The last four potential design variables are technically additions to other design variable enumeration values, but for clarity in this example, they have been drawn out explicitly to show how they relate to potential systems.[150] (These design options were not included in the original JDAM design, however, they could be considered as modifications to the existing system.)

The potential design variables represent attempts to expand the tradespace to consider designs that may perform better if preferences change. In particular, if increased performance or new attributes become important (e.g. if stand-off distance becomes an attribute, or minimum acceptable retargeting time becomes shorter.)

The design variables are entered into a DVM in Figure 134.

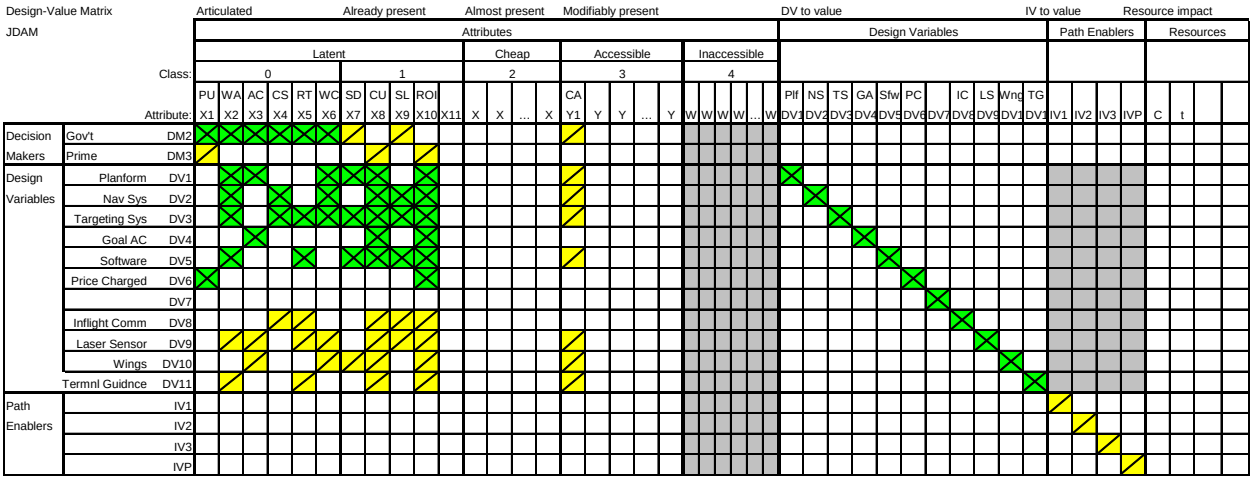


Figure 134 Design-Value Matrix for JDAM with Design Variables added

[149] For the purposes of the trade study, "planform" will be taken to mean the aeronautical concept, including the overall shape of the airframe and the movable control surfaces—in short, the system that results in air maneuverability.

[150] See "type" category for which design variables the last three design variables should fall under. For example "Wing" can be included in the "Planform" enumeration set, and "Laser sensor" can be included in the "Guidance System" (GS, consisting of Targeting System and Navigation System).

After the attributes and design variables have been proposed, a model must be developed. The notional flow for such a model is given in Figure 135 below. Both current and potential design variables and attributes are included for completeness. The Actual Current Position is estimated by the Navigation System. Together with an estimate for the Actual Target Position, the data is fed into the Control System ("software" design variable), which determines the best "path" to get from Current to Target Position, potentially including weapon orientation. Included in the Control System software is sophisticated aerodynamics models for the JDAM. The control data is passed to the Maneuvering System ("planform" design variable), which manipulates its control surfaces to affect the Actual Current Position of the JDAM. Both the Navigation and Targeting Systems update their estimates of the Actual Current and Target Positions, respectively, and the process repeats. The Aircraft Carrier Compatibility design variable acts as a constraint on the detailed design of the Navigation, Targeting, and Maneuvering Systems. The Goal Aircraft Compatibility design variable is likewise used as a variable constraint on the planform: the selected planform is "nibbled" in order to fit into the goal aircraft set.[151]

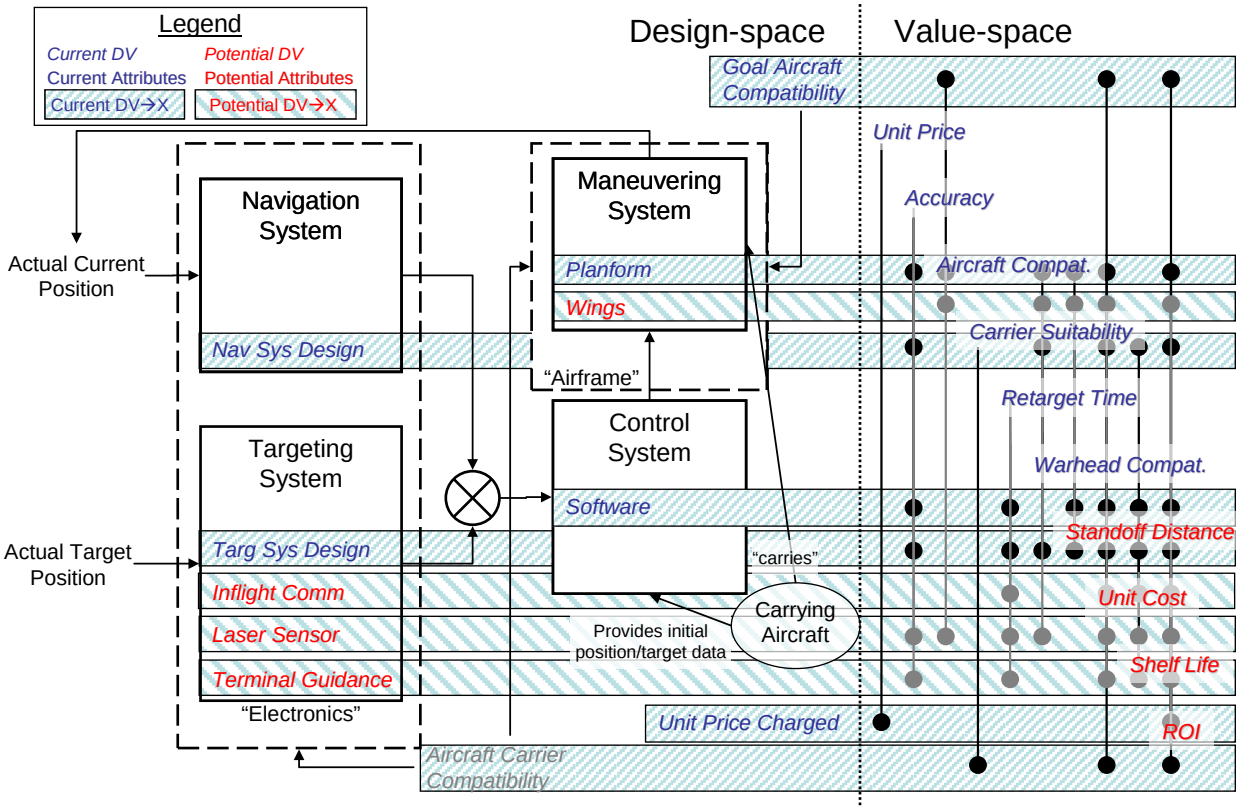


Figure 135 JDAM simple Design-Value model

[151] According to the JDAM Chief Systems Engineer, "nibbling" the planform means making minor cutouts and adjustments in the geometry of the airframe in order to fit under an aircraft. Wind tunnel tests and detailed aerodynamic simulations show little to no effect from "nibbling." It is conceivable that major "nibbling" may be required in some instances, resulting in actual aircraft compatibility being less than goal aircraft compatibility.

The model can be used to assess various designs in terms of their levels of the attributes, including cost.

9.2.4 Application of the Static MATE Framework

Strictly adhering to the MATE framework suggests the creation of models to accurately differentiate between design options in term of their attributes and cost. Determining the appropriate level of model fidelity requires knowledge of the relative importance of the attributes and their sensitivity to design values. The most important attribute for JDAM was the average unit procurement price, or PU from Table 15. In order to accurately model PU, details for unit cost must also be known.[152] Determining unit cost requires predicting the development cost, manufacturing, testing, and assembling costs, and warranty costs for JDAM as a function of units produced.[153] Such detailed modeling either requires proprietary data, or detailed design models, including component selection, beyond the scope of this case application. If a MATE analyst were part of the actual JDAM development team, such analysis would be possible

For the current MATE analysis of JDAM, a detailed quantitative model was not available due to researcher resource constraints (time and knowledge). Instead, a semi-quantitative evaluation framework was applied. In particular, due to imprecise cost estimates, the differentiation of design points has too much uncertainty to draw definitive conclusions. Instead, point designs can be compared qualitatively to determine "best" options. (Since the cost estimates are uncertain, the "answers" are likewise uncertain. The analysis process, however, can still be followed for insights. Once proper cost models or data are available, they can be readily considered and used to reduce the uncertainty.[154] The following analysis assumes the cost data is appropriate for pedagogical purposes.)

Figure 136 below shows the resulting Government Utility-Cost tradespace from running the model. The lower strip of zero utility designs is the set of "dumb" bomb configurations, without any guidance control unit.[155]

[152] Presumably McDonnell Douglas will set the price such that expected revenues exceed expected costs for actual procurement levels of production.

[153] pp. 50. Ingols and Brem "Implementing Acquisition Reform: A Case Study on Joint Direct Attack Munitions."

[154] The cost model used in this case study is a simple additive one with cost data collected from various sources including reports, case studies, and estimates by analogy to publicly available technology. A more advanced cost model using grass roots cost estimation and actual parts costs would vastly improve the cost predictions for the design points and likewise the government utility. No price elasticity data was used to determine the relation between price and demand for units of JDAM. Such data would improve the model as well.

[155] Strictly speaking, the "dumb" bomb configurations provide undefined utility since they perform worse than the "least acceptable" level of the attributes and do not have zero utility. They are included in the plot as zero utility to show the large number of unacceptable designs.

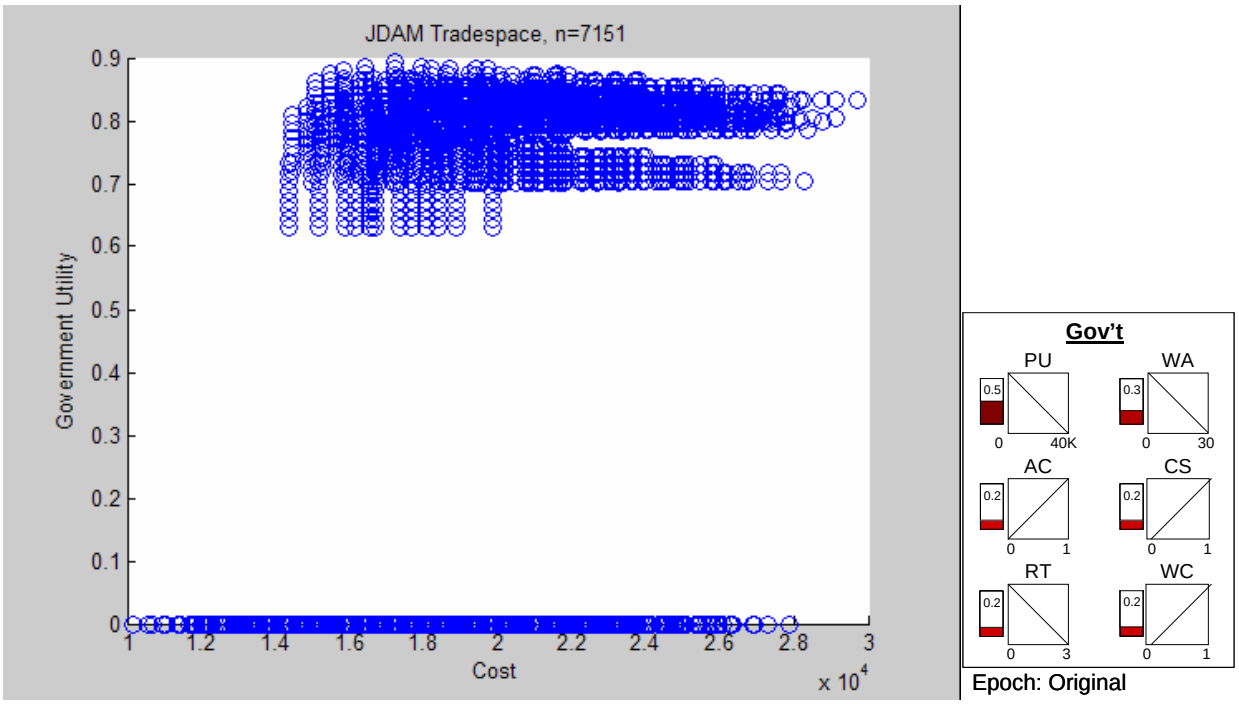


Figure 136 JDAM Government Utility-Cost Tradespace

Figure 137 below shows the same tradespace in terms of Government and Prime utility. The "best" set of designs in terms of being non-dominated solutions, lie furthest to the right or top. Notice that the zero Government utility designs still provide utility to the Prime. Unfortunately for Prime, since those designs do not provide value to the customer, the utility can not be realized.

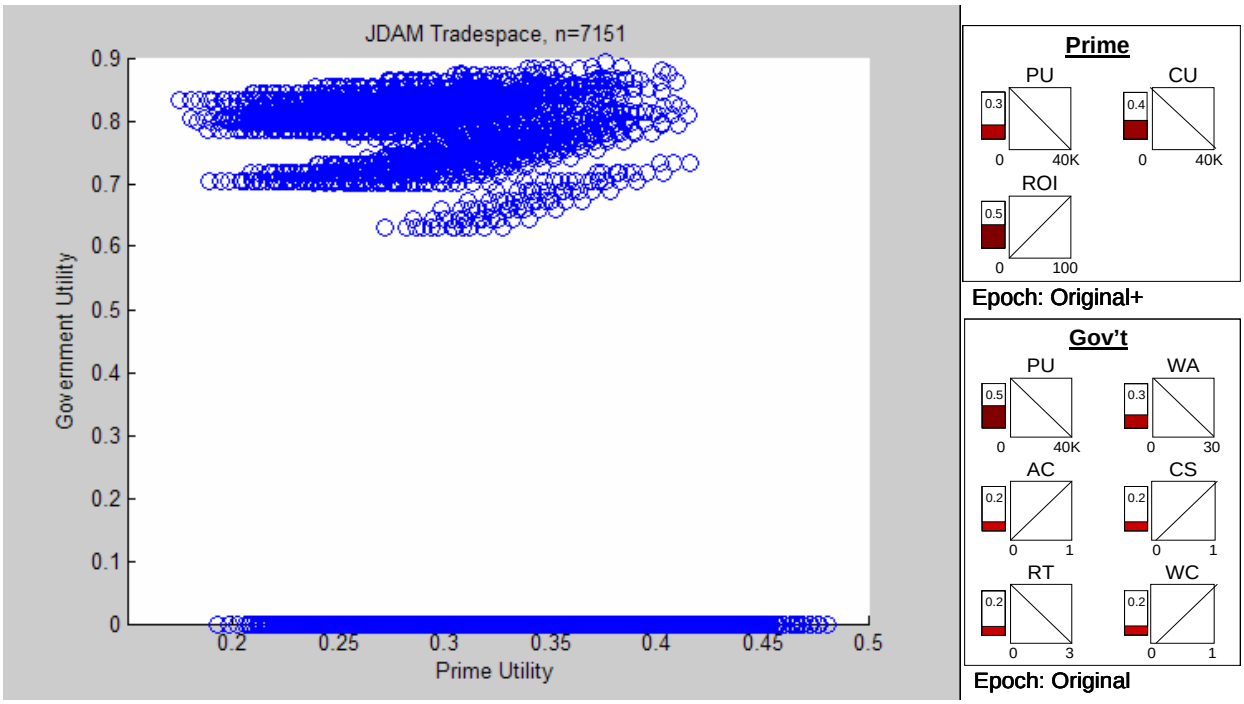


Figure 137 JDAM Government Utility-Prime Utility Tradespace

9.3 Dynamic Analysis

After the static analysis is complete, the next step is to consider potential changed contexts, or Epochs, for the system. In general, change types can include the following: changes in technology, available concepts, usage or function, value proposition or requirements, physical properties, policies, or market conditions.[156] Assuming a JDAM system is developed, the context in which the system may be used will change with time. Possible contexts include the following:

Constraint change (resource, political, market, physical, operational, etc)

Δmarket, political: Following successful use in Kosovo in 1999, and the recent move to combat in the Middle East (2002+), the number of JDAMs ordered has increased beyond original projections. Larger production scales can enable better leverage with suppliers to create cheaper components, resulting in larger ROI.

Preference-space change ({DM}, $\{X^{Mi}\}$, $\{k^{Mi}\}$, $U^i(X^i)$, $\hat{C}$,$\hat{t}$)

$\Delta\{k^{Mi}\}$, $U^i(X^i)$: The government decides that it wants improved accuracy (either an increase in the priority, or k_i value, for that attribute, or a shifting of the utility curve to a lower best and/or minimally acceptable level).

$\Delta\{k^{Mi}\}$, $\{X^{Mi}\}$: The government decides to "allow" trades, such as for reduced poor weather performance, or improved clear weather performance at higher cost.

$\Delta\{X^{Mi}\}$, $U^i(X^i)$: The government desires a farther standoff distance, the distance from a target when the JDAM is released, in order to further reduce risk to pilots and their aircraft. Another possible desire is for new warhead or aircraft compatibility.

Δ{DM}, $\{X^{Mi}\}$: The opening of foreign markets, especially European allies, expands the potential warhead and aircraft compatibility sets, as well as introduces additional key decision makers into consideration (including potential policy constraints).

Design-space change (Technologies, concepts)

Δtechnology: Additional design variables that can improve the accuracy can be considered, as technology improves for differential GPS, or wireless targeting updates to the JDAM in flight.

Facing a potentially changing context, JDAM changeability should be considered. A changeable JDAM is one that has many "ways" to turn into other design instantiations at "cheap" cost in order to achieve new "displayed" attributes and attribute levels.

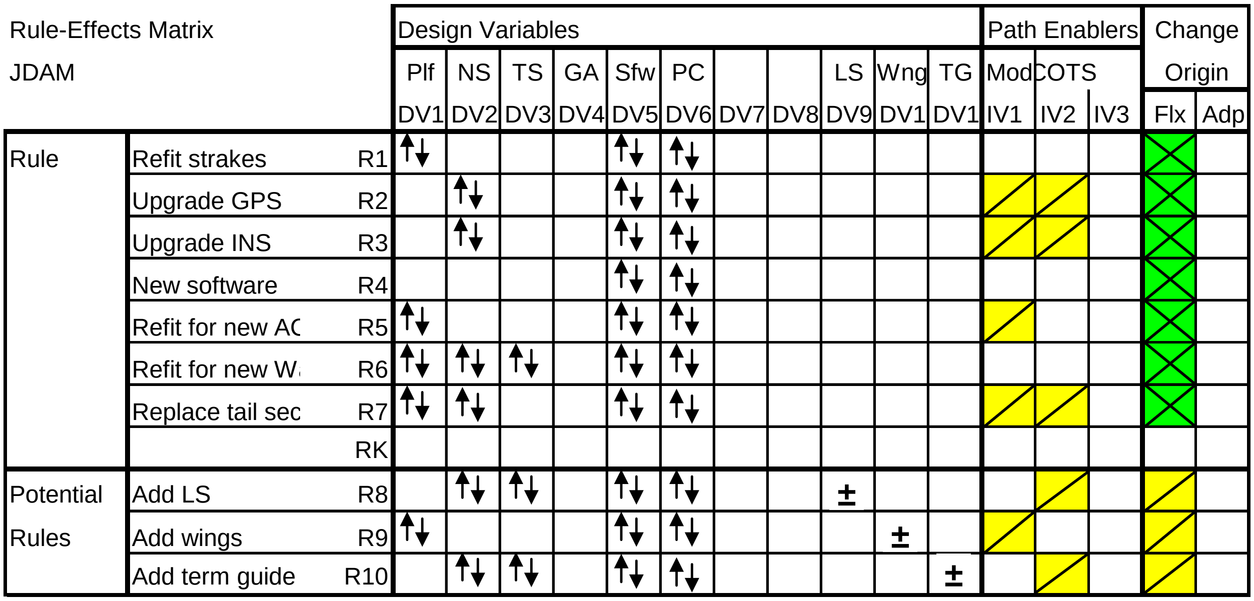
Table 20 lists proposed rules for changing JDAM from one design instantiation into another. Figure 138 below places these rules into a Rules-Effects Matrix (REM) to display the effects of the rules on the design variables. The listed Path Enablers are "Modularity" (Mod) and "Using Commercial Components" (COTS). The indication of "potential" for the path enablers means that even though not required, if the enablers are present, the cost for the change path will be reduced, thereby increasing the perceived changeability. Notice that the origin for all of these listed changes is external, meaning the changes are "flexible" as opposed to "adaptable." Figure

[156] This list of potential changes is not exhaustive.

139 below wraps the REM data into the DVM for completeness. One of the implications apparent in the DVM is that if changeability is desired, both modularity and use of commercial components should be embraced, since they positively affect the attributes of interest to both decision makers.

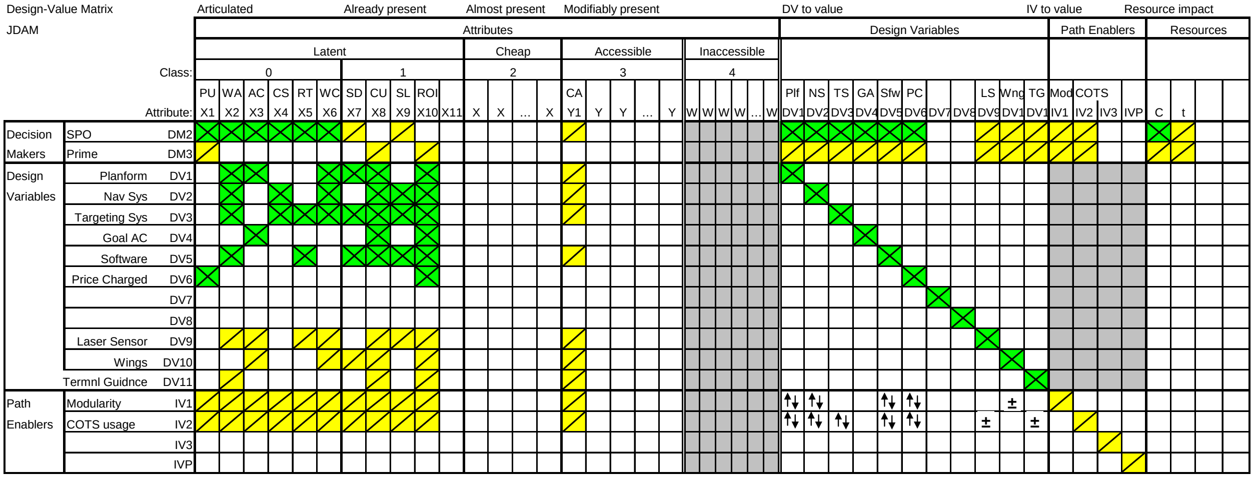
Table 20 Proposed JDAM Transition Rules

Rule	Description	Change agent origin
R1: Refit strakes	Alter planform, plus software model and price	External (Flexible)
R2: Upgrade GPS	Alter navigation system, plus software model and price	External (Flexible)
R3: Upgrade INS	Alter navigation system, plus software model and price	External (Flexible)
R4: New software	Alter software model, plus price	External (Flexible)
R5: Refit for new Aircraft	Alter planform to fit on added aircraft, plus software model and price	External (Flexible)
R6: Refit for new Warhead	Alter planform, navigation and targeting system to fit on added warheads, plus software and price	External (Flexible)
R7: Replace tail section	Alter planform, plus navigation system, software model, and price	External (Flexible)
R8: Add laser sensor	Add laser sensor, alter navigation and targeting systems, software, and price	External (Flexible)
R9: Add wings	Add wings, alter planform, software and price	External (Flexible)
R10: Add terminal guidance	Add terminal guidance, alter navigation and targeting systems, software, and price	External (Flexible)



Rule-Effects Matrix			Design Variables											Path Enablers			Change	
JDAM			Plf	NS	TS	GA	Sfw	PC			LS	Wng	TG	Mod	COTS		Origin	
			DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	DV1	DV1	IV1	IV2	IV3	Flx	Adp
Rule	Refit strakes	R1	↑↓				↑↓	↑↓									🟩	
	Upgrade GPS	R2		↑↓			↑↓	↑↓						🟨	🟨		🟩	
	Upgrade INS	R3		↑↓			↑↓	↑↓						🟨	🟨		🟩	
	New software	R4					↑↓	↑↓									🟩	
	Refit for new AC	R5	↑↓				↑↓	↑↓						🟨			🟩	
	Refit for new W.	R6	↑↓	↑↓	↑↓		↑↓	↑↓									🟩	
	Replace tail sec	R7	↑↓	↑↓			↑↓	↑↓						🟨	🟨		🟩	
		RK																
Potential	Add LS	R8		↑↓	↑↓		↑↓	↑↓			±				🟨		🟨	
Rules	Add wings	R9	↑↓				↑↓	↑↓				±		🟨			🟨	
	Add term guide	R10		↑↓	↑↓		↑↓	↑↓					±		🟨		🟨	

Figure 138 Proposed Rule-Effects Matrix for JDAM



Design-Value Matrix			Articulated						Already present					Almost present				Modifiably present											DV to value										IV to value				Resource impact				
JDAM			Attributes																										Design Variables											Path Enablers				Resources			
			Latent											Cheap				Accessible					Inaccessible																								
		Class:	0						1					2				3					4																								
			PU	WA	AC	CS	RT	WC	SD	CU	SL	ROI						CA											Plf	NS	TS	GA	Sfw	PC			LS	Wng	TG	Mod	COTS						
		Attribute:	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X	X	…	X	Y1	Y	Y	…	Y	W	W	W	W	…	W	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	DV1	DV1	IV1	IV2	IV3	IVP	C	t		
Decision	SPO	DM2	🟩	🟩	🟩	🟩	🟩	🟩	🟨		🟨							🟨					▒	▒	▒	▒	▒	▒	🟩	🟩	🟩	🟩	🟩	🟩			🟨	🟨	🟨	🟨	🟨			🟩	🟨		
Makers	Prime	DM3	🟨							🟨		🟨											▒	▒	▒	▒	▒	▒	🟨	🟨	🟨	🟨	🟨	🟨			🟨	🟨	🟨	🟨	🟨			🟨	🟨		
Design	Planform	DV1		🟩	🟩			🟩	🟩	🟩		🟩						🟨					▒	▒	▒	▒	▒	▒	🟩											▒	▒	▒	▒				
Variables	Nav Sys	DV2		🟩		🟩		🟩		🟩	🟩	🟩						🟨					▒	▒	▒	▒	▒	▒		🟩										▒	▒	▒	▒				
	Targeting Sys	DV3		🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩						🟨					▒	▒	▒	▒	▒	▒			🟩									▒	▒	▒	▒				
	Goal AC	DV4			🟩					🟩		🟩											▒	▒	▒	▒	▒	▒				🟩								▒	▒	▒	▒				
	Software	DV5		🟩			🟩		🟩	🟩	🟩	🟩						🟨					▒	▒	▒	▒	▒	▒					🟩							▒	▒	▒	▒				
	Price Charged	DV6	🟩									🟩											▒	▒	▒	▒	▒	▒						🟩						▒	▒	▒	▒				
		DV7																					▒	▒	▒	▒	▒	▒							🟩					▒	▒	▒	▒				
		DV8																					▒	▒	▒	▒	▒	▒								🟩				▒	▒	▒	▒				
	Laser Sensor	DV9		🟨	🟨		🟨	🟨		🟨	🟨	🟨						🟨					▒	▒	▒	▒	▒	▒									🟩			▒	▒	▒	▒				
	Wings	DV10			🟨			🟨	🟨	🟨		🟨						🟨					▒	▒	▒	▒	▒	▒										🟩		▒	▒	▒	▒				
	Termnl Guidnce	DV11		🟨						🟨		🟨						🟨					▒	▒	▒	▒	▒	▒											🟩	▒	▒	▒	▒				
Path	Modularity	IV1	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨						🟨					▒	▒	▒	▒	▒	▒	↑↓	↑↓			↑↓	↑↓				±		🟨							
Enablers	COTS usage	IV2	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨						🟨					▒	▒	▒	▒	▒	▒	↑↓	↑↓	↑↓		↑↓	↑↓			±		±		🟨						
		IV3																					▒	▒	▒	▒	▒	▒														🟨					
		IVP																					▒	▒	▒	▒	▒	▒															🟨				

Figure 139 Design-Value Matrix for JDAM with Path Enablers added

9.4 Results

The following sections describe the dynamic MATE analysis results.

9.4.1 Comparison to Actual Designs

Since the JDAM concept was fixed as an INS/GPS tail kit modification, the actual JDAM development team did not consider as broad a conceptual design tradespace as this study. The phase I design work was done at a detailed level, so the primary design variables considered by the McDonnell Douglas team reflect a more detailed-design orientation. After planform selection, the variables considered were: tail control fin, tail actuator system, tail fairing, guidance control unit, wire harness, and strakes. Figure 140 shows the physical layout of the strakes and tail in relation to the warhead. The guidance control unit is housed within the tail. According to the JDAM Chief Systems Engineer, extensive trades were done on the planform to be used. The key trades involved affecting the shape of "footprint" and cost. Cost estimates were based on design

all the way down to circuit card manufacturing, with some higher cost circuit components being traded as well.

Prior to JDAM, internally funded research and development efforts had been conducted at McDonnell Douglas on guidance sets with tightly coupled GPS and INS. The team modified that work to improve its affordability, but essentially began with the already developed guidance technology.

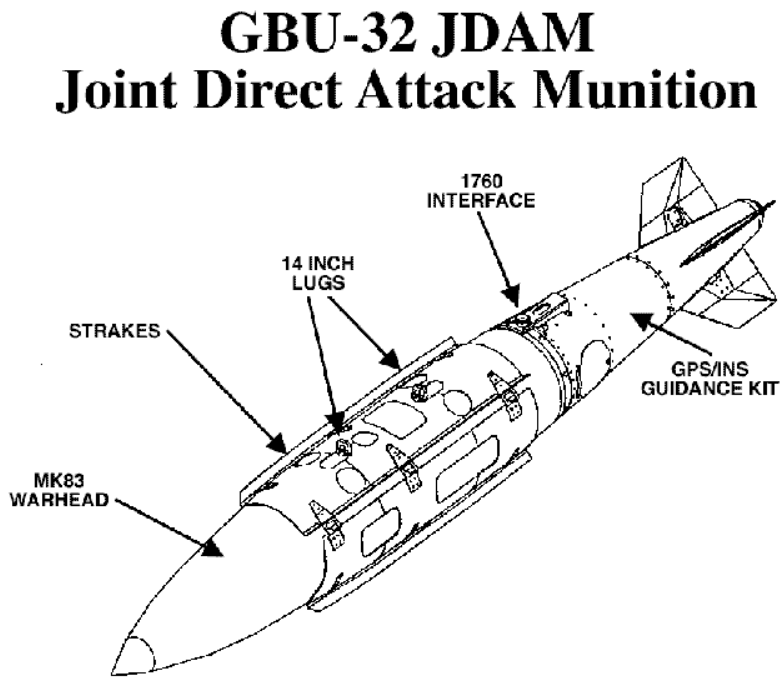


Figure 140 Sketch of JDAM with major components[157]

The concept tradespace for JDAM was not explored beyond the GPS/INS tail kit. Principal trades involved the planform, and component architecture and selection for affordability. The planform selected was a maneuverable tail fin and strake combination. The tail fin altered the JDAM flight path, while the strakes provided additional lift. Aircraft compatibility was treated as a constraint, since it represented a larger "potential market" for the JDAM. Likewise, warhead compatibility was assumed to be for 2000 lb and 1000 lb bombs, plus the unasked for 500 lb bomb since the largest stockpiles were of these three classes (and thus represented the largest "potential market" for selling JDAM).

Due to variation with the geometry of warhead types, variants of the planform had to be developed. Strakes had to be customized for each warhead, and tail fairings had to be scaled for the size of the warhead as well. The guidance control unit was identical in all variants, and the software highly common. Due to differences in the airframes among the variants, the software

[157] From Federation of American Scientists website http://www.fas.org/man/dod-101/sys/smart/jdam.htm Cited 3/7/06

had minor modifications to account for the differences. Figure 141 shows the principal warhead types with JDAM kits installed. The current JDAM variants and warhead types include:

Warhead type	JDAM Variant	Size
MK-84/BLU-109	GBU-31	2000 lb
MK-83	GBU-32	1000 lb
BLU-110	GBU-35	1000 lb
MK-82	GBU-38(30)	500 lb
MK-81	GBU-29	250 lb

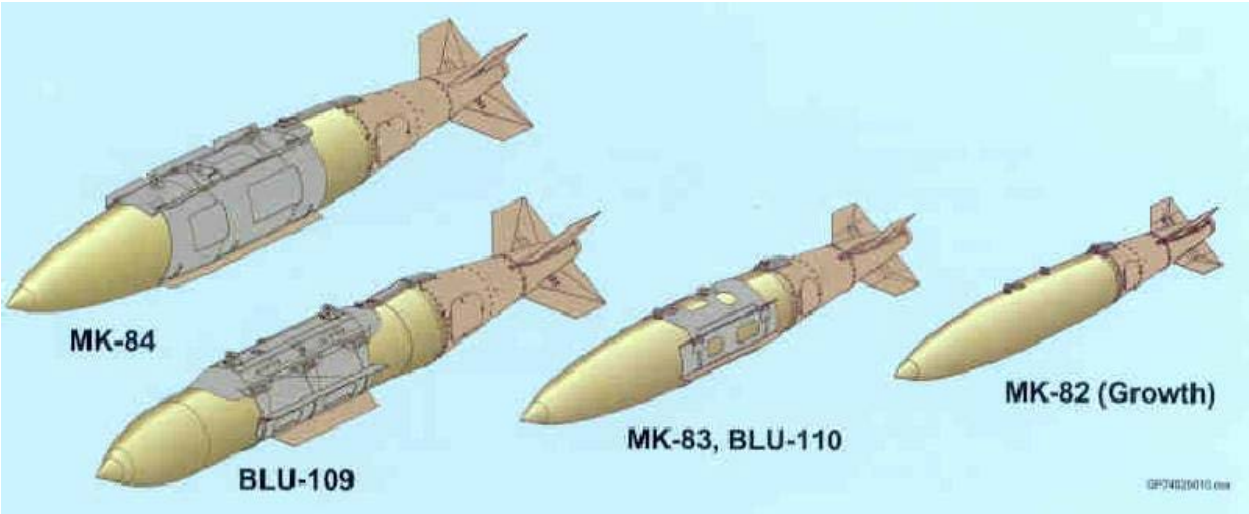


Figure 141 JDAM variants for various warheads[158]

The accuracy achieved by the GPS/INS readily exceeded the 13m CEP requirement and was not actively improved since it would require an increase in cost. "Affordability at any cost" drove the team to not consider trades that would increase the constantly decreasing average unit procurement price (AUPP). The trading of "performance exceeding requirements" for slightly higher cost is considered to be "requirements creep" and in the acquisition reform environment, considered unacceptable.[159]

In summary, the actual JDAM system had the design variable and attribute values shown in Table 21.

[158] From Federation of American Scientists website http://www.fas.org/man/dod-101/sys/smart/jdam.htm Cited 3/7/06

[159] The cost-performance trade-off was encouraged for non key performance parameters, but not for the "live-or-die" requirements. See Lucas. Supplier Management Practices of the Joint Direct Attack Munition Program.

Table 21 JDAM Actual Design Variable and Attribute Values

DV Name		Value	Attribute Name		Value
Planform	Plf	strakes w/tail fins	Average Unit Procurement Price	PU	$21000[160]
Navigation System	NS	INS/GPS	Adverse Weather Accuracy[161]	WA	10 (30) m CEP[162]
Targeting System	TS	Input static data[163]	Aircraft Compatibility	AC	0.943[164]
Goal AC	GA	0.9914[165]	Aircraft carrier operability	CS	1 (yes)
Software	Sfw	version X.X?[166]	Retargeting Time	RT	>2 min?[167]
Aircraft Carrier Compatibility	Acomp	1 (yes)	Warhead Compatibility	WC	1 (all)
Unit Price Charged	PC	$21000	Average Unit Cost	CU	<$21000[168]
Laser Sensor	LS	0 (no)	Standoff Distance	SD	8 n mi
Wings	Wng	0 (no)	Shelf Life	SL	20 yrs
Terminal Guidance	TG	0 (no)	Return on Investment	ROI	>0?[169]
			Clear weather enhanced accuracy	CA	9 (30) m CEP

Figure 142 and Figure 143 below show the same tradespace from Figure 136 and Figure 137, but with the JDAM actual design added for comparison. The presence of multiple points reflects allowing the price charged to vary. The JDAM plotted is considered "version 1" and corresponds to the initial capability of the system when declared operational. (For these plots a utility of zero does not correspond to "minimally acceptable" but rather to "unacceptable" and were included solely to demonstrate the large number of unacceptable designs.)

[160] FY2001 dollars, from Air Force military spec sheet (http://www.af.mil/factsheets/factsheet.asp?id=108, Cited 3/11/06)

[161] An important consideration in accuracy is the fact that "hitting the target" requires accurate target position data. Improvements in target position determination, external to JDAM, will improve the accuracy of the system in practice (such as enhanced synthetic aperture radar (SAR) onboard B2-A aircraft for real-time updating of JDAM target information prior to JDAM release).

[162] The actual accuracy, according to Boeing sources, is around 10 m with GPS/INS. If GPS is unavailable, the highly robust INS can provide about 30 m accuracy.

[163] Targeting data is downloaded into the JDAM prior to release from the carrying aircraft, loaded either on the ground or captive in-flight carriage.

[164] According the Air Force military spec sheet (http://www.af.mil/factsheets/factsheet.asp?id=108, Cited 3/11/06) in addition to the minimally acceptable set, JDAM is compatible with {F-16C/D, F-15E, F/A-18E/F, F-14A/B/D}, but not yet {F-117, AV-8B, S-3} or P-3. This gives the compatibility X=[1,1,0,1,0,1,0,0] now, with soon X=[1,1,1,1,1,1,0,1], leading an increase in AC from the current 0.943 to 0.9974, assuming the same priority rankings for goal compatible aircraft.

[165] According to the JDAM Chief Systems Engineer, compatibility with the S-3 was not sought since the aircraft was intended to be retired soon.

[166] The actual software algorithm employed is proprietary information

[167] Since the targeting data is fixed after release, the retargeting time is at minimum the duration of flight after release from carrying aircraft. Assumes at least a 2 minute flight (actual time will vary: the closer to target the release, the shorter the retarget time).

[168] Implied by the financial success of the program, average unit costs must be less than average unit procurement price.

[169] Calculation of ROI requires proprietary information not accessible to the researcher. The design team would have this information, however.

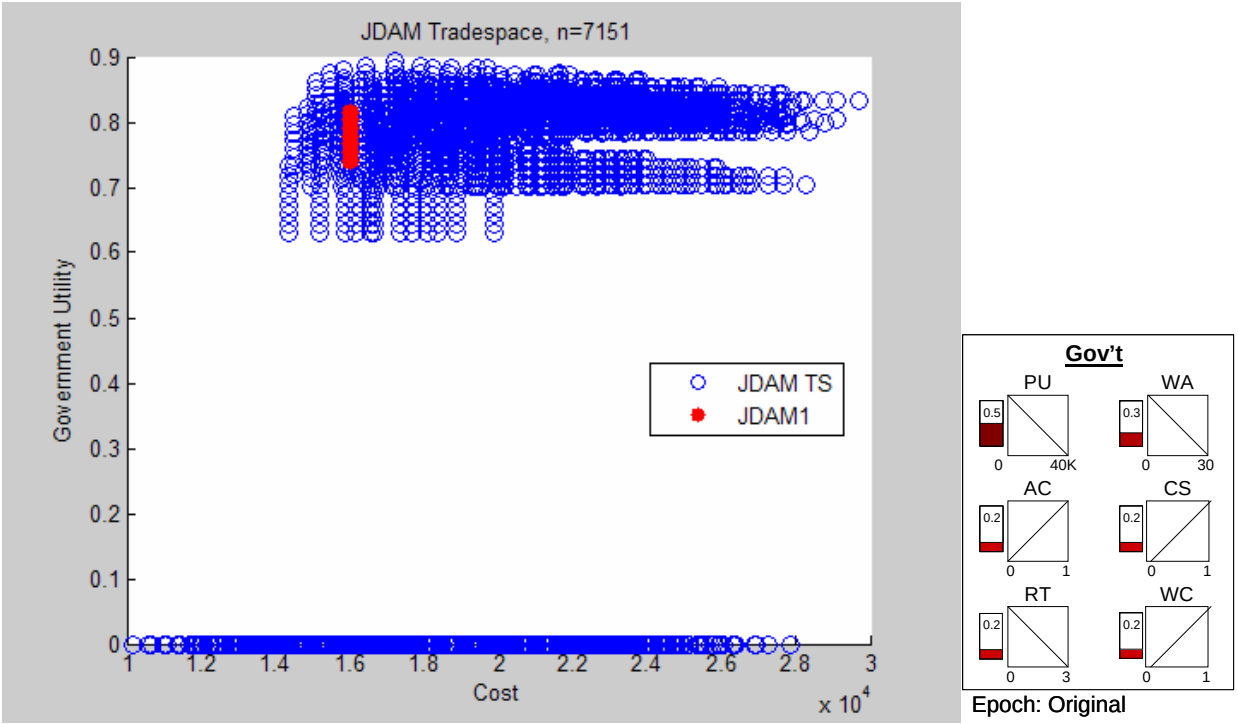


Figure 142 Government Utility-Cost tradespace with JDAM version 1

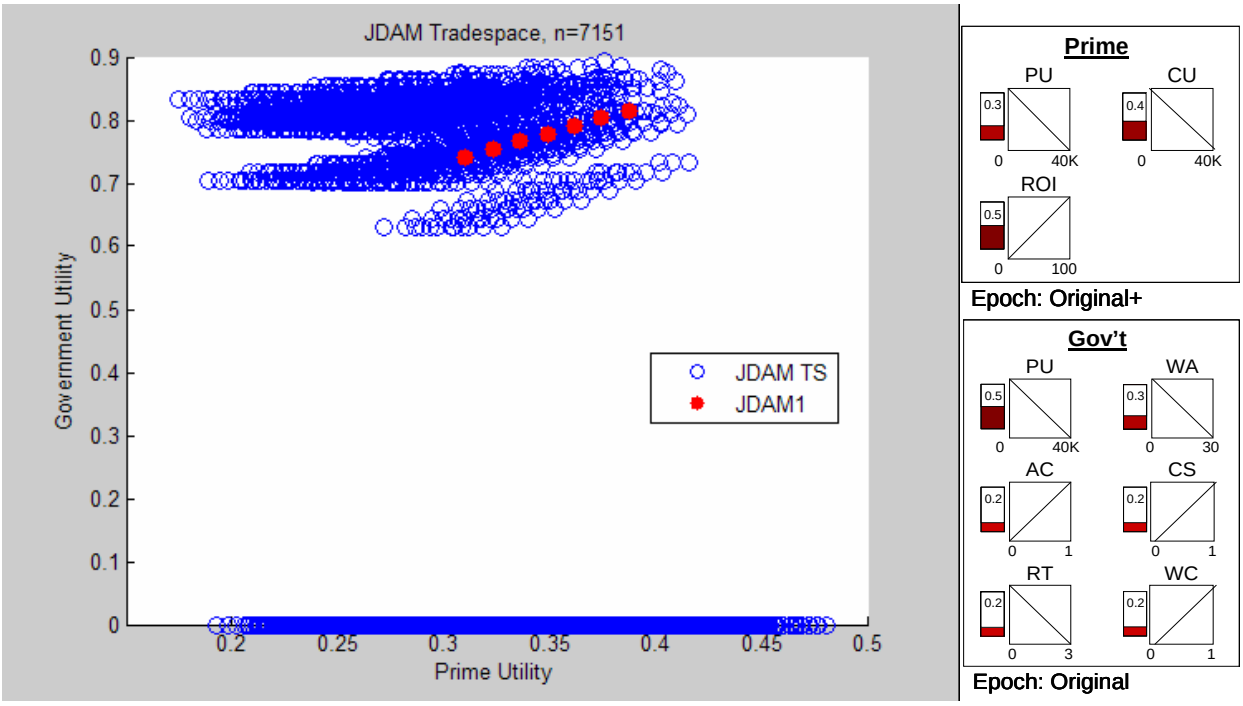


Figure 143 Government Utility-Prime Utility tradespace with JDAM version 1

In addition to the originally developed system, newer JDAM versions have since been developed or proposed, including the addition of laser sensors to improve clear weather accuracy, foldable wings to increase standoff distance, advanced GPS to improve all-weather accuracy, terminal

guidance to improve targeting on moveable targets, and consideration for application to additional classes of warheads and aircraft.[170]

9.4.2 Analyzing Changing Contexts

The tradespace figures in this section show how the tradespace reacts to new contexts: various Epochs. The Epochs considered were: "Clear weather replacement", "Standoff added", and "Desire faster retarget time." Figure 144 shows the preference set for the Government in each of the three Epochs, with utility functions and k_i weights indicated.

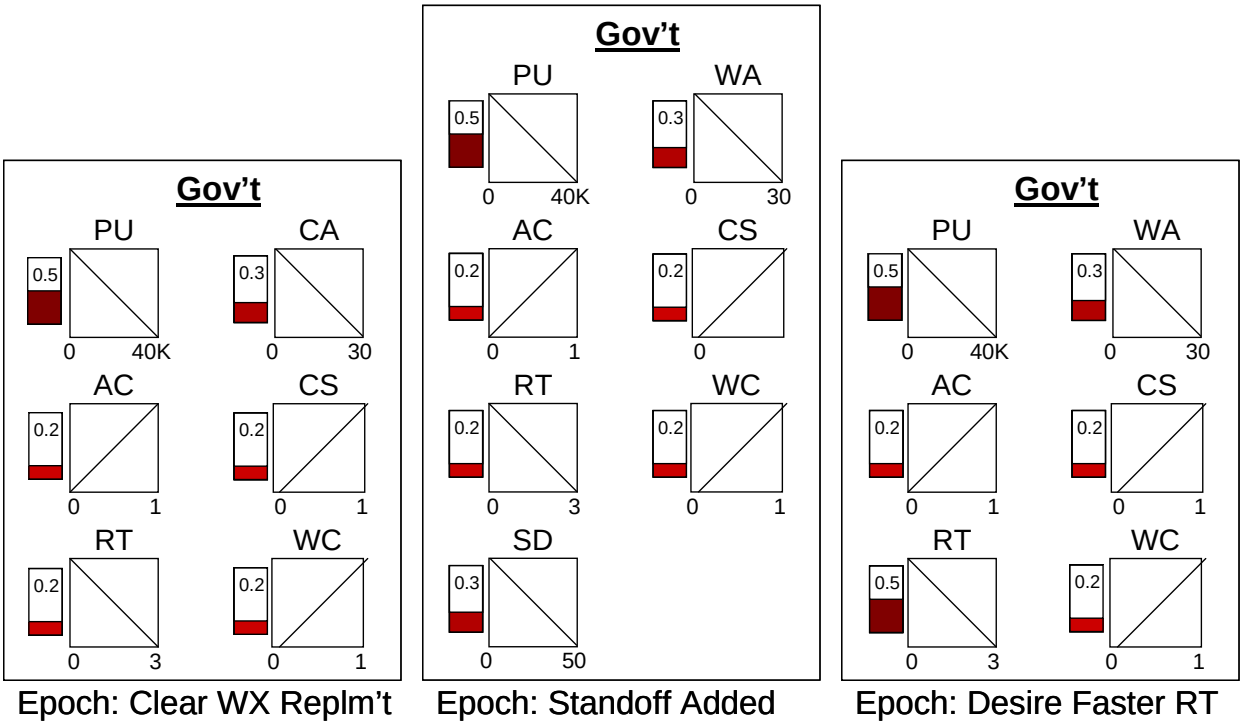


Figure 144 Government preferences in three potential Epochs

The range of points for each system is due to allowing the procurement price charged (PC) to vary across its range. The original JDAM system is "JDAM1." The recent version of JDAM is "JDAM2." The extended range variant with wings is "JDAM-ER." The variant with a nose-mounted terminal seeker is "JDAMASK." The variant with a nose-mounted laser sensor is "Laser JDAM." The "WiFi JDAM" is a variant proposed by this researcher and since discovered to be a real system in development.[171] "WiFi" has wireless communication updating of its GCU.

[170] The JDAM-ER, for example, has "diamond back" wings to extend range from 8 to 24 nmi when released at 20000 ft. The DAMASK add-on features a nose-mounted seeker that adds updated targeting information during flight to target, improving the accuracy to less than 3m. Also, proposed new compatible warheads include naval mines, heavy penetrators, and new specialty warheads. From Boeing IDS website http://www.boeing.com/defense-space/missiles/jdam/index.htm Cited 3/7/06.

[171] Conversation with Program Manager (private communication)

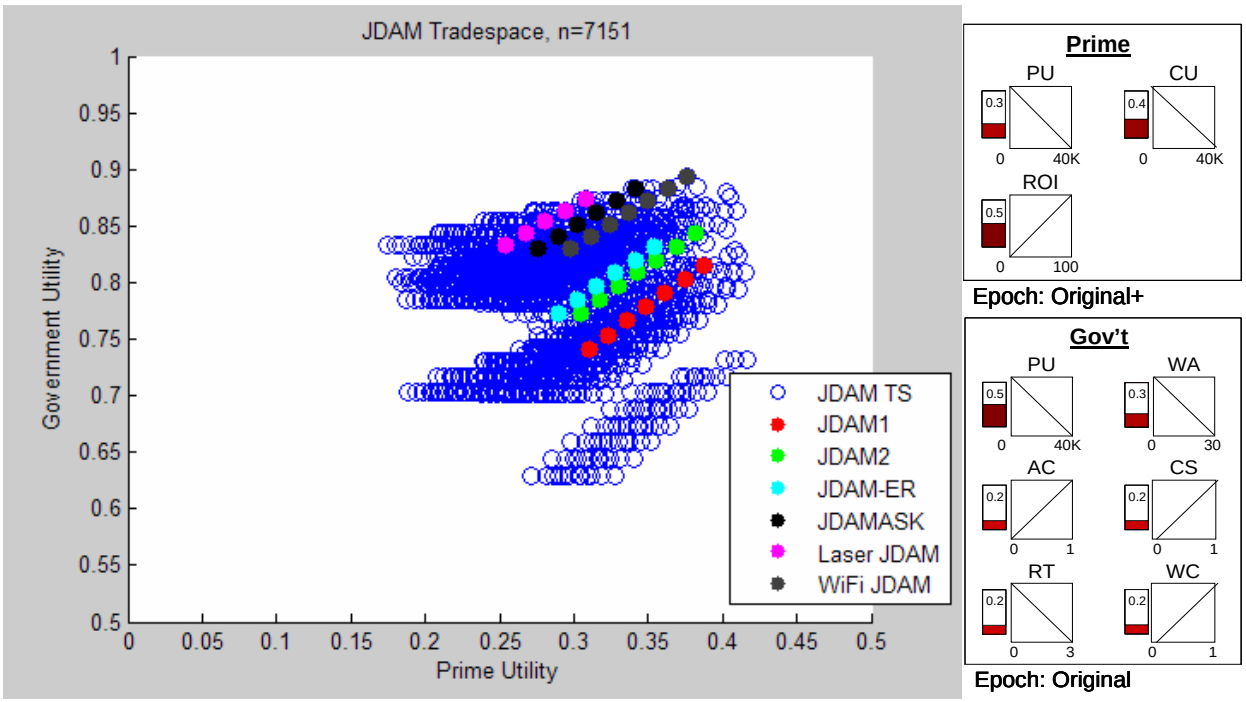


Figure 145 Epoch Orig: JDAM Government Utility-Prime Utility tradespace with actual systems

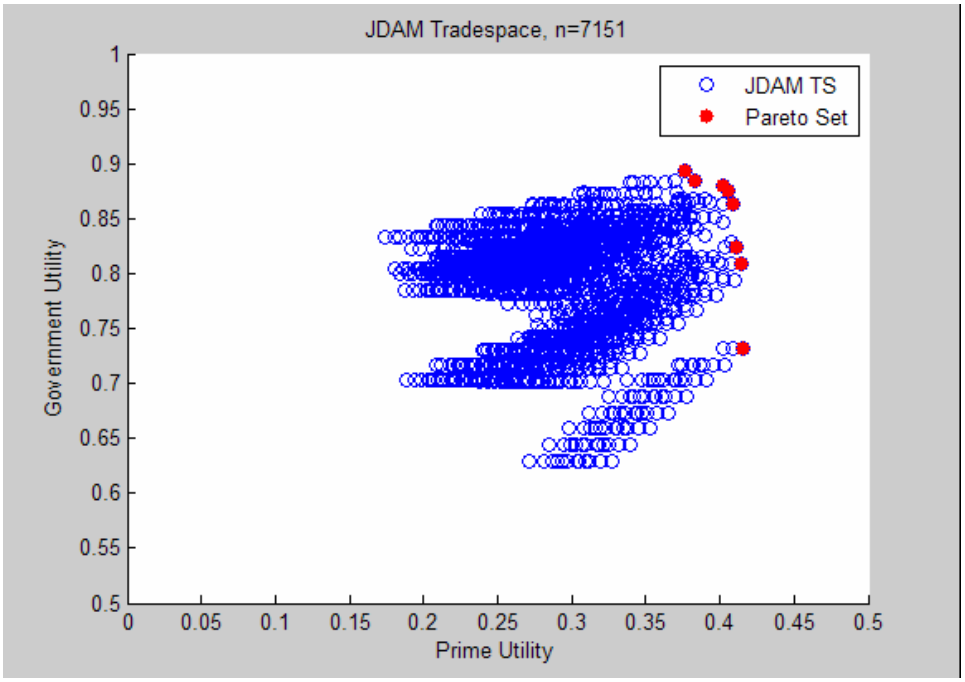


Figure 146 Epoch Orig: JDAM Gov't Utility-Prime Utility showing Pareto Set

Figure 145 shows the original epoch, with the actual JDAM variants for comparison. Figure 146 shows the same epoch with the Pareto Set designs highlighted.

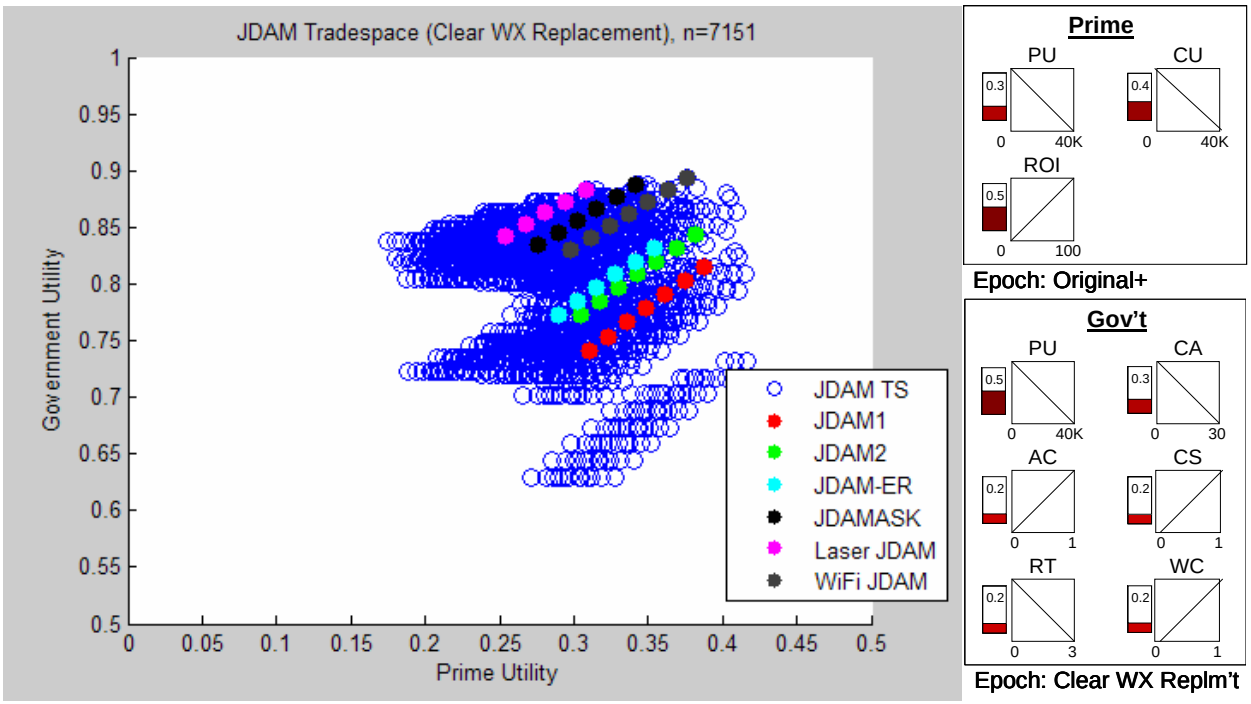


Figure 147 Epoch Clear Weather Replacement: JDAM Government Utility-Prime Utility tradespace with actual systems

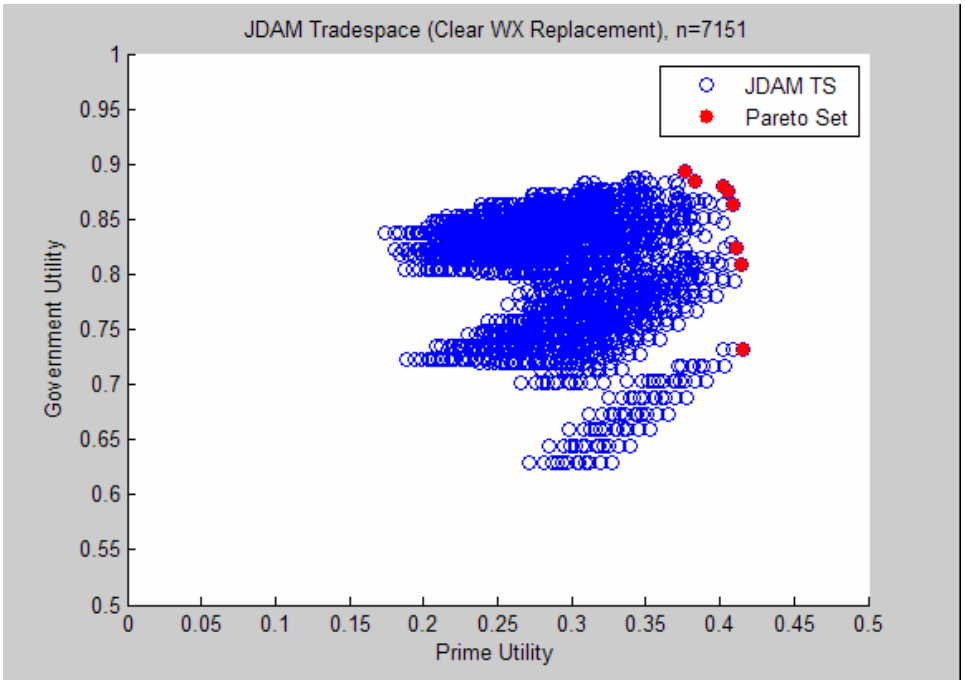


Figure 148 Epoch Clear Weather Replacement: JDAM Gov't Utility-Prime Utility showing Pareto Set

Figure 147 shows the tradespace for the "Clear Weather Replacement" Epoch, reflecting a desire by the government for enhanced clear weather accuracy. Figure 148 shows the same epoch with the Pareto Set designs highlighted.

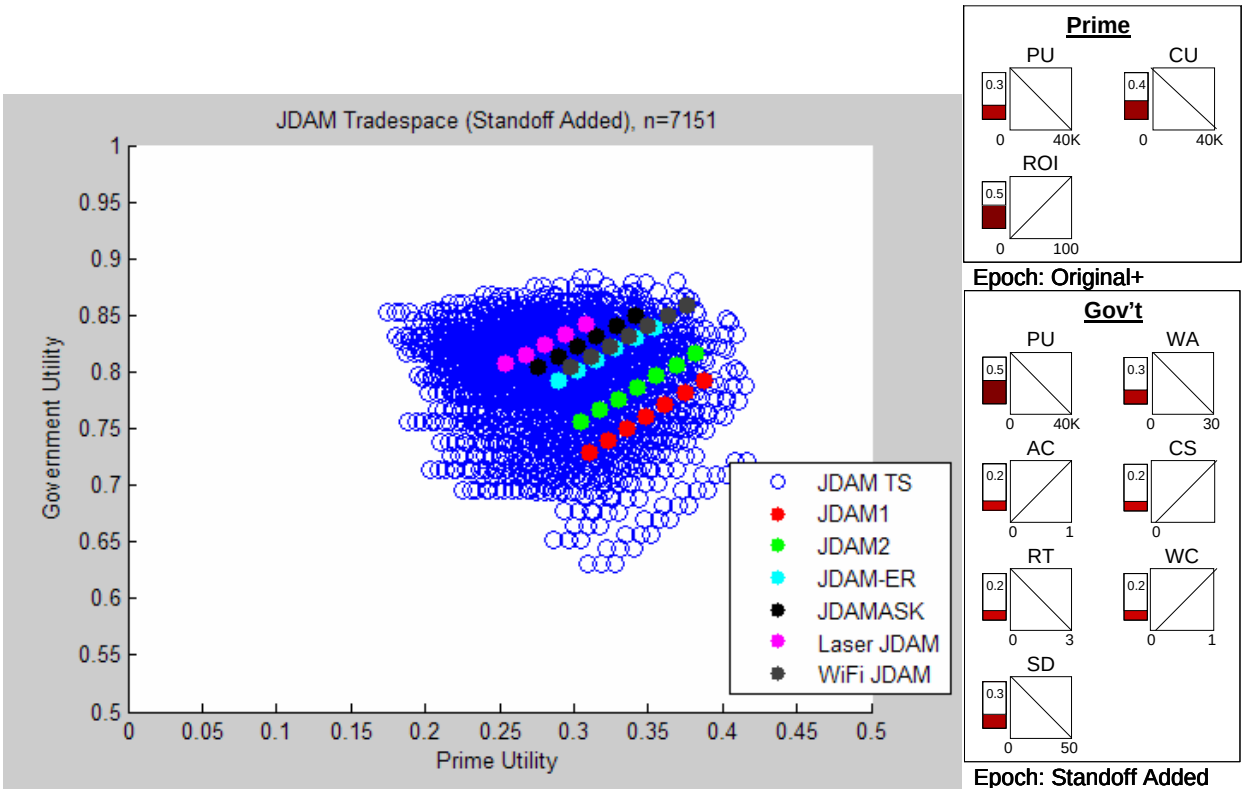


Figure 149 Epoch Standoff Added: JDAM Government Utility-Prime Utility tradespace with actual systems

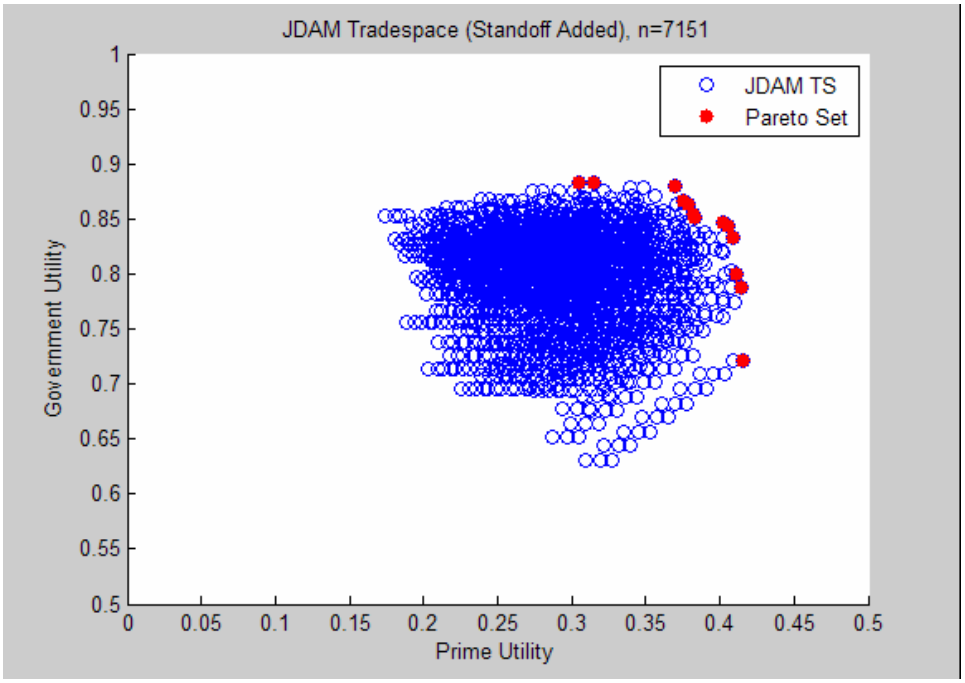


Figure 150 Epoch Standoff Added: JDAM Gov't Utility-Prime Utility showing Pareto Set

Figure 149 shows the tradespace for the "Standoff Added" Epoch, where the government desires farther standoff distance. Figure 150 shows the same epoch with the Pareto Set designs highlighted.

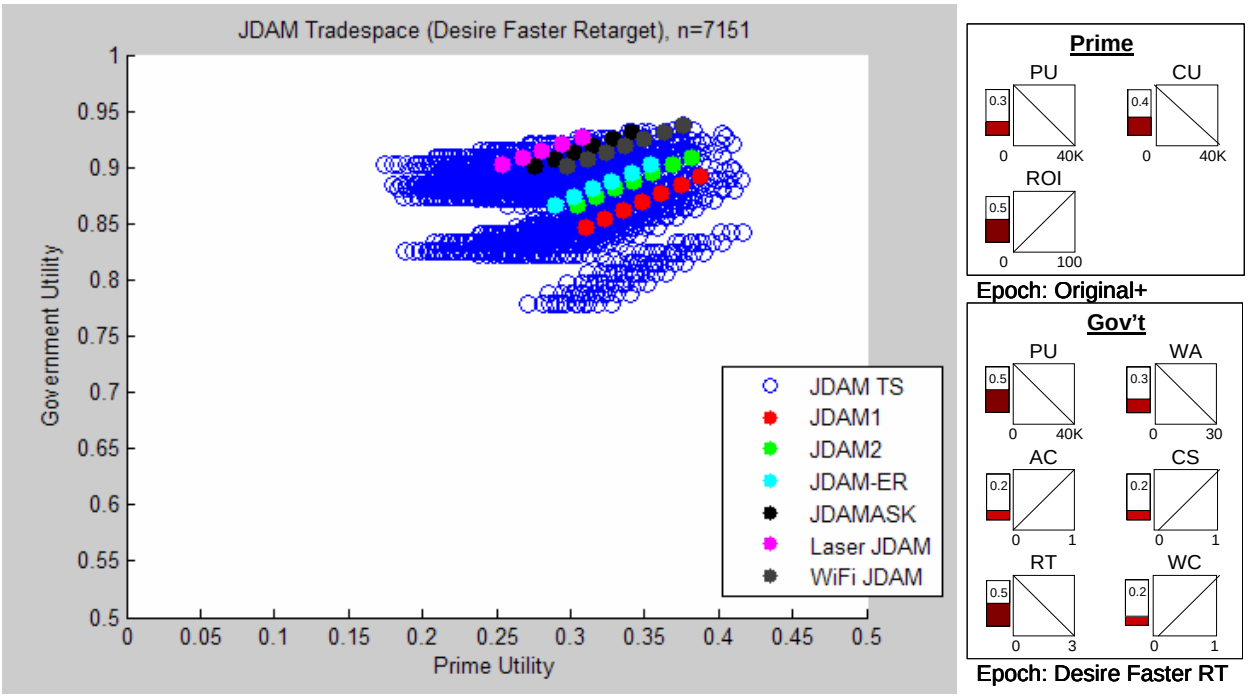


Figure 151 Epoch Desire Faster Retarget Time: JDAM Government Utility-Prime Utility tradespace with actual systems

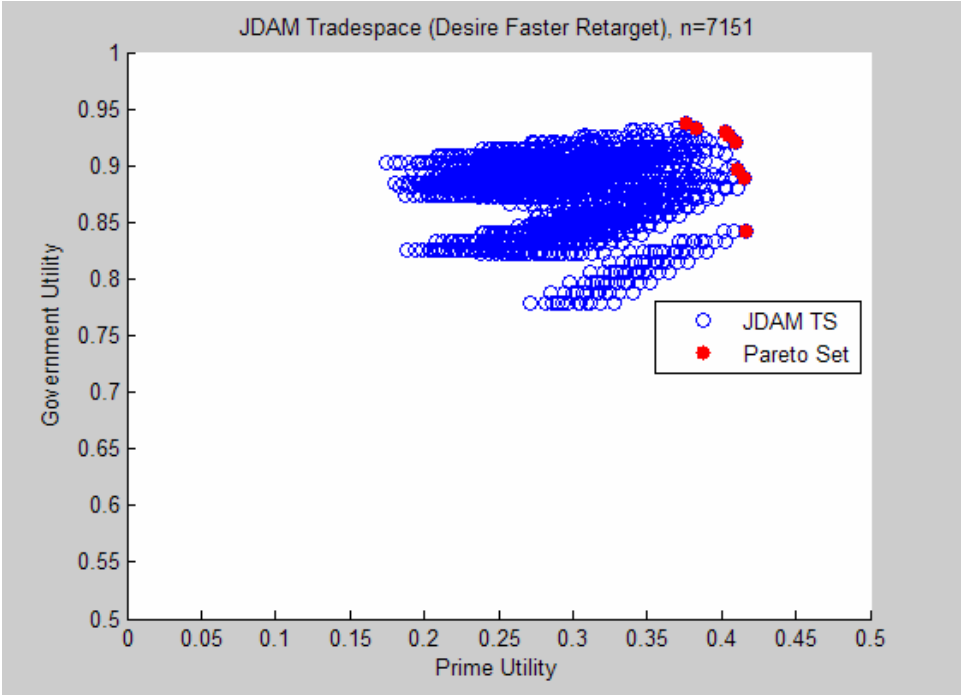


Figure 152 Epoch Desire Faster Retarget Time: JDAM Gov't Utility-Prime Utility showing Pareto Set

Figure 151 shows the tradespace in the "Desire Faster Retarget Time" Epoch, where the government may desire the ability to retarget in-flight to hit moving or opportunistic targets. Figure 152 shows the same epoch with the Pareto Set designs highlighted.

Discovering the Pareto Trace across these four Epochs will give insight into systems that display static value robustness. Eight designs in the considered tradespace appear in all four Pareto Sets, giving them a Pareto Trace Number of four (the highest possible for this study).

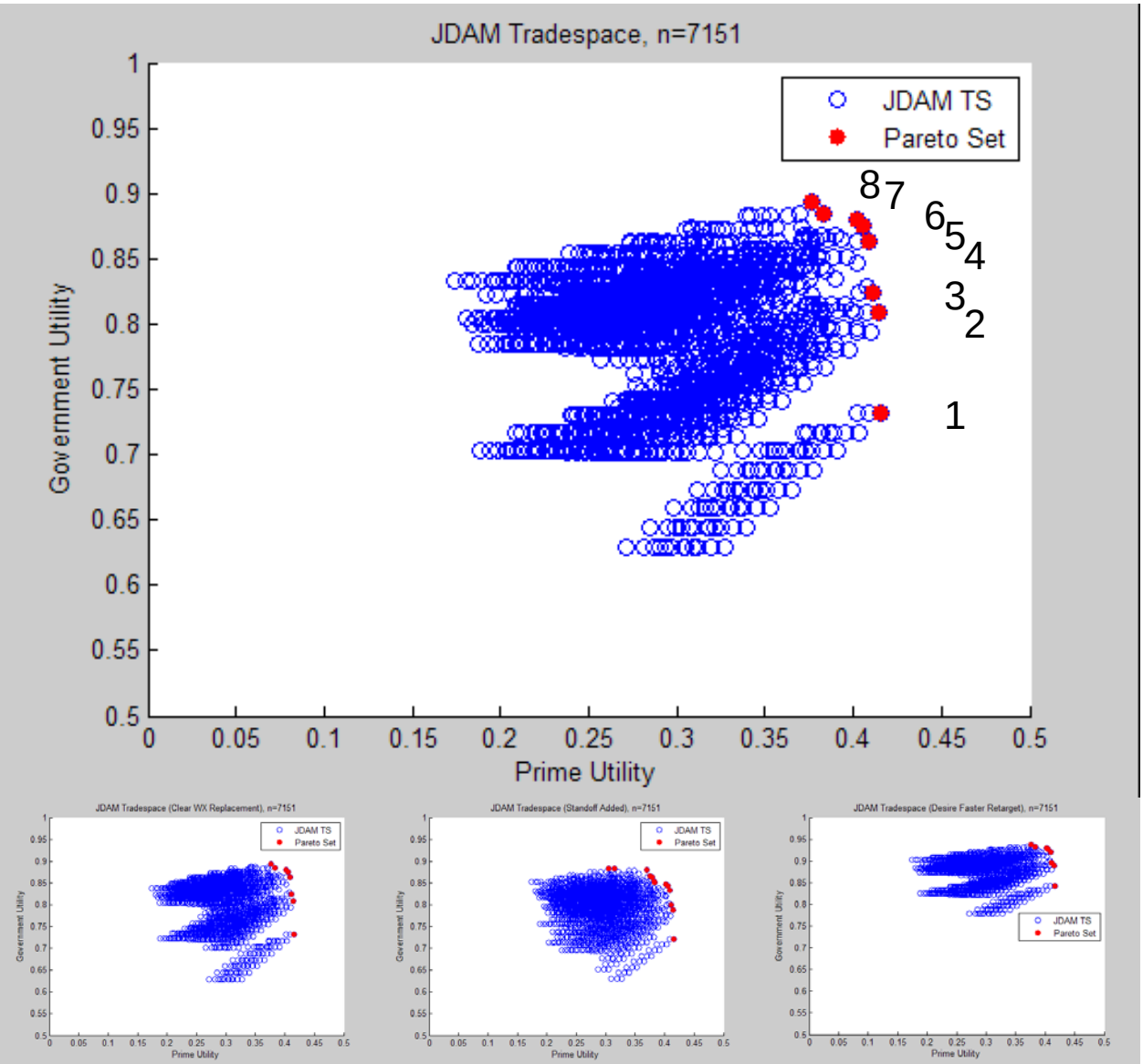


Figure 153 JDAM Pareto Trace designs across the four Epochs

Table 22 Design Variable values for Pareto Trace points, plus JDAM1 and JDAM2

DV	1	2	3	4	5	6	7	8, WiFi	JDAM1	JDAM2
Plf	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin
NS	INS only	GPS only	INS/ GPS	GPS only	INS/ GPS	INS/ GPS/A Cup	INS/ GPS+/ ACup	INS/ GPS+/ ACup	INS/ GPS/ ACup	INS/ GPS+/ ACup
TS	Static data	Static data	Static data	Far comm	Far comm	Far comm	Far comm	Far comm	Static data	Static data
GA	All	All	All	All	All	All	All	All	All	All
Sfw	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Med	Med	Med
PU	16K	16K	16K	16K	16K	16K	18K	18K	21K	21K
LS	None	None	None	None	None	None	None	None	None	None
Wng	None	None	None	None	None	None	None	None	None	None
TG	None	None	None	None	None	None	None	None	None	None
U_{DM1}	.732	.810	.823	.863	.875	.880	.885	.894	.797	.826
U_{DM2}	.416	.415	.411	.409	.406	.402	.384	.376	.368	.362

Table 23 Attribute values for Pareto Trace points, plus JDAM1 and JDAM2

X	1	2	3	4	5	6	7	8, WiFi	JDAM1	JDAM2
PU	16K	16K	16K	16K	16K	16K	18K	18K	21K	21K
WA	30 m	13 m	10 m	13 m	10 m	9 m	5 m	3 m	10(30)	5(30)
AC	All	All	All	All	All	All	All	All	0.943	0.943
CS	All	All	All	All	All	All	All	All	All	All
RT	2 min	2 min	2 min	.1 min	.1 min	.1 min	.1 min	.1 min	1.7 min	1.7 min
WC	All	All	All	All	All	All	All	All	All	All
SD	8 nmi	8 nmi	8 nmi	8 nmi	8 nmi	8nmi	8nmi	8 nmi	8 nmi	8 nmi
CU	14.4K	14.5K	14.9K	15.1K	15.5K	15.8K	16.4K	17.2K	<21K	<21K
SL	20 yrs	20 yrs	20 yrs	10 yrs	10 yrs	10 yrs	10 yrs	10 yrs	20 yrs	20 yrs
ROI	11%	11%	7.6%	6.2%	3.4%	1.1%	9.6%	4.5%	>0	>0
CA	30 m	13 m	10 m	13 m	10 m	9 m	5 m	3 m	9(30)	4(30)
U_{DM1}	.732	.810	.823	.863	.875	.880	.885	.894	.797	.826
U_{DM2}	.416	.415	.411	.409	.406	.402	.384	.376	.368	.362

Figure 153 shows the eight high Pareto Trace designs. Table 22 lists the design variable values for these eight designs plus the two JDAM versions for comparison. The attribute values for these designs are listed in Table 23. It is interesting to note that none of these designs have any of the “accessories”: laser sensor, wing, or terminal guidance. The reason may be that given the cost model used, the same performance improvement given to the system by these accessories can be compensated for by cheaper alternatives, or increased value in other attributes. It is also interesting that seven out of eight designs have simple software models, implying that the error introduced by the simpler software can be made up for by better hardware performance, at lower cost. The “WiFi” JDAM concept appears as one of the Pareto Trace designs, and represents a potentially very cheap, but valuable, alternative for various Epochs. A note of caution: the low fidelity of the cost models may render these conclusions baseless; however the insights from the analysis are still useful since they reflect a trading of preferences in an aggregate sense, not readily apparent through consideration of single attributes in isolation.

9.4.3 Design Changeability

Implementation of the transition rules proposed in Table 20 requires adequate modeling of the system to understand the path cost and time. Due to low system model fidelity, a changeability model of appropriate fidelity should be used. Qualitatively, the changeability analysis needs to address whether a specific design can follow a given transition rule and at what cost and time. More changeable designs will have a higher outdegree than less changeable designs.[172]

Rule-Effects Matrix			Design Variables											Path Enablers			Change	
JDAM			Plf	NS	TS	GA	Sfw	PC		IC	LS	Wng	TG	Mod	COTS		Origin	
			DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	DV10	DV11	IV1	IV2	IV3	Flx	Adp
Rule	Refit strakes	R1	↑↓				↑↓	↑↓										
	Upgrade GPS	R2		↑↓			↑↓	↑↓										
	Upgrade INS	R3		↑↓			↑↓	↑↓										
	New software	R4					↑↓	↑↓										
	Refit for new AC	R5	↑↓				↑↓	↑↓										
	Refit for new Warhead	R6	↑↓	↑↓	↑↓		↑↓	↑↓										
	Replace tail section	R7	↑↓	↑↓			↑↓	↑↓										
		RK																
Potential Rules	Add IC	R8		↑↓	↑↓		↑↓	↑↓		±								
	Add LS	R9		↑↓	↑↓		↑↓	↑↓			±							
	Add wings	R10	↑↓				↑↓	↑↓				±						
	Add term guide	R11		↑↓	↑↓		↑↓	↑↓					±					

Figure 154 Proposed JDAM transition rules

Since the models are not accurate enough to perform detailed quantitative tradespace network analysis, instead a semi-quantitative approach can be used to assess the changeability of the JDAM designs. A review of the proposed change rules is given in Figure 154.

	1	2	3	4	5	6	7	8
Plf	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin	Strake/ Fin
NS	INS only	GPS only	INS/ GPS	GPS only	INS/ GPS	INS/ GPS/A Cup	INS/ GPS+/ ACup	INS/ GPS+/ ACup
TS	Static data	Static data	Static data	Far comm	Far comm	Far comm	Far comm	Far comm
GA	All	All	All	All	All	All	All	All
Sfw	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Med
PU	16K	16K	16K	16K	16K	16K	18K	18K
LS	None	None	None	None	None	None	None	None
Wng	None	None	None	None	None	None	None	None
TG	None	None	None	None	None	None	None	None
U_{DM1}	.732	.810	.823	.863	.875	.880	.885	.894
U_{DM2}	.416	.415	.411	.409	.406	.402	.384	.376

Figure 155 JDAM Pareto Trace designs

[172] The Outdegree is a measure of number of paths from a given design. The higher the Outdegree, the more possible transitioned end states. In changeability quantification, the Filtered Outdegree is the Outdegree considering only paths costing less than the "cost threshold". Cost can be in terms of money and time.

The designs to consider for the changeability assessment will be the eight designs from the Pareto Trace, recaptured in Figure 155. A simplification to replace calculation of the full tradespace network outdegree for each design is to assess the number of rules that can be followed from a particular design. Given a cost threshold for acceptability, the number of accessible rules will reflect the changeability of each design. Supposing cost and time can be categorized as "low", "medium" and "high," the eight designs can be assessed in terms of how much each rule "costs" for dollars and time.

OD Assessment		Design ID number																	
Without MOD, COTS		1		2		3		4		5		6		7		8		9	
		$	t	$	t	$	t	$	t	$	t	$	t	$	t	$	t	$	t
Refit strakes	R1	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L		
Upgrade GPS	R2	H	H	M	M	M	M	M	M	M	M	M	M	M	M	M	M		
Upgrade INS	R3	M	M	H	H	M	M	H	H	M	M	M	M	M	M	M	M		
New software	R4	H	L	H	L	H	L	H	L	H	L	H	L	H	L	M	L		
Refit for new AC	R5	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H		
Refit for new Warhead	R6	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H		
Replace tail section	R7	M	L	M	L	M	L	M	L	M	L	M	L	M	L	M	L		
Add IC	R8	H	H	H	H	H	H	M	M	M	M	M	M	M	M	M	M		
Add LS	R9	H	M	H	M	H	M	H	M	H	M	H	M	H	M	H	M		
Add wings	R10	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		
Add term guide	R11	H	M	H	M	H	M	H	M	H	M	H	M	H	M	H	M		
MaxOD		11		11		11		11		11		11		11		11			
OD(<C,t): (M,M)		**4**		**4**		**5**		**5**		**6**		**6**		**6**		**6**			

Figure 156 Qualitative changeability assessment for JDAM Pareto Trace designs

Figure 156 captures the qualitative assessment of costs in terms of dollars and time for following each rule for each of the Pareto Trace designs. The maximum rule outdegree, or MaxOD, is the total number of rules: in this case 11. The filter is set at a "Medium" dollar cost and a "Medium" time cost; only paths that cost "M" or less will be counted towards the outdegree. The red bars indicate rules that cannot be followed given the subjective threshold.[173] The results in this figure are qualitative, but nevertheless, instructive. The following figures will consider the effect of adding the path enablers Modularity and COTS to the designs. These path enablers will differentially affect the "cost" to follow each rule for each design option. The outdegree assessment done here can be used as a filter for refining system designs at the more detailed level. Additional path enablers could be proposed at this stage as the changeability becomes a more central consideration of the analysis.

[173] The outdegree function can be derived by varying the $\hat{C}$ and $\hat{t}$ and calculating the resulting outdegree. It is apparent that the changeability of each design is subjectively affected by how much a decision maker is willing to "spend" to get the desired change.

OD Assessment		Design ID number																	
With MOD, w/o COTS		1		2		3		4		5		6		7		8		9	
		$	t	$	t	$	t	$	t	$	t	$	t	$	t	$	t	$	t
Refit strakes	R1	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L		
Upgrade GPS	R2	H	M	M	L	M	L	M	L	M	L	M	L	M	L	M	L		
Upgrade INS	R3	M	M	H	M	M	L	H	M	M	L	M	L	M	L	M	L		
New software	R4	H	L	H	L	H	L	H	L	H	L	H	L	H	L	M	L		
Refit for new AC	R5	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H		
Refit for new Warhead	R6	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H		
Replace tail section	R7	M	L	M	L	M	L	M	L	M	L	M	L	M	L	M	L		
Add IC	R8	H	M	H	M	H	M	M	L	M	L	M	L	M	L	M	L		
Add LS	R9	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L		
Add wings	R10	M	M	M	M	M	L	M	L	M	L	M	L	M	L	M	L		
Add term guide	R11	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L		
	MaxOD	11		11		11		11		11		11		11		11			
	OD(<C,t): (M,M)	**4**		**4**		**5**		**5**		**6**		**6**		**6**		**6**			

Figure 157 Qualitative changeability assessment for JDAM Pareto Trace designs, including Modularity path enabler

OD Assessment		Design ID number																	
W/o MOD, w/COTS		1		2		3		4		5		6		7		8		9	
		$	t	$	t	$	t	$	t	$	t	$	t	$	t	$	t	$	t
Refit strakes	R1	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L		
Upgrade GPS	R2	M	H	L	M	L	M	L	M	L	M	L	M	L	M	L	M		
Upgrade INS	R3	M	M	M	H	L	M	M	H	L	M	L	M	L	M	L	M		
New software	R4	H	L	H	L	H	L	H	L	H	L	H	L	H	L	M	L		
Refit for new AC	R5	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H		
Refit for new Warhead	R6	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H		
Replace tail section	R7	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L		
Add IC	R8	M	H	M	H	M	H	L	M	L	M	L	M	L	M	L	M		
Add LS	R9	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		
Add wings	R10	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		
Add term guide	R11	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		
	MaxOD	11		11		11		11		11		11		11		11			
	OD(<C,t): (M,M)	**6**		**6**		**7**		**7**		**8**		**8**		**8**		**9**			

Figure 158 Qualitative changeability assessment for JDAM Pareto Trace designs, incl. COTS path enabler

OD Assessment		Design ID number																	
With MOD, COTS		1		2		3		4		5		6		7		8		JDAM2	
		$	t	$	t	$	t	$	t	$	t	$	t	$	t	$	t	$	t
Refit strakes	R1	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Upgrade GPS	R2	M	M	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Upgrade INS	R3	M	M	M	M	L	L	M	M	L	L	L	L	L	L	L	L	L	M
New software	R4	H	L	H	L	H	L	H	L	H	L	H	L	H	L	M	L	M	L
Refit for new AC	R5	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
Refit for new Warhead	R6	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
Replace tail section	R7	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Add IC	R8	M	M	M	M	M	M	L	L	L	L	L	L	L	L	L	L	M	M
Add LS	R9	M	L	M	L	M	L	M	L	M	L	M	L	M	L	M	L	M	L
Add wings	R10	M	M	M	M	M	L	M	L	M	L	M	L	M	L	M	L	M	L
Add term guide	R11	M	L	M	L	M	L	M	L	M	L	M	L	M	L	M	L	M	L
	MaxOD	11		11		11		11		11		11		11		11		11	
	OD(<C,t): (M,M)	**8**		**8**		**8**		**8**		**8**		**8**		**8**		**9**		**9**	

Figure 159 Qualitative changeability assessment for JDAM Pareto Trace designs, including Modularity and COTS path enablers (and showing JDAM2)

Figure 157 shows the qualitative assessment with the inclusion of Modularity into the designs. The effect is predominantly a decrease in transition time for several, but not all of the rules. For the case studied here, none of the filtered OD are changed over the non-modularity cases, suggesting it does not increase the subjective changeability of the system. Figure 158 shows the qualitative assessment with the inclusion of COTS into the designs. The effect is predominantly a decrease in dollar cost for several, but not all of the rules. For the case studied here, all of the designs see an increase in apparent changeability. Figure 159 shows the qualitative assessment with the inclusion of both Modularity and COTS into the designs. Since these path enablers tend to work on different "costs" they work synergistically to increase the changeability across the designs, in particular raising the changeability of the least changeable designs from the first assessment. The actual JDAM system is added to this last figure for comparison.

The actual JDAM system did in fact incorporate several path enabling aspects. According to the person in charge of the original JDAM airframe design, and current JDAM "accessory" manager, the system embraced the following three concepts: use of modularity, use of commercial off the shelf (COTS) parts, and the use of simple interfaces with excess capacity. The first path enabler, modularity, while not in use throughout the system, was used when possible in order to isolate the system from component changes and to speed up assembly time of the system in the field. Modularity also gave the system the ability to be readily upgraded. The tail fin section has three motors, each controlling a single fin. The motor assembly was designed as a module for simple insertion into the system. For all JDAM variants, except for one, the motor module is the same. The exception is the smallest variant of JDAM, whose tail section is too small to house a modular motor. The "cost" of modularity for the motor is a larger size, which cannot be accommodated by the smaller tail section on the JDAM variant for the Mark-82 warhead.

In order to reduce cost, the team embraced the second path enabler, a COTS philosophy, seeking an already developed commercial alternative to a higher grade military-spec hardware. The commercial components had to meet stringent reliability and performance measures, but were hands down less expensive than custom hardware.[174] Using COTS extended to JDAM "accessories," or upgrades, will reduce the cost of changing the system.

The third path enabler was simple, excess capacity interfaces. A single 1760 standard interface provided connectivity to the aircraft carrying the JDAM. Extra pins in the connector were provided in order to have extra capacity. The designers could have reduced cost by having fewer pins and smaller cables, but felt that the system should have extra capacity "in case of future needs."[175] Another example is in the selection of GPS receiver. The GPS receiver is plugged into the Guidance Control Unit, or the "brain" of the bomb. The interface to the GPS receiver was designed to have 12 channels, even though the original receiver had only 5 channels and the software could not yet handle additional channels. When newer GPS receivers were later developed, it could be easily installed into the JDAM, with the software upgrades happening even later.

[174] In fact according to Lucas 1996, ~30% of the cost savings for the system resulted from using the lower cost materials and parts. pp. 129. Lucas. Supplier Management Practices of the Joint Direct Attack Munition Program.
[175] JDAM engineer (private communication).

These three path enablers result in the ability to alter the JDAM system at relatively low cost and time. The generic nature of the interface standard does not over constrict the possibilities for add-ons either, thereby increasing the number of "paths" from the current system.

9.5 Discussion

One of the key aspects of the actual JDAM system development effort was the focus on affordability. Since the Government priority for affordability was so high, in effect it was the main determinant of Government utility (given the other attributes were at least at their minimal acceptable level). In order to realize cost savings, the design team worked as an integrated product team (IPT), similar to a multi-disciplinary, cross-organizational concurrent design team. Over 30% of the cost savings was due to Design for Manufacturability and Assembly (DFMA), a detailed-design level activity. An additional 30% was saved through the use of lower cost parts and materials.[176] Neither of these considerations is typically realizable at the conceptual design level of a typical MATE study. During the preliminary design phase that follows Conceptual Design level MATE, a focus on DFMA can take place, however.[177] The value of MATE applied to JDAM at the phase the McDonnell Douglas team took over is less on the cost savings side, and more on the value-space understanding side.

The JDAM development benefited from acquisition reform reducing non-value adding activities that would have added to development schedule and cost. Additionally, representatives from the Government side were included on the development team in a cooperative, open communication arrangement, as opposed to the typical competitive, limited communication arrangement. This relationship enabled better communication of Government utility and focused efforts on delivering best value. One of the benefits of the MATE approach is the focus on value through the use of decision maker proxies (attributes and utility functions). For JDAM, representatives from the SPO played the same role and the increased cooperation between developers and acquirers has been attributed as a major contributor to program success.[178]

An open question is whether JDAM is an exceptional case in aerospace system development. Its special status as a test program for acquisition reform freed the team from the burden of paperwork and constraints on design. The class 2 change authority and ownership of the design specs gave the Prime both power to make value-adding decisions, and the incentive to produce a high quality product. The retention of ownership, in particular, enabled the Prime to take on the cost burden of building in the path enablers. In general, if a decision maker does not articulate the desire for changeability, he will be unwilling to pay for it since it may represent unused functionality. In the case of JDAM, the Prime "paid" for the unused functionality by anticipating the need to change. In effect, JDAM reduced its time constant to change by having the path enablers. The Prime must have decided that the cost of "carrying" the path enablers was lower

[176] pp 129. Lucas. Supplier Management Practices of the Joint Direct Attack Munition Program.

[177] The key differences between Conceptual Design level and Preliminary Design level analyses are the level of detail and fidelity of models. The fidelity-cost tradeoff for creating models usually precludes the ability to create detailed models during Conceptual Design for all of the concepts being considered. DFMA and component selection to improve affordability may be differentially applicable to different concepts, so insights at the Conceptual Design phase would be valuable. Further research into incorporating DFMA in Conceptual Design should be done.

[178] Lucas. Supplier Management Practices of the Joint Direct Attack Munition Program.

over the long run than developing a new system when the demand for change arrived from the customer.

9.6 Conclusion

A key motivating question for this case application was to determine whether the JDAM system is "flexible," as claimed by General Jumper. In order to be flexible, the system must be able to be changed by an external agent for relatively little "cost". The JDAM system requires little effort to use since it is lightweight, has few parts, and has a simple interface.[179,180] The unit cost is also very low when compared to other munitions, at a $21000 (FY91) per kit.[181] A major change that can occur with the JDAM is its target location information. The very fact that the JDAM can be reprogrammed—retargeted—relatively simply through an interface with its carrying aircraft computer system means that JDAM is flexible with respect to target. The target of a JDAM, however, is not really an attribute of the JDAM, but rather of the mission.[182]

The oft-cited "flexibility" of JDAM is not in fact the flexibility of JDAM itself; rather JDAM enables a "flexible" mission: a mission that can be changed in terms of targets, since the JDAM on-board targeting data can be updated via the umbilical link between its Guidance Control Unit and the aircraft computer system. Since JDAM is "leave and forget," it allows pilots to have more time to use toward other missions, thus reducing the "cost" of a mission. Also, the high accuracy of the weapon results in fewer repeat runs for missions, enabling a "one bomb, one target" capability.

It turns out that the physical system itself is also quite flexible. The presence of several path enablers reduces the "cost" and increases the number of change possibilities for the system. Modularity reduces the time for change, while COTS reduces the cost for change. The simple, excess capacity interfaces increases the potential change types for the system.

In terms of static value robustness, the "WiFi JDAM" merits further research. It appears in all four considered Epochs and appears to enable even more mission flexibility by reducing the time to retarget the munition.

In summary, the JDAM system itself is quite flexible. In addition to being able to readily "wear" various "accessories," it enables mission flexibility by reducing the cost and effort to achieve military objectives. Since JDAM provides a basic functionality required by the military, but at *lower cost and higher effectiveness* than alternatives, it is not only a flexible system, but a very versatile one as well.

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[179] "the whole kit weighs less than 100 pounds. It's easy to lift and install. And a four-member bomb-building crew can master the upgrade in less than a day." Arana-Barradas, Master Sgt. Louis A. (2001). Joint direct attack munition gives aging B-52 bomber more clout. Airman Magazine.

[180] "It takes 10 minutes to add JDAM technology to the tail section of the one-ton, Vietnam-era MK48. "It's easy to handle…You only need to tighten 12 set screws." Sloyan. "The Bargain Basement Bomb."

[181] According to the Wikipedia entry for "Joint Direct Attack Munition" http://en.wikipedia.org/wiki/Joint_Direct_Attack_Munition (cited 3/9/06)

[182] Enabling an aircraft to more accurately drop "dumb" bombs on target does not increase the flexibility of the dumb bomb. The ability of the pilot to change targets makes the mission adaptable, not the bomb or the airplane.

Key References

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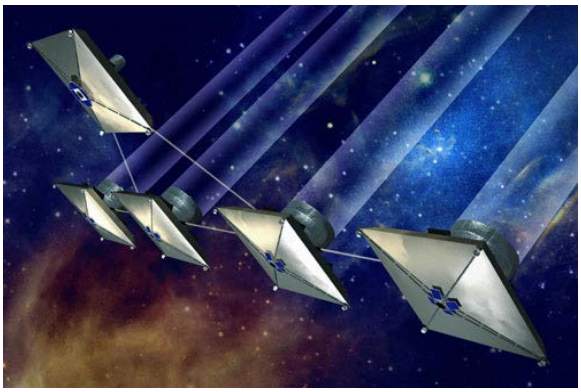
Lucas, M. V. "Supplier Management Practices of the Joint Direct Attack Munition Program". *Aero/Astro*. Cambridge, MA, MIT**:** 174. 1996

Sloyan, P. J. "The Bargain Basement Bomb". *Long Island Newsday*. 1999

Chapter 10: Case #2: Currently Designed System (Terrestrial Planet Finder, TPF)

From the times of the ancient Greek and medieval scholars, many have speculated that other worlds must exist and that some would harbor other forms of life. But up to now, no instrument, not even the Hubble Space Telescope (HST), has had the sensitivity to see even one of the large planets now known to exist around nearby stars. But a new kind of telescope, an infrared interferometer, offers the sensitivity and imaging capability to detect and characterize planets as small as the Earth in orbit around nearby stars. Modern technology has brought the centuries-long interest in finding habitable planets of other stars within our grasp.[183]



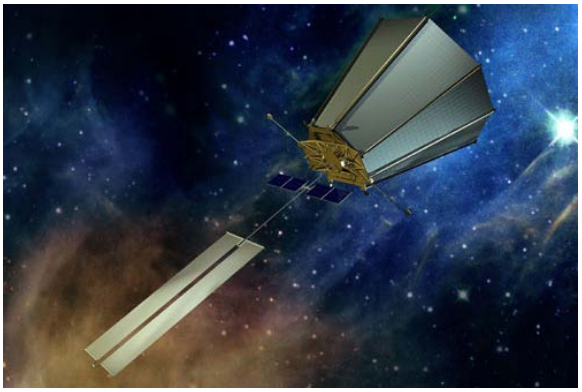


Figure 160 The Terrestrial Planet Finder, infrared interferometer and visible coronagraph[184]

10.1 Overview

"NASA's Terrestrial Planet Finder project is designed to address one of the most fundamental questions in science: whether life exists on other worlds." – NASA JPL TPF website describing the science goals of the mission.

The TPF mission objective has been a longstanding question in the science community, but until recently was technically infeasible. A number of studies conducted over the past fifteen years have built a consensus in the scientific community of the need for such a system, though the details have evolved with technology.[185] The technology for TPF, while tantalizingly close by astronomical standards, is still at least a decade off. The need for affordability in space science has led NASA to adopt an incremental approach through the Origins Program. The goals of TPF will be met by building off of a series of precursor missions that will feed forward technology and science knowledge, thereby reducing the cost and risk to TPF implementation.

Currently the status of TPF is in question as the priorities of NASA shift in favor of human spaceflight over space science. TPF has waited decades and will likely have to wait a few more

[183] From the Introduction of the TPF Book, pp 7. Beichman, CA, N.J. Woolf, et al. (1999). "The Terrestrial Planet Finder (TPF): A NASA Origins Program to Search for Habitable Planets." T. T. S. W. Group. JPL Publication 99-003. Pasadena, CA, JPL**:** 158.

[184] Images from TPF website, http://planetquest.jpl.nasa.gov/TPF/tpf_what_is.cfm, cited 3/22/06.

[185] See Chapter 1. Beichman, Woolf, et al. "The Terrestrial Planet Finder (TPF): A NASA Origins Program to Search for Habitable Planets."

years. Though the science case is compelling and is likely to remain relatively constant, technology will only continue to improve, further increasing the potential TPF performance and reducing the technical risk.

10.2 Static Analysis

The following section is a partitioning of the design problem, utilizing the classic MATE perspective.

10.2.1 Decision Makers, Requirements and Attributes

The key Decision Makers for TPF can be considered to be the following:

Congress: As the funding arm for executive agencies, such as NASA, Congress has both direct (earmarks) and indirect (budgeting approval) control over monetary resources available for TPF.

NASA: As the developing agency, NASA determines acceptable designs and allocates money and effort from its available resources for TPF. Budget and schedule constraints dominate. Another consideration is their role as an agent of the President. (Within-agency priorities reflect Presidential initiatives, such as the recent emphasis on human spaceflight over robotic missions.)

Science community: As the users of the system, the scientists provide the driving need for the existence of the system, though they typically do not pay for its development.

For the purposes of the TPF MATE study, **NASA** shall be called "**Agency**" and the **science community** shall be called "**Science**." **Congress** will not be explicitly considered, however their main interest would be on system cost profile and relative national importance.[186]

According to (Makins 2002), citing science objectives from the Jet Propulsion Laboratory, the following are the four principal science objectives for TPF:

(1) to survey some 200 solar-type stars from 5 to 15 parsecs from the solar system; each detection should take at most 2 hours
(2) to characterize the spectral components indicative of an Earth-like atmosphere for about 30 of these stars; each medium spectroscopy should take at most 2 days
(3) to characterize the spectral components indicative of photosynthetic life for about 5 of these stars; each deep spectroscopy should take at most 2 weeks
(4) to image approximately 800 astrophysical structures with a minimum resolution of 0.75 milli-arcseconds (mas) for 3 μm wavelength observations. Astrophysical imaging constitutes half of the mission life - a bit more than 1 target per day for a 5 year mission.

[186] NASA could be seen as an agent of both the President (through directives and policies) and the Congress (through budget constraints and earmarks), indirectly capturing the "political" stakeholders through the Agency preferences. (In practice the effectiveness of NASA as an agent for government through preference filtering suffers from delay and bias, but presumably captures the important features. Both the President and Congress can directly affect NASA's resources and structure if the agency is not making appropriate representations of the respective government branches.)

These four objectives can be characterized as four lifetime science requirements:

1. Number of surveys = 200
2. Number of medium spectroscopy observations = 30
3. Number of deep spectroscopy observations = 5
4. Number of images = 800

The objectives can be cast in terms of attributes, with the "requirements" set as the minimally acceptable level for the attribute. The TPF Science attributes are listed in Table 24. Drawing further from the Makins requirements discussion, the Agency attributes are proposed to be Lifecycle Cost and Operational Lifetime. The requirements state that the system "should cost less than $1 billion" and "shall last 5 years" but "should last 10 years." Clearly the Agency cares about the system cost and operational life, though the requirements do not dictate binary value; a system costing less of lasting longer could provide additional value. These attributes are listed in Table 25 below.

In addition to the articulated value listed in prior mentioned two tables, additional attributes reflecting unarticulated value are listed in Table 26 below. These attributes include the relaxed image attributes Image Short and Image Long, with halved ranges from the Images attribute. These represent sub-types of images done at short and long baselines respectively.[187] The Annual Ops Cost attribute represents an attribute of interest to the Agency if they desire to extend the mission beyond its initially intended life, as many recent science missions have been prone to do. (Galileo, and Hubble, for example, were repeatedly extended beyond their initial design missions.)

Table 24 Proposed TPF Science Attributes

Name	Short Name	Units	"Best" level[188]	"Worst" level[189]	Direction of increasing utility	Definition
Number of Surveys	S	num	500	200	higher	Number of stars surveyed from 5-15 pc
Num Medium Spectroscopies	MS	num	100	30	higher	Number of stars spectrally characterized Earth-like atmospheres
Num Deep Spectroscopies	DS	num	25	5	higher	Number of stars spectrally characterized for life

[187] Makins differentiates between the image types due to the technical difficulty achieving the long baseline images, which are specifically mentioned as desirable by the TPF Science Working Group.

[188] pp 41. Makins, Brian J. (2002). Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission. SM thesis in Aero/Astro. Massachusetts Institute of Technology. Cambridge, MA: 270. The "best" level, or most acceptable level, is equivalent to the "goal" requirement level.

[189] pp 27 Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission. The "worst" level, or least acceptable level, is equivalent to the requirement level. (5 year mission)

Number of Images[190]	I	num	1600	800	higher	Number of images with min resolution 0.75 mas at 3μm

Table 25 Proposed TPF Agency Attributes

Name	Short Name	Units	"Best" level	"Worst" level[191]	Direction of increasing utility	Definition
Lifecycle Cost	LC	$M	1	1000	lower	Cost to develop, build, launch and operate system over lifecycle
Operational Lifetime	OL	years	10	5	higher	Number of years of useful system operation

Table 26 Potential TPF Attributes

Name	Short Name	Units	"Best" level	"Worst" level[192]	Direction of increasing utility	Definition
Num Long Baseline images	IL	num	800	400	higher	Number of images taken at long baseline (1km) (Better resolution)
Num Short Baseline images	IS	num	800	400	higher	Number of images taken at short baseline (100m)
Annual Ops Cost	Ops	$M	1	50	lower	Cost to operate system yearly

[190] Makins uses the proxy of short baseline images in place of the intended long baseline images because *none* of the considered designs could meet the minimum requirements set by the TPF Science Working Group. When "images short", or IS, is used as a proxy, the assumption is that half of the images are taken at short baselines and half are taken at long baselines, with ranges matching those in Table 26. The TPF SWG proposes 1600 images, not 800.

[191] pp 35. Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission. The "worst" level, or least acceptable level, is equivalent to the requirement level. (5 year mission)

[192] pp 35. Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission. The "worst" level, or least acceptable level, is equivalent to the requirement level. (5 year mission)

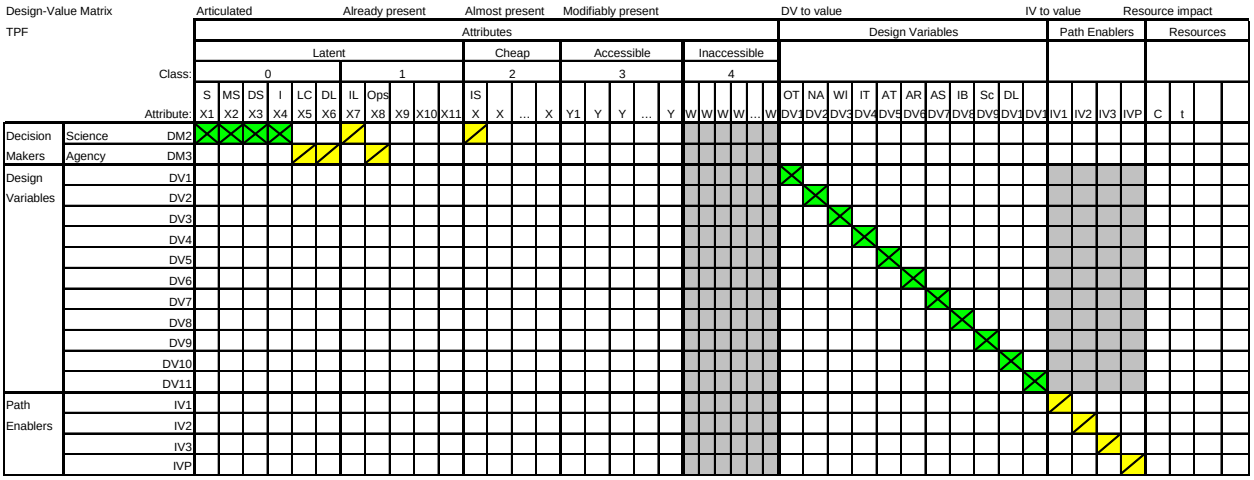


Figure 161 Design-Value Matrix for TPF with Decision Makers and Attributes Added

Figure 161 shows the Design-Value Matrix (DVM) for TPF with the Science and Agency decision makers added and both the articulated and unarticulated attributes.

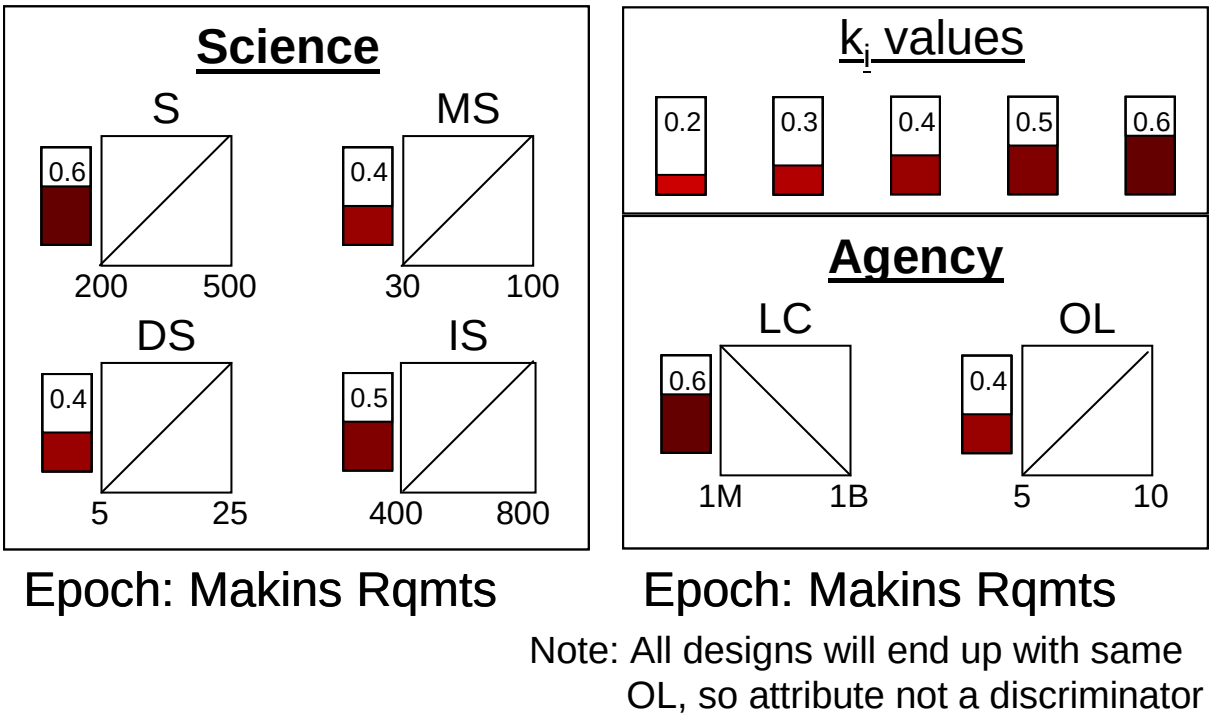


Figure 162 Science and Agency Utility functions

The utility functions for Science and Agency, including their k_i weights—their "priorities"—are shown in Figure 162. Linear utility functions were used for this case, as interview data was unavailable. The sets shown in this figure correspond to the "Makins Requirements" Epoch for TPF, meaning the requirements laid out by the TPF Science Working Group (SWG) as interpreted by (Makins 2002), setting the expectations and constraints for the system.[193]

[193] Since the operational life was not varied in the actual study that attribute ended up not being a discriminator.

10.2.2 Context and Constraints

The Origins space science program within NASA seeks to answer fundamental questions within science involving the origins of the universe and life within it. In particular, Origins seeks to answer the following fundamental questions[194]:

1. Are we alone in the Universe?
2. How did we get here?
3. What is the origin of the Universe?
4. Is there another Earth-like planet in our celestial neighborhood?

TPF is intended to be a critical mission within that program (see Figure 163 below for the TPF mission in the context of the Origins Program mission set). The scientific motivation and goals for TPF have been mentioned in numerous papers and reports over the past decade, reflecting a general consensus of expectation in the science community. The constraints considered for TPF include the following: 1) the system must be compatible with launch and operations environment, and 2) the system must be ready for launch by 2010 (2015).[195]

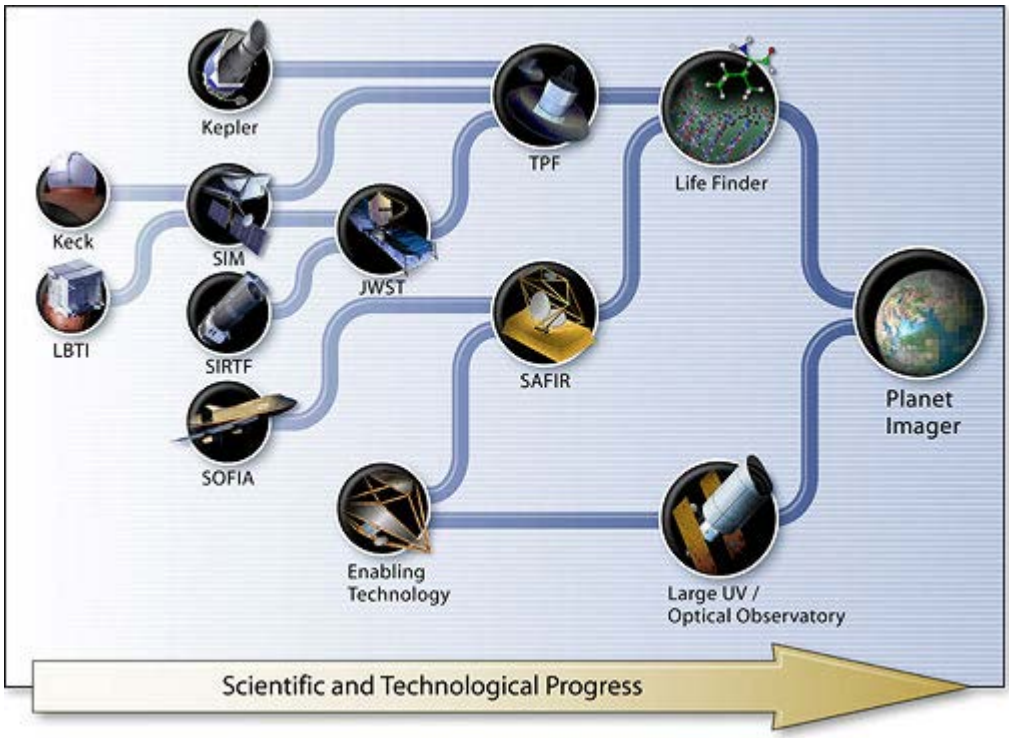


Figure 163 Origins Program Mission Set[196]

10.2.3 Concepts

The concepts that can be considered for Terrestrial Planet Finder are numerous. (Makins 2002) points out that among the various concepts, those that focus on the infrared part of the spectrum

[194] From JPL Origins Program web site (Cited 3/17/06)
[195] pp. 35. Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission.
[196] Image from JPL Origins Program web site (http://origins.jpl.nasa.gov/missions/timeline-tech.html) Cited 3/17/06.

are closer to technical feasibility in the near term (2010-2020) and have more biomarkers for consideration. The masked chronograph concept operating in the visible spectrum is considered to be more costly to develop and technically difficult to achieve.[197] Due to the resolving constraints for creating the desired images, and the payload volume constraints for launch vehicles, the TPF system must consist of components put together over separate launches, or at least cannot be a monolithic imager.[198] The concept of interferometer has been selected due to its component nature and ability to fit within the launch constraints.

An interferometer consists of separate apertures that collect the starlight and recombine the observing data to derive the image. The interferometer, in effect, creates a virtual larger telescope without having the filled aperture of its single "mirror" monolithic brothers. Three types of interferometers are considered in this study: the structurally connected interferometer (SCI), the separated spacecraft interferometer (SSI), and the tethered spacecraft interferometer (TSI). These concepts are illustrated in Figure 164, Figure 166, and Figure 165 respectively. Accurate relative position information for each of the apertures in an interferometer is necessary in order to reconstruct an image, while the size of the baseline affects its resolution. The SCI concept has high accuracy in determining aperture position, but less ability to vary its baseline. The SSI concept has tremendous difficulty achieving position accuracy, but a lot of ability to vary its baseline. The TSI concept is a hybrid of the previous two, though the dynamics of a tethered spacecraft system is poorly understood at present.

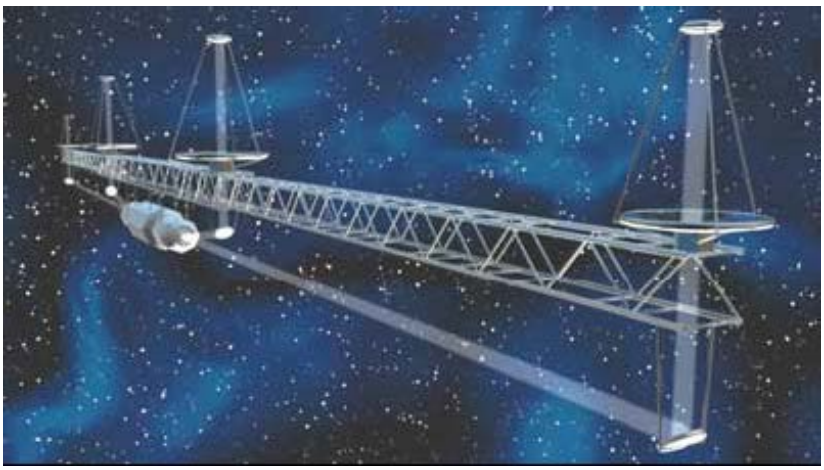


Figure 164 Structurally Connected Interferometer (SCI)[199]

[197] pp. 66.. Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission.

[198] The necessary "size" of the imager scales with distance to be viewed due to fewer incident photons: the farther the star, the fewer the photons that arrive per unit area. In order to detect these faint objects, more light collecting area is needed.

[199] pp 20. Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission. citing (Boeing-SVS 2000) and Terrestrial Planet Finder: Origins of Stars, Planets and Life, "Earth-likePlanets," http://tpf.jpl.nasa.gov/earthlike/earth-like.html , cited 1/2001.

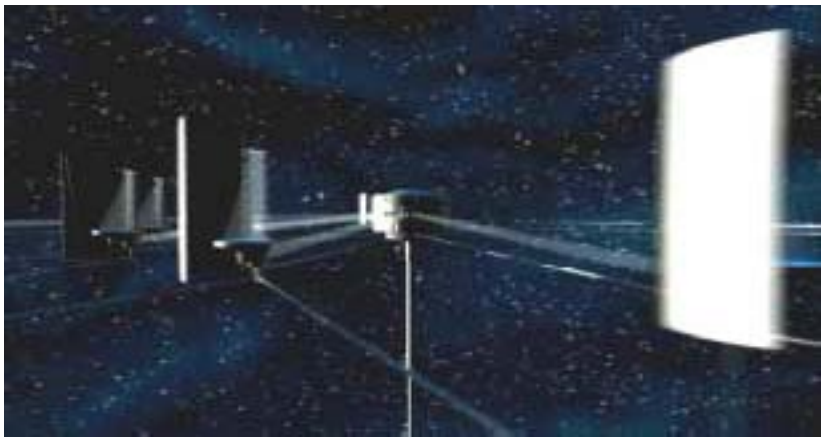


Figure 165 Tethered Spacecraft Interferometer (TSI)[200]

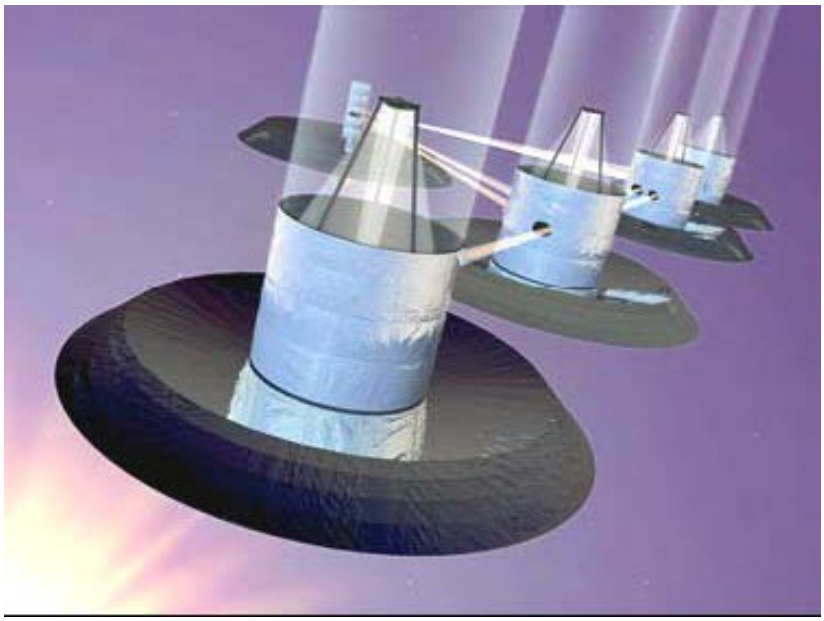


Figure 166 Separated Spacecraft Interferometer (SSI)[201]

In addition to the interferometer type, the other design variables are listed in Table 27. The orbit affects the operating environment for the system, including incident radiation from the sun and Earth. The number of apertures affects the cost of the system, as well as its performance. The wavelength affects the scale of the system optics, and the likelihood of making important science discoveries. The aperture type, ratio, and size all affect the system performance, as does interferometer baseline. The schedule is the allocation of time during a year to each of the four mission objectives: surveys, medium spectroscopy, deep spectroscopy, and imaging. The design lifetime is treated as fixed for this study at 5 years.

Table 27 Proposed TPF Design Variables

Name	Short Name	Units	Range	Type	Definition

[200] Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission.
[201] Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission.

Name	Short Name	Units	Range	Type	Definition
Orbit Type	OT	user-defined	{L2, LO, DA}	current	Orbit for system, including Sun-Earth L2 Direct, Earth L2 Halo, and Drift Away
Num Apertures	NA	num	4,6,8,10	current	Number of apertures in interferometer
Wavelength	Wl	microns	7, 10, 20	current	Optimized observational wavelength
Interferometer Type	IT	user-defined	{sci, ssi, tsi}	current	Type of interferometer (structurally connected, separated spacecraft, or tethered spacecraft)[202]
Aperture Type	AT	user-defined	{circular_optics, strip_optics}	current	Type of aperture used in interferometer
Aspect Ratio	AR	user-defined	{multi, const}	current	Either variable or fixed aspect ratio for aperture
Aperture Size	AS	user-defined or meters	See Table 28	current	Size of aperture for variable or fixed aspect ratio
Interferometer Baseline	IB	meters	See Table 29	current	Distance between interferometer apertures
Schedule	Sc	fraction year in each obs mode	[0-1] for each obs mode each year	potential	Fraction of year in each observation mode for each year in design life
Design Lifetime	DL	years	5 or 10	fixed	Designed for useful operational life for system

Table 28 Aspect Size (AS) Design Variable Range

AT=circular_optics		AT=strip_optics	
AR=multi	AR=const	AR=multi	AR=const
{min, mid, max}	1-4	{min, mid, max}	4-8

Table 29 Interferometer Baseline (IB) Design Variable Range

	AT=circular_optics		AT=strip_optics	
Num Apertures	AR=multi	AR=const	AR=multi	AR=const
4	30-120	30-120	40-120	30-120
6	50-120	60-120	50-120	60-120
8	70-120	70-120	80-120	70-120
10	90-120	100-120	100-120	100-120

[202] See Figure 164, Figure 166, and Figure 165 for illustrations of SCI, SSI, and TSI respectively.

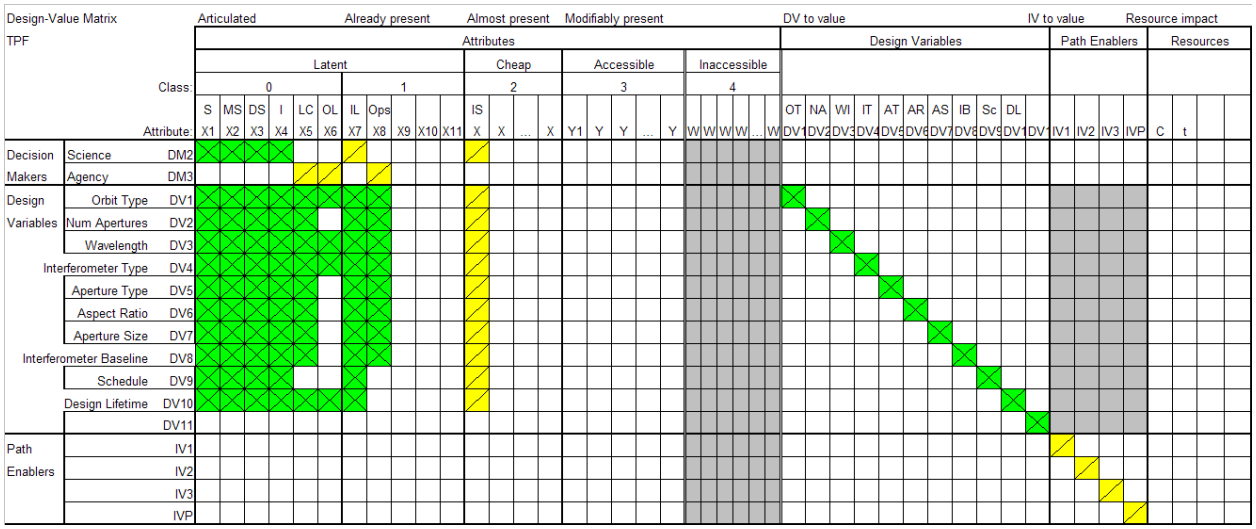


Figure 167 Design-Value Matrix for TPF with Design Variables added

Figure 167 shows the Design-Value Matrix for TPF with the design variables added, including their notional effects on the attributes, both articulated and unarticulated. Of particular note is the fact that the design variable to attribute matrix is almost full, showing a design relationship that is highly coupled: a variation in any design variable is likely to have an affect on most of the attribute values.

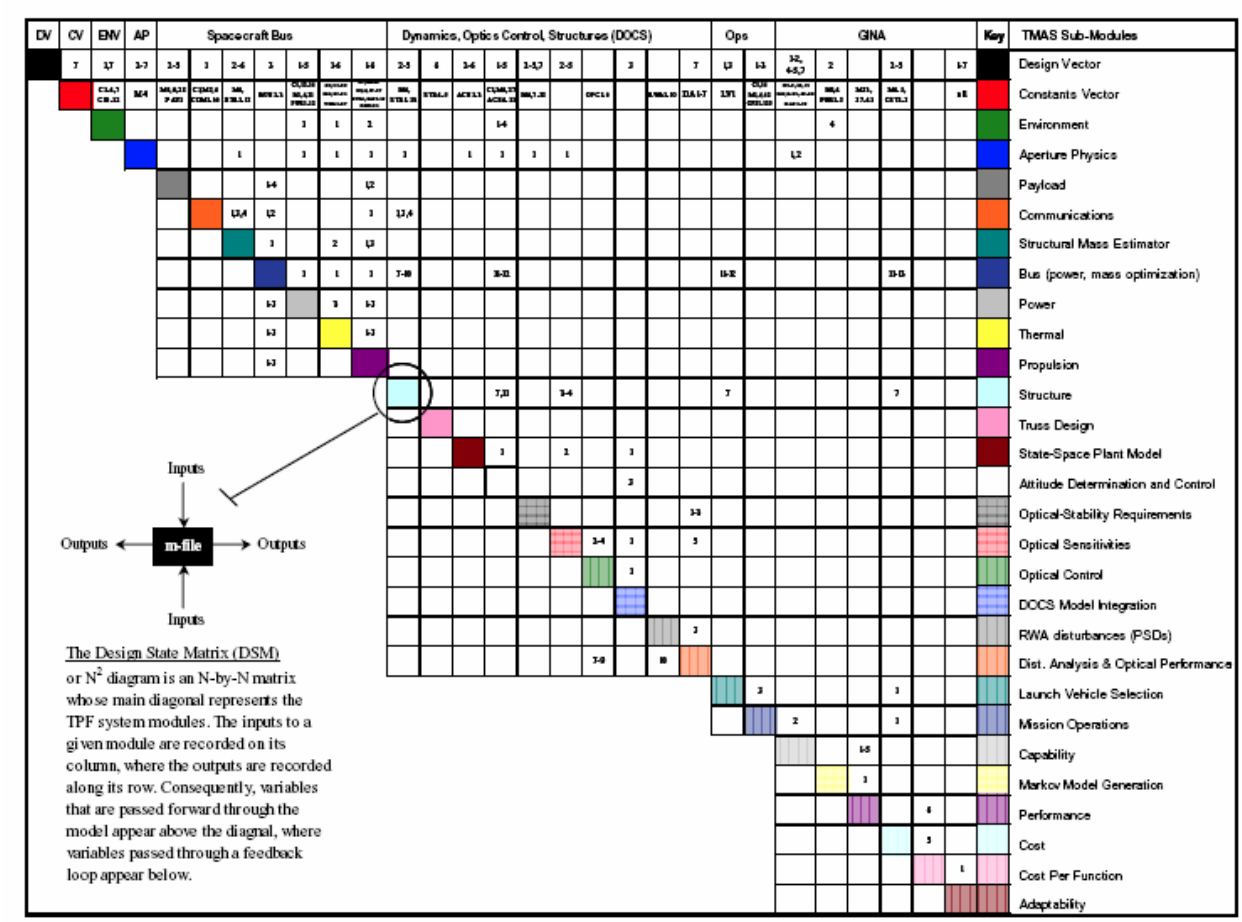


Figure 168 The N-squared matrix showing the model data flow for TPF Mission Analysis Software (TMAS)[203]

The next step is to develop a model to map design variable values to attribute values. The structure of the model used is depicted in the N-squared matrix shown in Figure 168. The entries show the data structures passed from model sub-modules to other sub-modules. The model used is the TPF Mission Analysis Software (TMAS) developed by the MIT Space System Laboratory (SSL), and further refined by Brian Makins in his 2002 Masters thesis.

10.2.4 Application of the Static MATE Framework

The principal model utilized in this work was the MIT SSL TMAS, with the Makins improvements.[204] The model was developed principally to explore the TPF concept tradespace spanning SSI, SCI, and TSI architectures, computing both cost and performance metrics for each architecture. The design variables used are the same as those listed in Table 27 except for the inclusion of schedule.[205] The Makins TPF model was used to explore approximately 11,000 combinations of design vector values in terms of the attributes listed in Table 24, Table 25, and

[203] Figure from pp 246 of Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission.

[204] Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission. Code used with permission from MIT Space System Lab (SSL).

[205] In TMAS, "schedule" was treated as fixed and was based upon a notional science schedule proposed in the TPF Book (1999). Makins recommended trading this parameter in future studies.

Table 26. Linear utility functions were used with k_i values based upon priorities inferred from the TPF Science Working Group as interpreted by Makins.[206] Table 30 lists these k_i values. Since the Design Life was fixed at 5 years, the only attribute for Agency that is changing is lifecycle cost. Since no utility interview data is available for Agency preferences on lifecycle cost, a linear utility function would be used. As such, a single attribute linear utility function would give the same orderings as using the attribute itself. *Thus the Lifecycle Cost attribute will be used as a proxy for the Agency utility*. For completeness Lifecycle Cost and Design Life could be wrapped together into a multiattribute utility function, but it would have no effect on the orderings in the tradespace.

Table 30 Science Attribute k_i values (per Makins 2002)

Attribute Name	Short	Rank	k_i value
Number of Surveys	S	1	0.6
Num Medium Spectroscopies	MS	2	0.4
Num Deep Spectroscopies	DS	3	0.4
Number of Images Short BL	IS	4	0.5

Figure 169 below depicts the Science Utility-Cost tradespace for the TPF mission using the Science Attribute k_i values mentioned above. 10,611 instantiations of the design vector were evaluated.

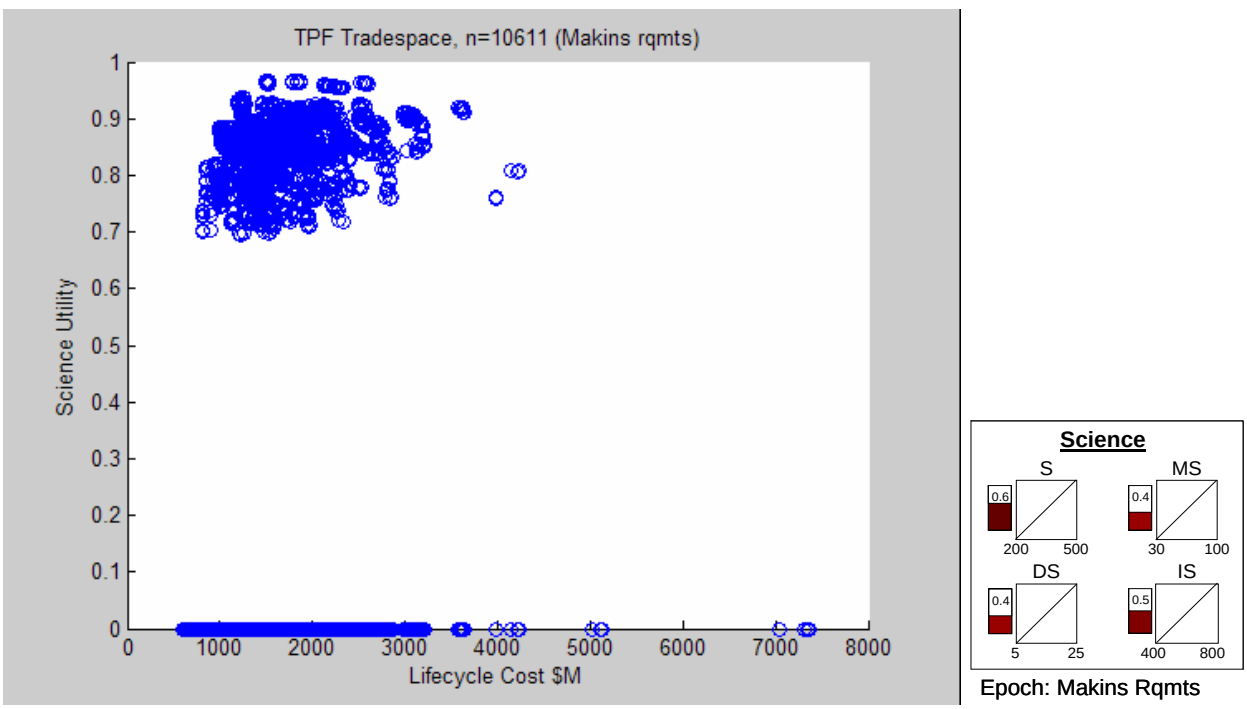


Figure 169 TPF Static Science Utility-Cost tradespace for Makins-defined requirements

[206] pp 4. Beichman, CA, D.R. Coulter, et al. (2002). "Summary Report on Architecture Studies for the Terrestrial Planet Finder." JPL Publication 02-011 Version 1, Rev. A. Pasadena, CA, Jet Propulsion Laboratory**:** 161. The attribute k_i values were assigned in correspondence to their relative rank as done in (Spaulding 2003).

An addition to the Makins code was made by adding the ability to vary the observing schedule. A schedule optimizer, which seeks to maximize utility over the life of the system, varies the amount of time in each of four observing modes for each year: surveys, medium spectroscopies, deep spectroscopies, and imaging. Due to the time required to run the schedule optimizer, the original fixed schedule Makins code was run over the tradespace, with the Pareto Set options chosen to be run in the optimizer to determine if additional utility could be extracted.[207] As can be seen by the results below, additional utility is indeed possible, so more of the tradespace should be explored with a variable schedule. Fixing the schedule can make designs look far less appealing than is actually the case.

The assumed "fixed" schedule is shown in Figure 170. The first year requires 20% of the time devoted to on-orbit checkout. Of the remaining time, 50% is devoted to conducting surveys, and 10% each to medium spectroscopy, deep spectroscopy, and imaging. The ensuing years see increases in imaging, and reduction in surveys. The intent is to survey enough stars in order to have a good idea about which stars to conduct further analysis, including medium spectroscopy. Medium spectroscopy likewise informs scientists about candidates for further deep spectroscopy.

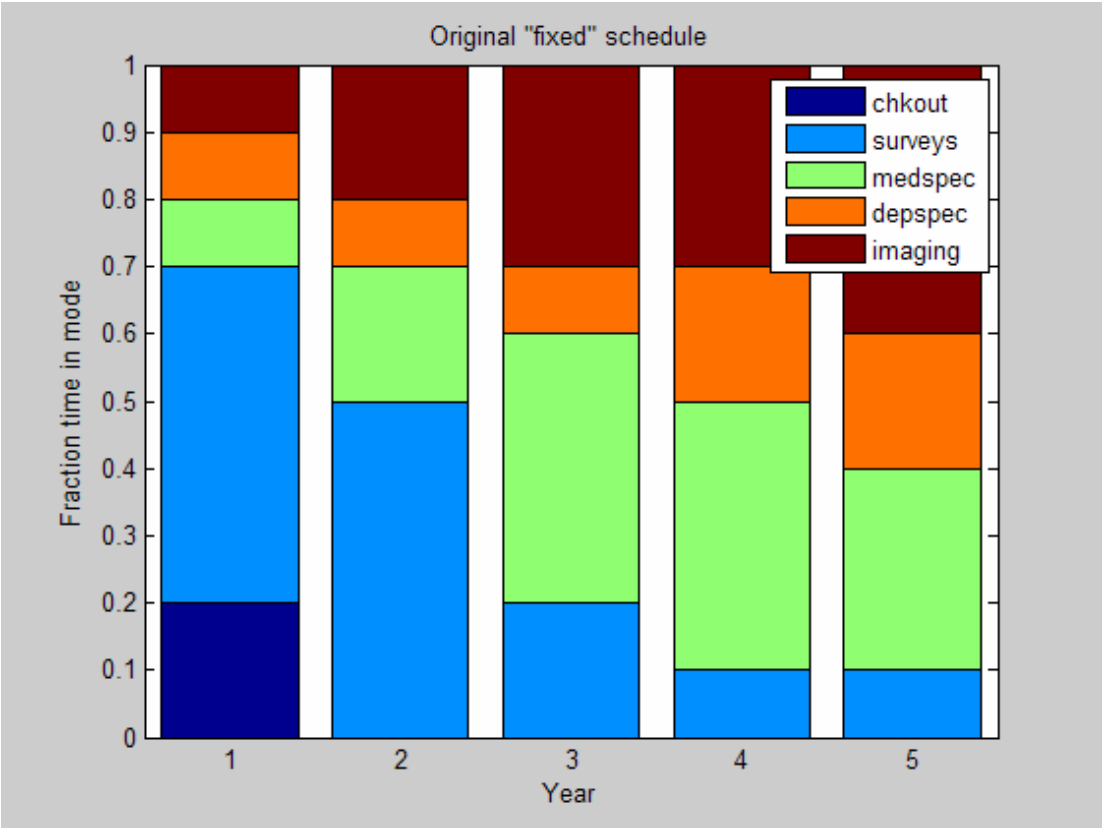


Figure 170 TPF assumed "fixed" schedule in Makins 2002, as proposed by TPF Book 1999.

The Pareto Set includes 130 designs, of which only 16 have nonzero utility. Figure 171 shows the design variable values for these 16 designs plus their associated lifecycle cost, utility with

[207] The particular algorithm used employed expert rules and inefficient option search. The algorithm required approximately 15 minutes to run per design on a 3 GHz computer. Running all 11000 designs would require far too much computation time: about 110 days.

original “fixed” schedule, and utility with “optimized” schedule. The “optimal” schedule for each design is depicted as well.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
ID num:	**5669**	**5646**	**5647**	**5650**	**5641**	**5654**	**5676**	**5655**	**2118**	**5683**	**5684**	**5686**	**6499**	**2962**	**6505**	**2968**
OT	LO	LO	LO	LO	LO	LO	LO	LO	L2	LO	LO	LO	LO	L2	LO	L2
NA	6	6	6	6	6	6	6	6	6	6	6	6	8	8	8	8
WI	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
IT	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi
AT	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir
AR	const	multi	multi	multi	multi	multi	const	multi	multi	const	const	const	const	const	const	const
AS	2	mid	mid	mid	min	max	3	max	max	4	4	4	3	3	4	4
IB	60	50	60	90	80	50	60	60	60	60	70	90	70	70	70	70
LC	816.6	842.1	853.5	873.1	941.4	985.7	1001.1	1031.5	1053.9	1185.7	1187.0	1191.2	1217.1	1261.0	1495.6	1520.0
U(orig)	0.7378	0.7897	0.8129	0.8138	0.8214	0.8806	0.8844	0.8856	0.8856	0.9320	0.9322	0.9322	0.9368	0.9368	0.9671	0.9671
U(opt)	0.8977	0.9295	0.9401	0.9390	0.9420	0.9928	1	1	1	1	1	1	1	1	1	1

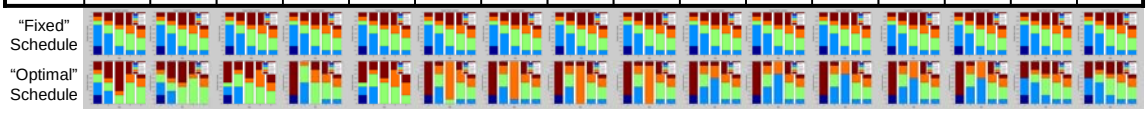


Figure 171 TPF Pareto Set with nonzero utility (16 designs)

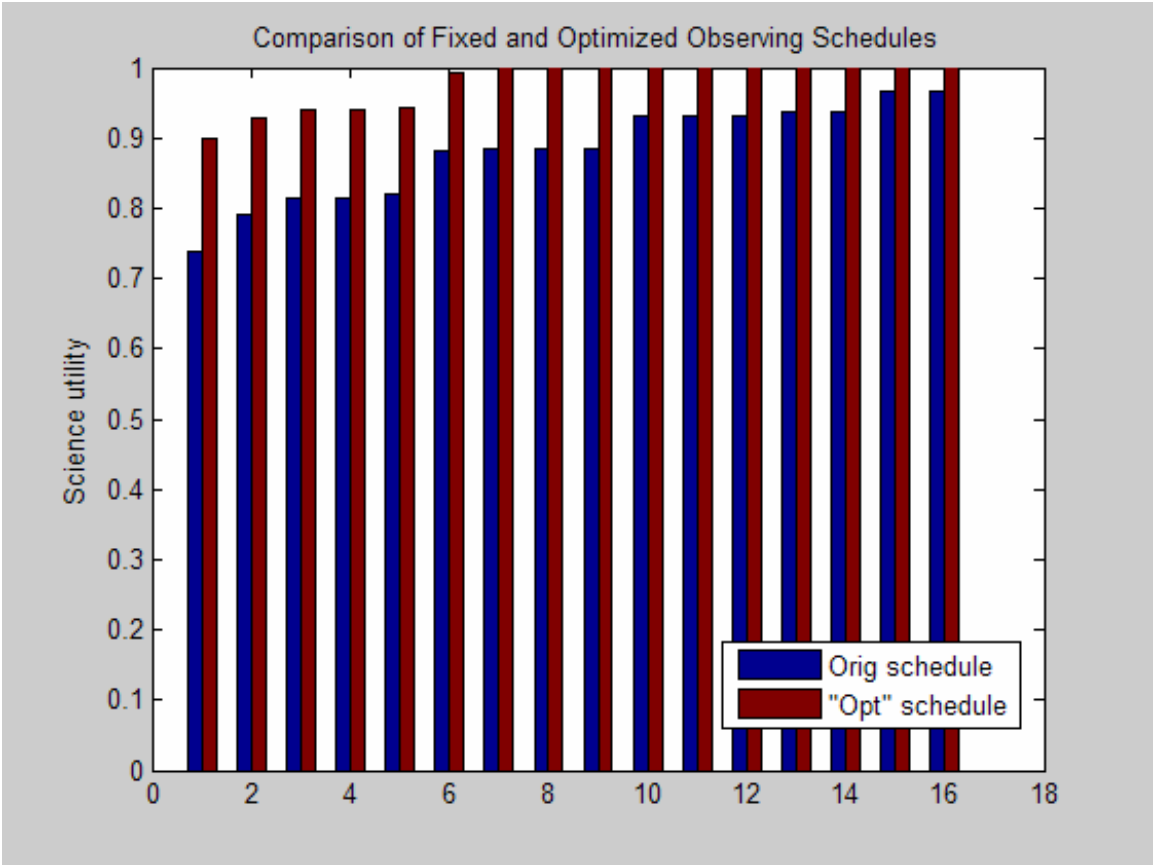


Figure 172 Utility comparison of fixed and optimized observing schedules for TPF Pareto designs

Figure 172 shows the results of the schedule optimization algorithm. For every design, additional utility was achieved, suggesting schedule to be an important design variable to be considered in the tradespace work. The original tradespace explored by Makins had the architectures over-

performing in their survey work, though he realized the effect was due to a "front-loading" of the observation schedule.[208] In order to improve the performance of the architectures in the underperforming attributes, it is necessary to give up performance in the overperforming attributes. The utility function instructs the analyst on how to trade these attributes in order to increase overall value.

Figure 173 below shows the attribute values for Pareto designs before and after the schedule optimization. "Best" and "worst" acceptable values for attributes are indicated by horizontal lines. Attribute values above the "best" level give virtually no extra value to the decision maker and could be using that time to improve underperforming attributes. Following this logic, the optimizer reduced the time spent on surveys and increased the deep spectroscopy and imaging time, enabling the values to fall within the acceptable range, preferably towards the "best" end of the range.

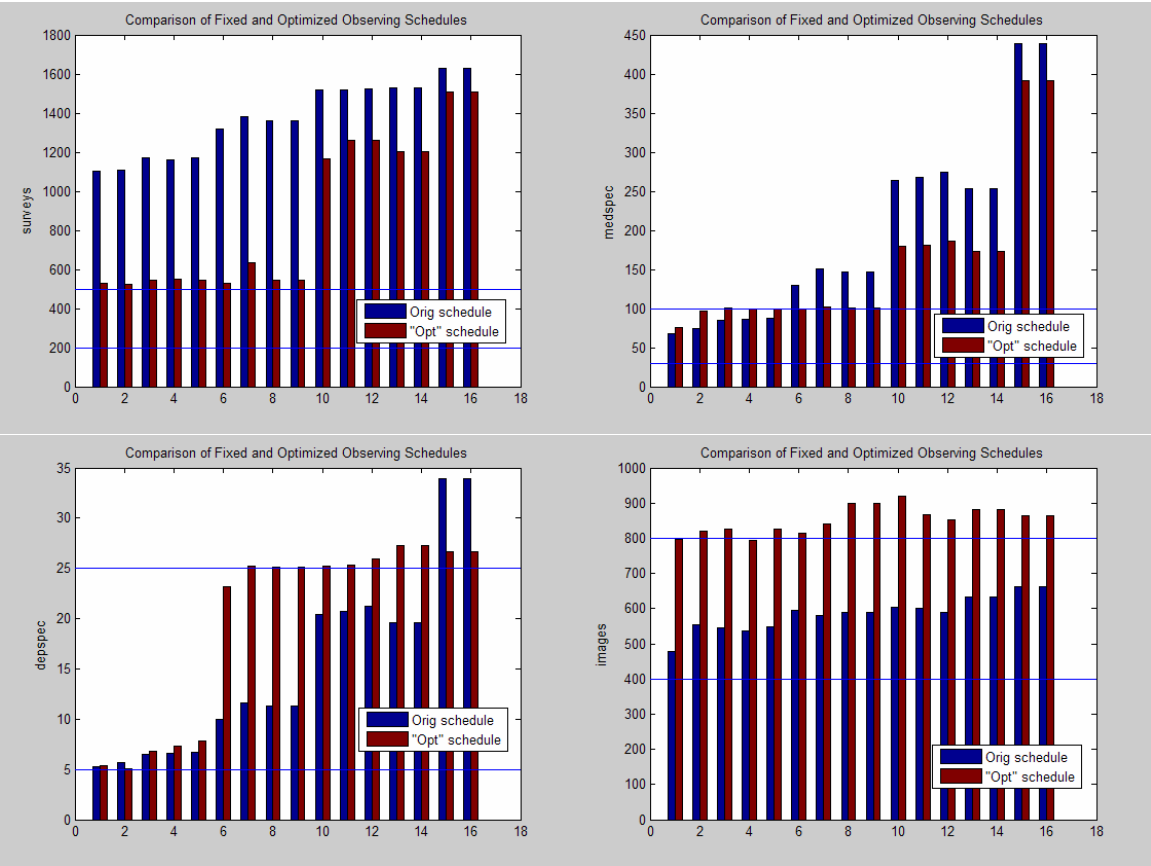


Figure 173 Attribute comparison of fixed and optimized observing schedules for TPF Pareto designs

[208] Makins specifically discusses the problem in his conclusion, though he doesn't show that the requirements could be met by the designs. "The current mission time-line is too front-loaded, i.e. too much time is budgeted for planet detection operation. A majority of the architectures far exceed the planet detection requirement. This time would be better spent taking deep spectroscopic and long baseline images. These operations were not budgeted adequate observation time and, as a result, it becomes cost prohibitive to meet the requirements. Future studies should optimize the mission time line so that most (if not all) operational modes can meet their performance goal." See pp 221. Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission.

The static data can be further analyzed by looking at the relationship between attribute performance and acceptability ranges for each attribute across the whole tradespace. Figure 174 through Figure 178 below show lifecycle cost versus attribute value for the TPF tradespace. Insights into how “easy” or “hard” it is to meet the requirements can be gleaned by noting the density of design options within the acceptability range for each attribute. In particular, Figure 178 shows that none of the designs reaches the minimum acceptable level for images long. The fact that the optimized schedule designs do perform better in images long than the fixed schedule designs suggests that schedule manipulation could possibly move designs into the acceptable region. The utility function used for the schedule optimization did not use image long as an attribute, but rather images short, per Makins 2002.

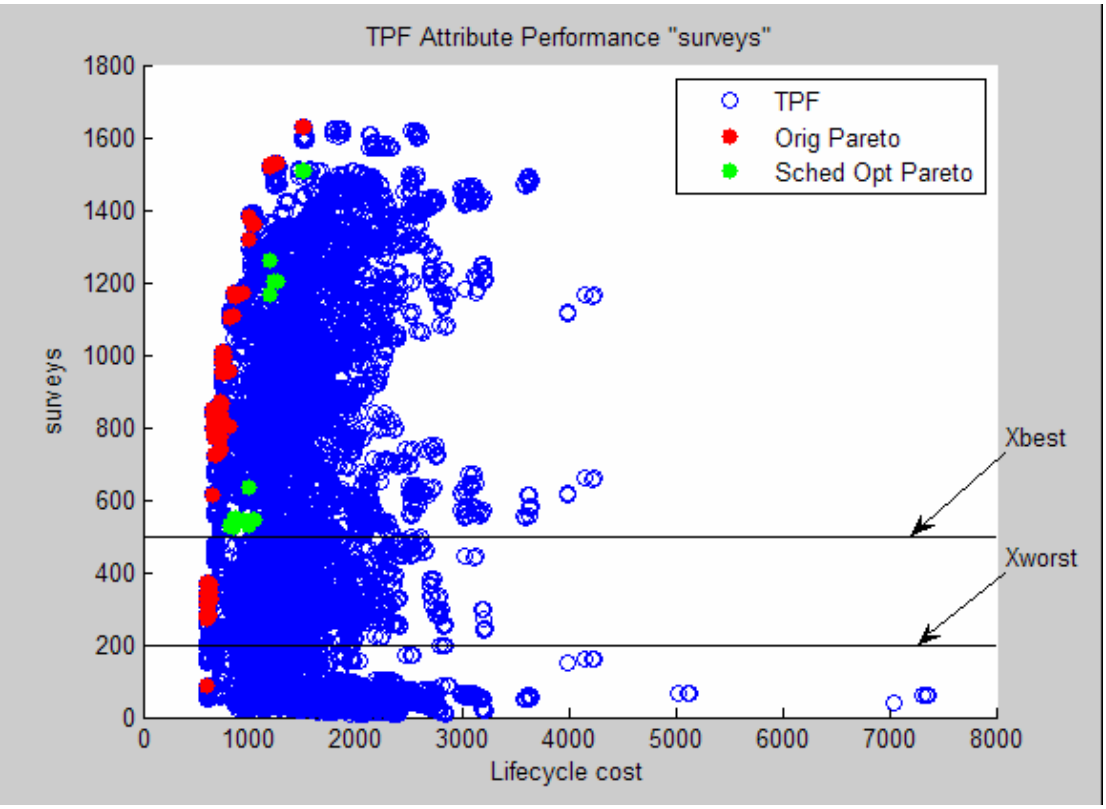


Figure 174 TPF attribute performance "surveys" versus cost, with acceptability thresholds indicated

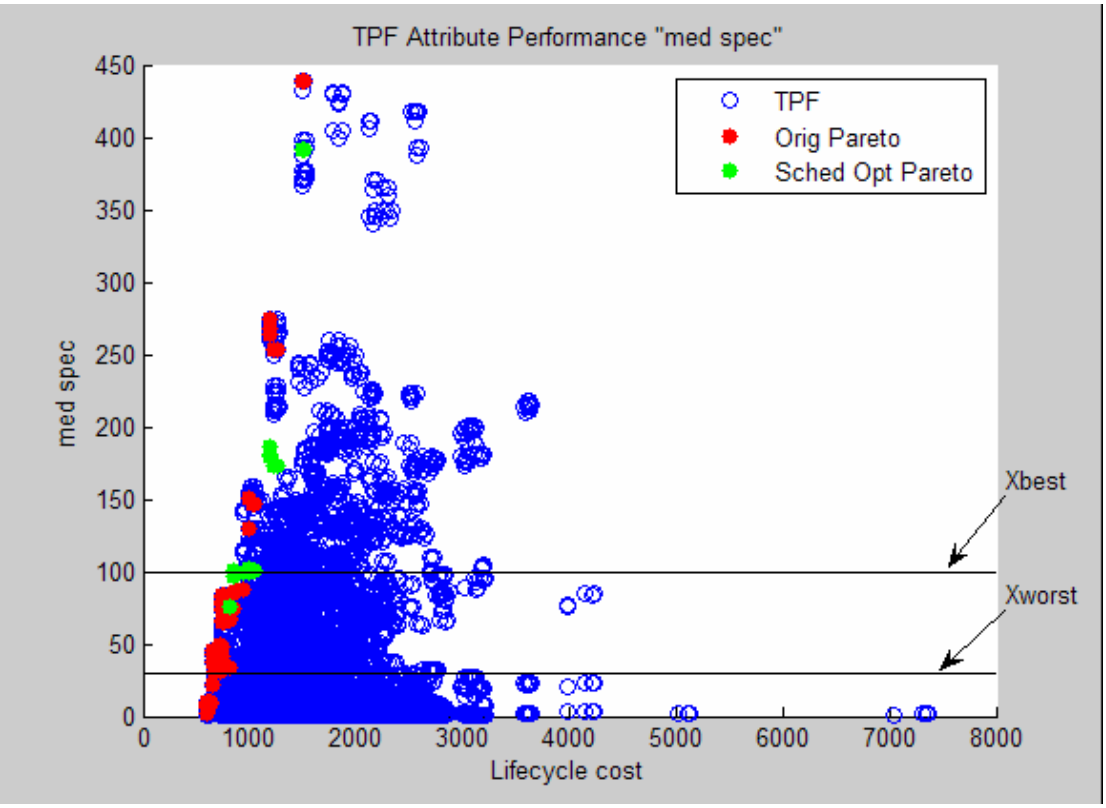


Figure 175 TPF attribute performance "med spectroscopy" vs. cost, with acceptability thresholds indicated

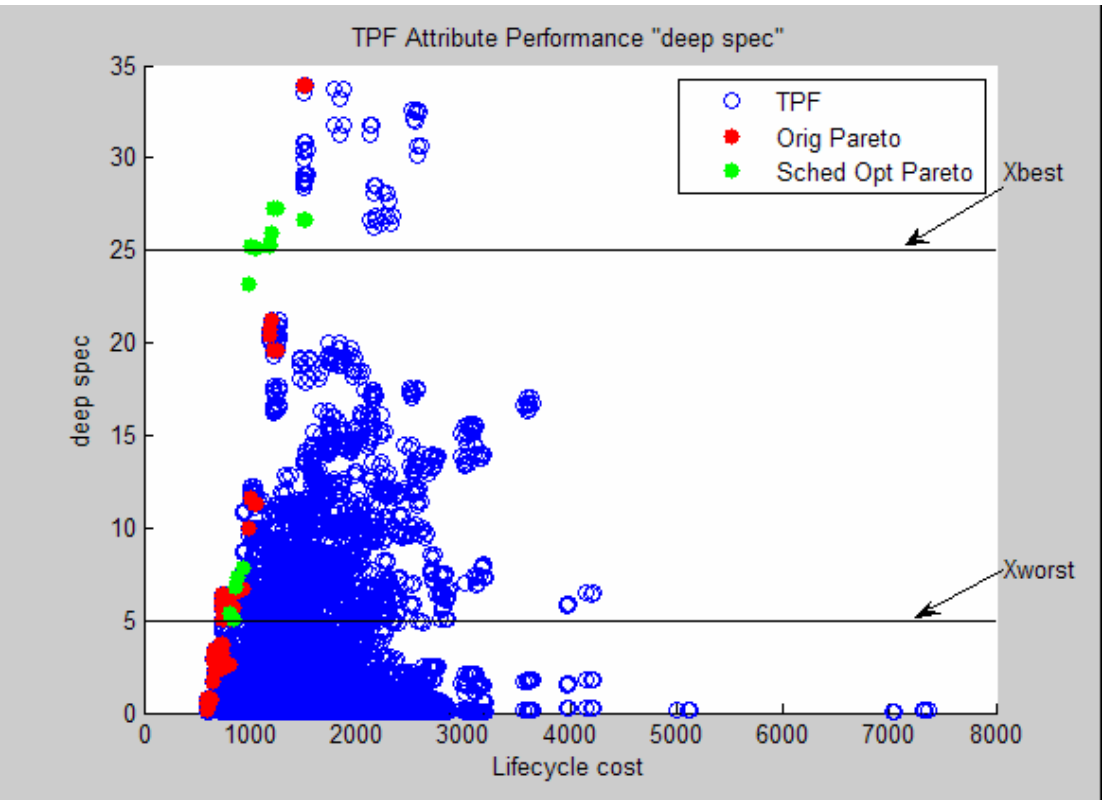


Figure 176 TPF attribute performance "deep spectroscopy" vs. cost, with acceptability thresholds indicated

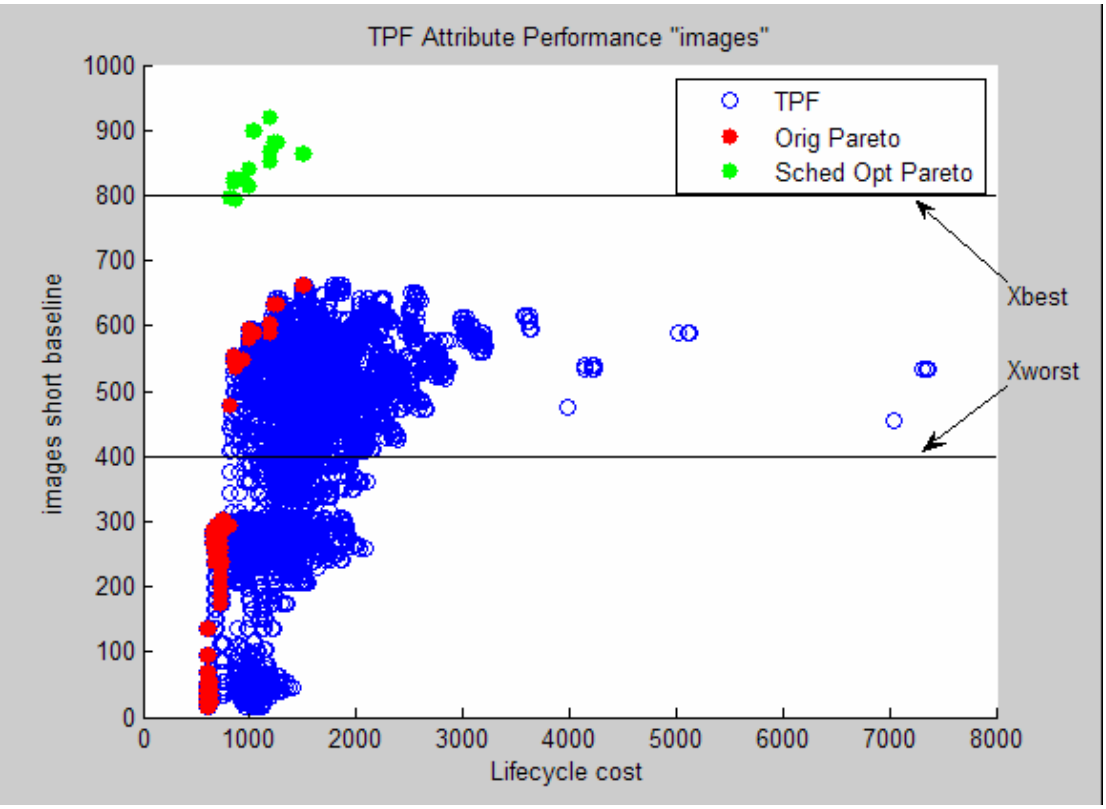


Figure 177 TPF attribute performance "images short" vs. cost, with acceptability thresholds indicated

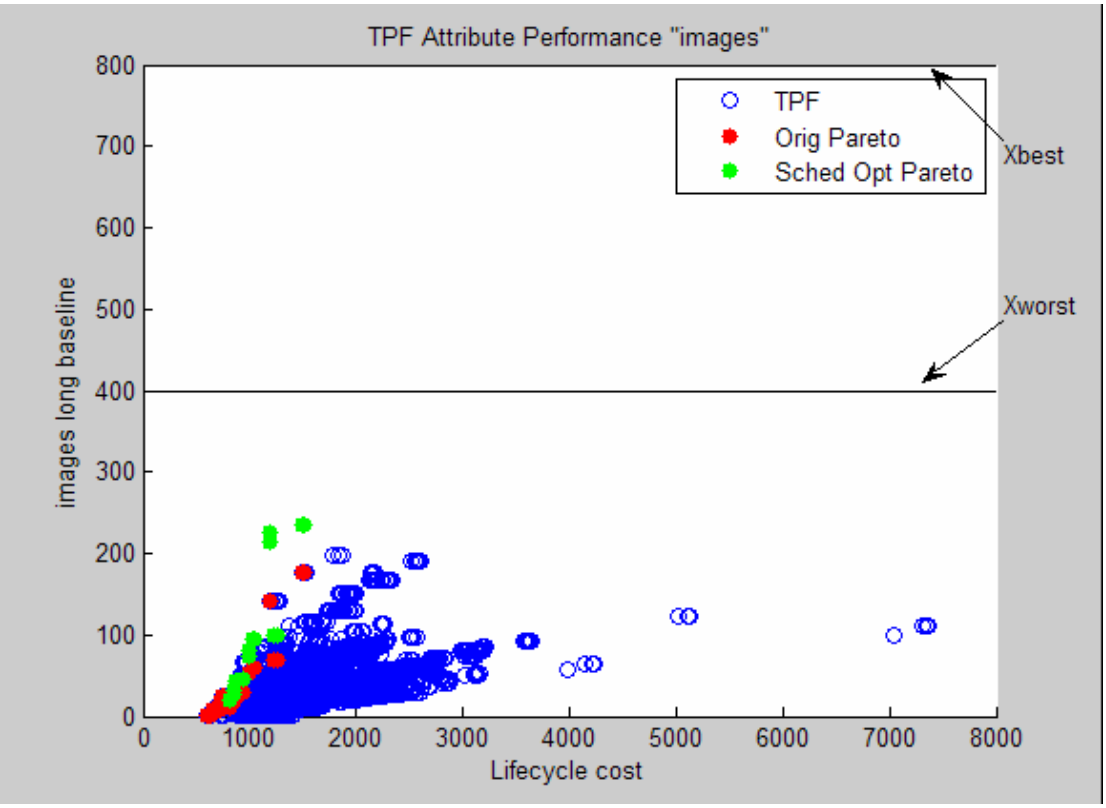


Figure 178 TPF attribute performance "images long" vs. cost, with acceptability thresholds indicated

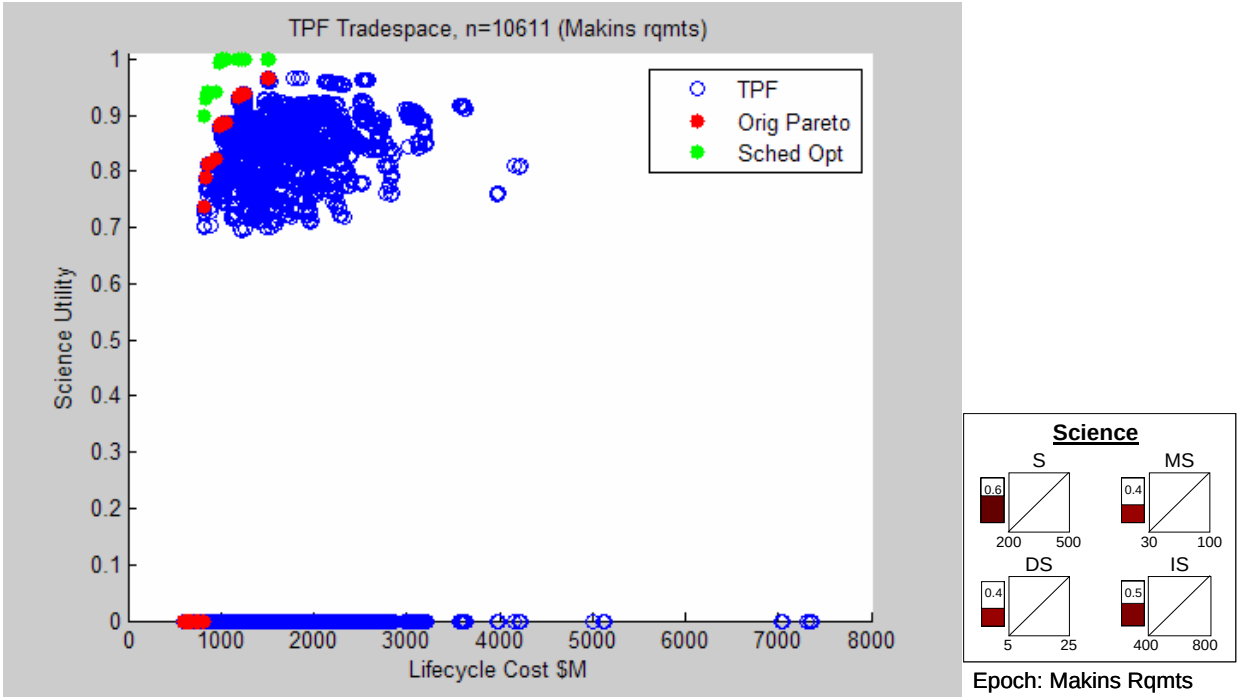


Figure 179 TPF Science Utility-Cost tradespace with Pareto and schedule "optimal" points

Figure 179 shows the effect of schedule optimization on the Science utility-cost tradespace. All of the schedule optimized points have higher utility than their fixed schedule counterparts.

In order to determine if the considered designs can ever meet the "images long" minimum acceptable level, another study was done with the schedule fixed at "always imaging." In the case the entire mission is dedicated to imaging, instead of the other three observing modes, the results are shown in Figure 180 below. A number of designs do meet the 400 image minimum, and a few even meet the 800 image "best" level. Unfortunately, none of the designs meet any of the other three attribute minimum levels since all time is spent on imaging. It may be possible to find a handful of designs that meet the minimum level in all four attributes, though further research is needed. [209] In any case, it seems the performance will be close to the minimum levels for the attributes, thereby creating a minimally acceptable system, suggesting the system is at the edge of feasibility. Any change in technology or preferences can push the system to the infeasible region, or add substantial perceived value to the system.[210]

[209] 486 designs out of 10611 had "images long" exceeding the 400 image minimum acceptable level. Of these, none met the other three attribute minimum levels, though they all had over 2000 "images short." Further model work should be done to enable variable imaging on short and long baselines. The Makins model assumes half of imaging time is spent on short baseline images and half on long baseline images. The science requirements suggest interest in being able to tune the interferometer to a particular planetary system.

[210] A reduction in the minimum acceptable level will increase the number of feasible designs, as will improvement in technology. On the other hand, an increase in the number of conflicting attributes will reduce the feasible set of designs. Discrete observational modes are an example of conflicting attributes since only one can be realized at a time.

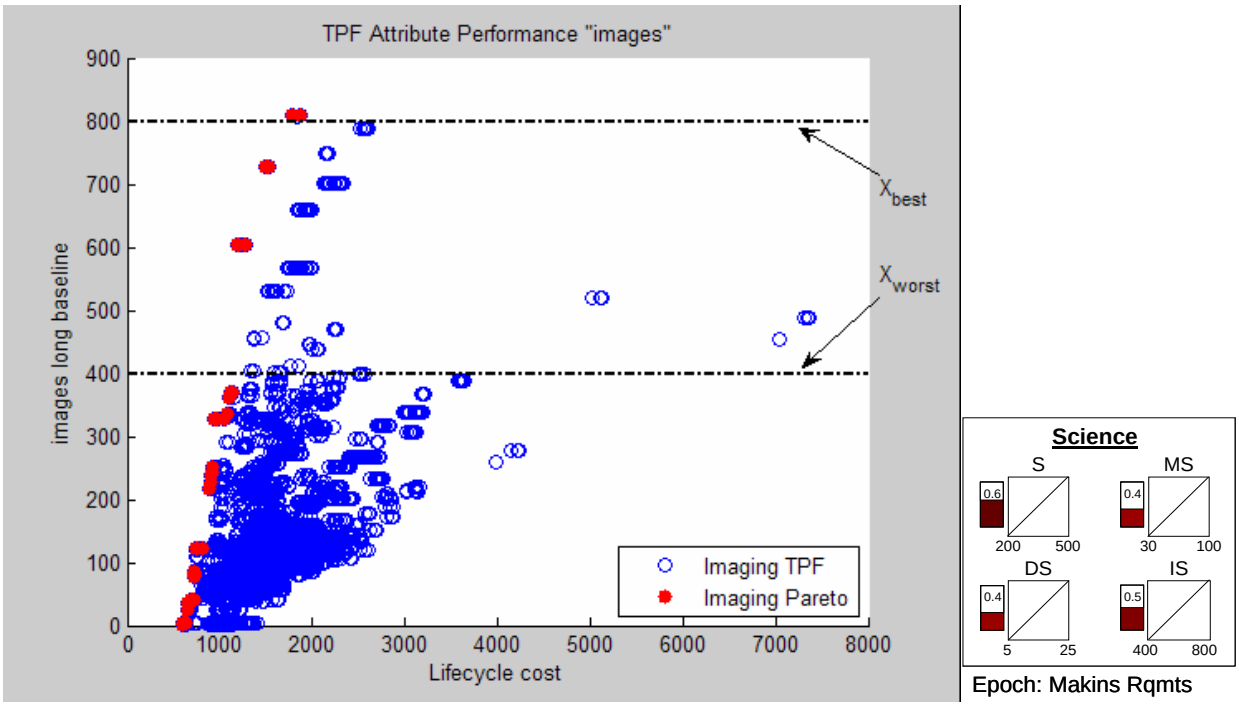


Figure 180 TPF attribute performance "images long" vs. cost for an "imaging only" mission

10.3 Dynamic Analysis

There are two principal motivations for technological change for telescopes: improving resolution and improving sensitivity. To increase sensitivity it is necessary to either increase the collecting area of the instrument or reduce the relative noise environment.[211] To increase resolution, it is necessary to increase the effective "size" (diameter) of the instrument. The "size" of an interferometer can be measured by its baseline. The farther a fixed set of apertures, the more sparse it becomes and the longer it takes to create an image due to the need to fill the u-v plane. Ideally a large telescope is completely "filled"—has a photon collector over its entire area—but such telescopes are impossible much farther beyond the volume constraints of current launch vehicles. The architectures considered in this study are interferometers and can scale up in size through the addition of more aperture elements or longer baselines.

Two principal forces for change confront the TPF mission: changing preferences and changing technology. Considering this fact, proposed TPF transition rules are listed in
Table 31.

[211] Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission.

Table 31 Proposed TPF Transition Rules

Rule	Description	Change agent origin
R1: Change baseline	Expand or contract baseline	Internal (adaptable)
R2: Increase NA	Add to number of apertures	External (flexible)
R3: Change schedule	Alter observation schedule	External (flexible)[212]
R4: Extend life	Add time to active mission duration	External (flexible)[197]

The proposed rules seek to alter the design variable values or set in order to change the system displayed attribute values or set. Figure 181 shows these transition rules with their anticipated effects on the design variables.

Rule-Effects Matrix			Design Variables											Path Enablers			Change	
TPF			OT	NA	WI	IT	AT	AR	AS	IB	Sc	DL		Mod	+Ap	Rc	Origin	
			DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	DV1	DV1	IV1	IV2	IV3	Flx	Adp
Rule	Change baseline	R1								↑↓						X		X
	Increase NA	R2		↑										/	/		X	
	Change schedule	R3									↑↓						X	
	Extend life	R4										↑					X	
		RK																

Figure 181 Rule-Effects Matrix for TPF

The Path Enabler variables are "Modularity", "Extra Apertures" and "Reconfigurability." The Modularity and Extra Apertures variables are not required, but reduce the "cost" to change, thereby increasing the likelihood that a particular change path will be perceived acceptable. Modularity is the partitioning of the system into loosely coupled components, which can be replaced with minimal impact on system performance. Embracing modularity would make it easier to add extra apertures to the system, either homogenous or heterogeneous with the existing apertures. Having extra apertures available either on the ground or in orbit would reduce the dollar cost and time required to increase the number of apertures. Reconfigurability is the ability for the system to physically alter its spatial orientation, in particular its observing components. This ability is necessary in order to change the baseline for the system since the baseline is a function of its geometry.

[212] The "location" for changing the schedule or extending life is deemed to be the operations center, which for this analysis, is not considered to be "internal" to the system. If the analyst chooses to define the operations center inside the system boundary, then the change would be considered an "adaptable" type instead.

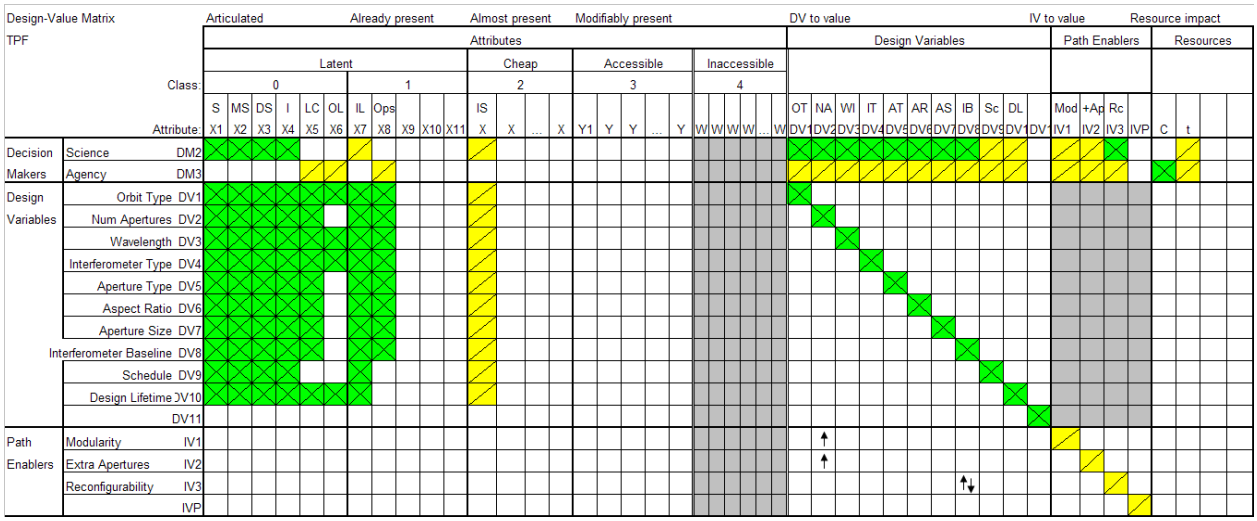


Figure 182 Design-Value Matrix for TPF with Path Enablers added

Figure 182 shows the Design-Value Matrix with the Path Enablers added. Additionally, the "design variables to value" are indicated for each of the decision makers. Since the design variables are highly coupled to the attributes, the decision makers' attributes of interest are affected by most of the design variables. The Path Enablers "of interest" are likewise indicated, with "Reconfigurability" of particular interest to the Science decision maker.

In addition to capturing the attributes, design variables, and path enablers, the DVM can also indicate qualitatively the distribution of costs and benefits of the system. "Resource" type attributes can be counted across each decision maker row and the sum can be indicated in the resources section of the DVM. For the TPF case, the Agency is the only decision maker with resource attributes, indicated by a "present" mark in the cost column under resources. The fact that only the Agency cares about resources, while Science cares about benefits attributes, suggests a potential conflict between the decision makers when negotiation must occur. The incentives for the two decision makers are in direct conflict: one seeks to minimize resources expended, the other seeks to maximize benefit accrued. When both cost and benefit are within the same decision maker, the trade-off between cost and benefit can occur more clearly since they are measured in effect "on the same scale." When distributed across decision makers, it is more difficult to assess how much a unit of benefit is worth to a different person who does not perceive the benefit. This problem is not unique to TPF and plagues all government funded science missions: no one knows how to put a dollar figure on an extra image.

10.4 Results

The following sections describe the dynamic MATE analysis results.

10.4.1 Analyzing Changing Contexts

Insight into changing attributes and design variables can be gleaned from inspecting the Origins Program roadmap references to TPF over the 1997-2003 time periods.

According to the 1997 roadmap[213]:

> The highest priority long-term mission is the Terrestrial Planet Finder (TPF). The TPF is currently envisioned as a long (several tens of meters) baseline infrared interferometer, operating in the wavelength range roughly from 7-20 µm. This region of the spectrum has been identified because it is an excellent region for the direct detection of terrestrial (i.e., small and rocky) planetary companions to other stars, as well as a region that is rich in molecular lines that could provide evidence as to the habitability of any planets that are discovered. The TPF, like the NGST, is a foundation stone in the Origins scientific pyramid.

Figure 183 and Figure 184 below show the TPF tradespace evaluated in terms of the attributes implied by the preceding statement and shown in Table 32. The latter figure shows negative utility values corresponding to the number of unacceptable attribute levels for a design.[214] Additionally, the document implies the investigation of structurally-connected interferometer (SCI) designs, which are highlighted in the tradespace in red.

Table 32 Attributes for Origins 1997 Roadmap

Attribute Name	Short	Rank	k_i value
Number of Surveys	S	1	0.5
Num Medium Spectroscopies	MS	2	0.4

[213] http://origins.jpl.nasa.gov/library/roadmap97/index.html (Cited 3/17/06)

[214] A utility value of -2, for example, means that design has two attributes worse than the "worst" acceptable level.

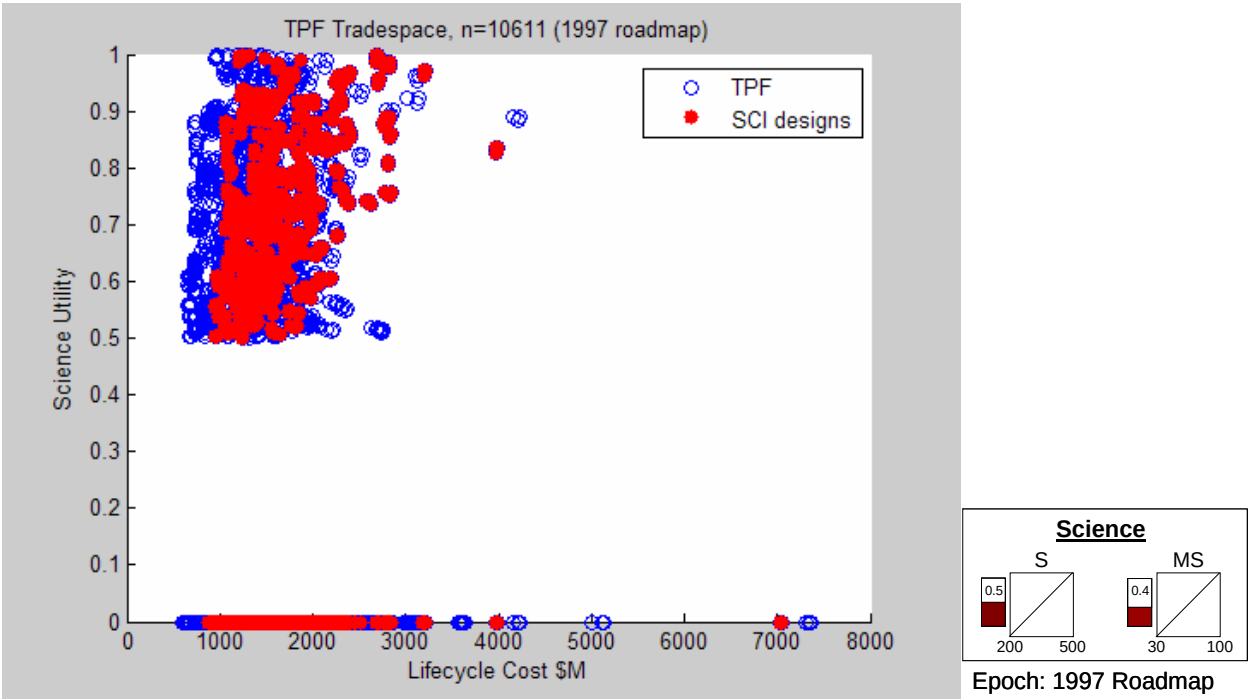


Figure 183 TPF Tradespace for 1997 Origins Roadmap

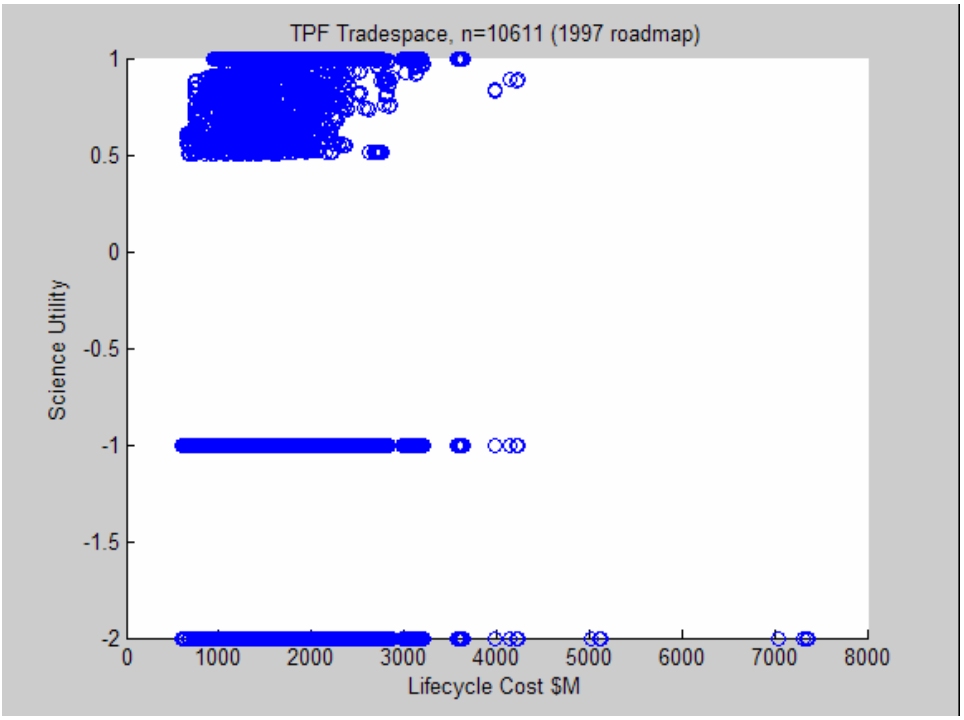


Figure 184 TPF Tradespace for 1997 Origins Roadmap, indicating number of unacceptable attributes

According to the 2000 roadmap[215]:

> As currently envisaged, TPF consists of four 3.5-m free-flying telescopes, each passively cooled to 35 K, and a central beam-combining facility. Planet detection and characterization will use a nulling interferometric mode at wavelengths from 7-20 µm with spectral resolution of ~20. TPF will also be able to operate as a general-purpose imaging interferometer at wavelengths from 3 to 30 µm with spectral resolutions as high as 300. With a maximum baseline of 1 km, TPF will offer angular resolution better than 1 milliarcsec to investigate astrophysical phenomena such as planet-forming protostellar disks and the energetic cores of active galaxies.

Figure 185 and Figure 186 below show the TPF tradespace evaluated in terms of the attributes implied by the preceding statement and shown in Table 33. The latter figure shows negative utility values corresponding to the number of unacceptable attribute levels for a design.[216] Additionally, the document implies the investigation of structurally-connected interferometer (SCI) designs as well as separated spacecraft interferometer designs (SSI), which are highlighted in the tradespace in red and green, respectively. Notice that *no designs* meet the minimum acceptable value for long baseline images.[217] The currently proposed designs are thus unacceptable, all with zero utility. New concepts, designs, or preferences are necessary to move forward.

Table 33 Attributes for Origins 2000 Roadmap

Attribute Name	Short	Rank	k_i value
Number of Surveys	S	1	0.5
Num Medium Spectroscopies	MS	2	0.4
Num Deep Spectroscopies	DS	3	0.3
Number of Images Long BL	IL	4	0.2

[215] http://origins.jpl.nasa.gov/library/roadmap00/index.html (Cited 3/17/06)

[216] A utility value of -2, for example, means that design has two attributes worse than the "worst" acceptable level.

[217] See Figure 178 for the tradespace plot of cost versus long baseline images. The minimum acceptable level exceeds the best performing option. Schedule optimization may enable realization of the minimum level. The more likely case for reaching the acceptable range is the creation of new concepts or technologies, or a lowering of expectations.

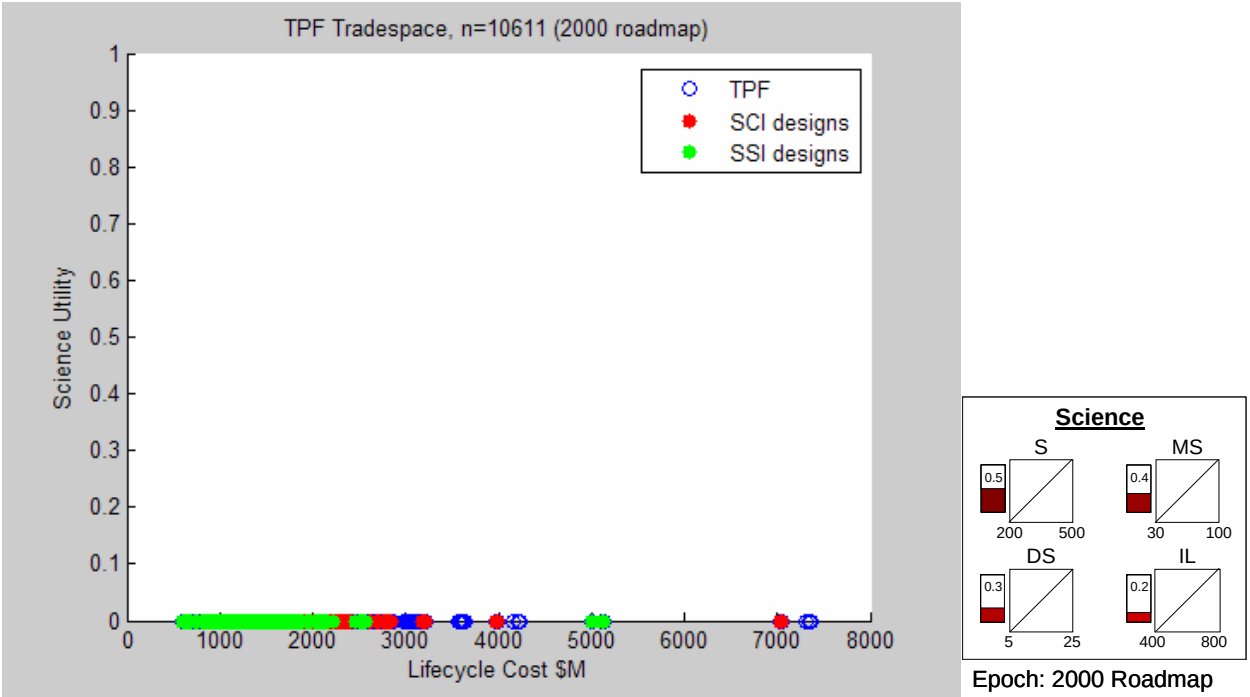


Figure 185 TPF Tradespace for 2000 Origins Roadmap

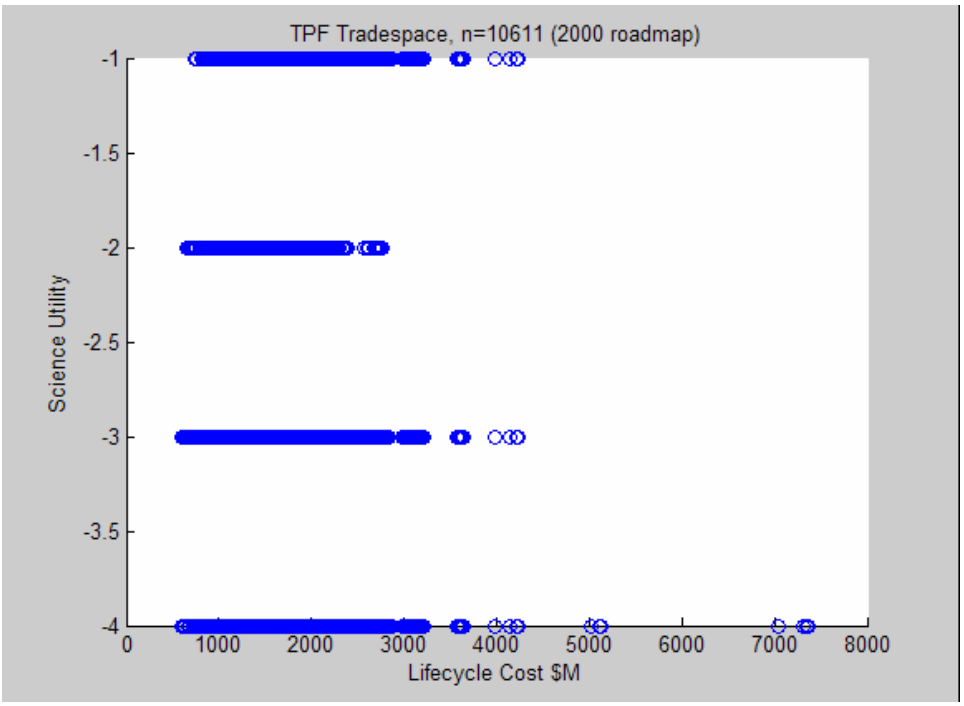


Figure 186 TPF Tradespace for 2000 Origins Roadmap, indicating number of unacceptable attributes

According to the 2003 roadmap[218]:

> TPF's ability to carry out a program of comparative planet studies across a range of planetary masses and orbital locations in a large number of new solar systems is an important scientific motivation for the mission. However, TPF's mission will not be limited to the detection and study of distant planets. An observatory with the power to detect an Earth orbiting a nearby star will also be able to collect important new data on many targets of general astrophysical interest.
>
> The TPF observatory will likely take the form of either a coronagraph operating at visible wavelengths or a large-baseline interferometer operating in the infrared. The visible-light coronagraph concepts would use a single telescope with an effective diameter of 8–10 meters, operating at room temperature, but required to achieve a billion-to-one image contrast. Very precise, stable control of the telescope optical quality would be required. The infrared interferometer concepts would use multiple (≈4), smaller, 3–4-meter-diameter telescopes configured as an array and spread out over a large boom of up to 40 meters or operated on separated spacecraft over distances of a few hundred meters. The telescopes would operate at extremely low temperatures of ≈40 kelvin, and the observatory would necessarily be large. However, the image contrast requirement, "only" a million to one, and thus the required system optical quality, would be much easier to achieve at infrared wavelengths.

Figure 187 and Figure 188 below show the TPF tradespace evaluated in terms of the attributes implied by the preceding statement and shown in Table 34. The priority for long baseline images has increased over the 2000 roadmap reflecting the increased desire to perform additionally astrophysical science besides the planet detection and characterization mission initially proposed. The latter figure shows negative utility values corresponding to the number of unacceptable attribute levels for a design.[219] The roadmap document implies the investigation of structurally-connected interferometer (SCI) designs as well as separated spacecraft interferometer designs (SSI), which are highlighted in the tradespace in red and green, respectively.[220] Notice that *no designs* meet the minimum acceptable value for long baseline images. The currently proposed designs are thus unacceptable, all with zero utility. New concepts, designs, or preferences are necessary to move forward.

Table 34 Attributes for Origins 2003 Roadmap

Attribute Name	Short	Rank	k_i value
Number of Surveys	S	1	0.5
Num Medium Spectroscopies	MS	2	0.4
Num Deep Spectroscopies	DS	3	0.3
Number of Images Long BL	IL	4	0.5

[218] http://origins.jpl.nasa.gov/library/roadmap03/index.html (Cited 3/17/06)

[219] A utility value of -2, for example, means that design has two attributes worse than the "worst" acceptable level.

[220] The roadmap also calls for the investigation of masked coronagraphs operating in the visible spectrum. Such concepts were not included in the Makins model due to the assumption of large technical cost at modest performance over infrared interferometers. Further models should incorporate this concept to aid mission planners in comparing the concepts more holistically.

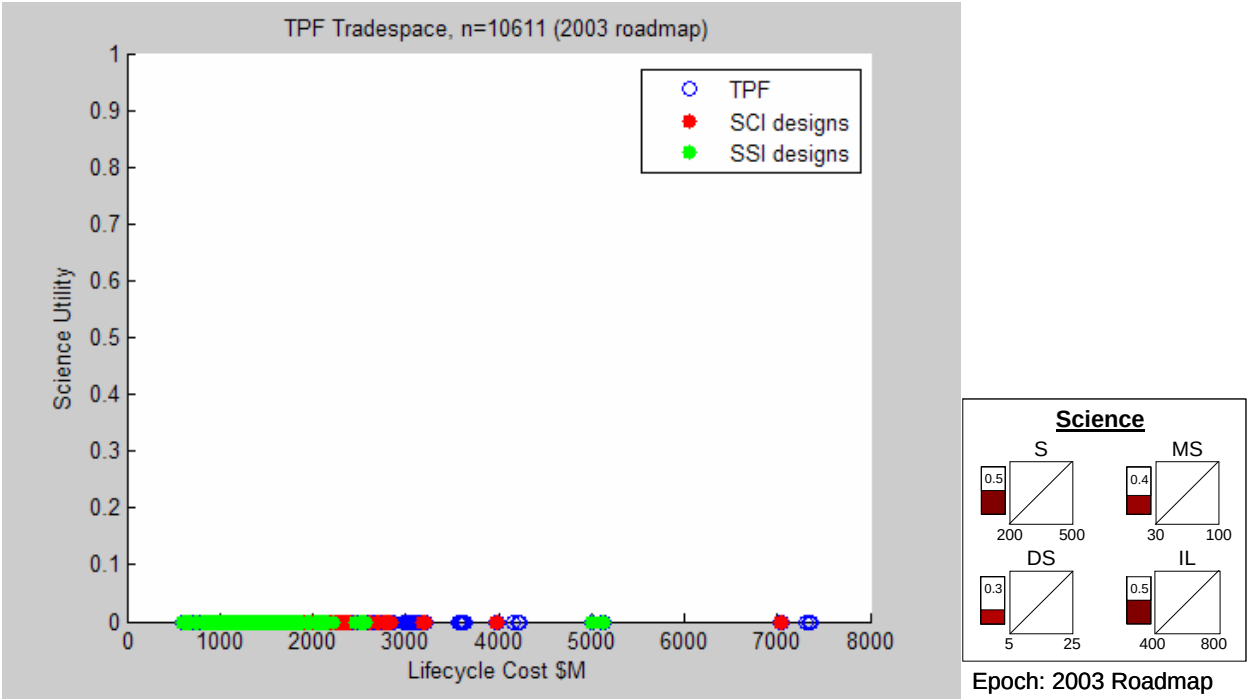


Figure 187 TPF Tradespace for Origins 2003 Roadmap

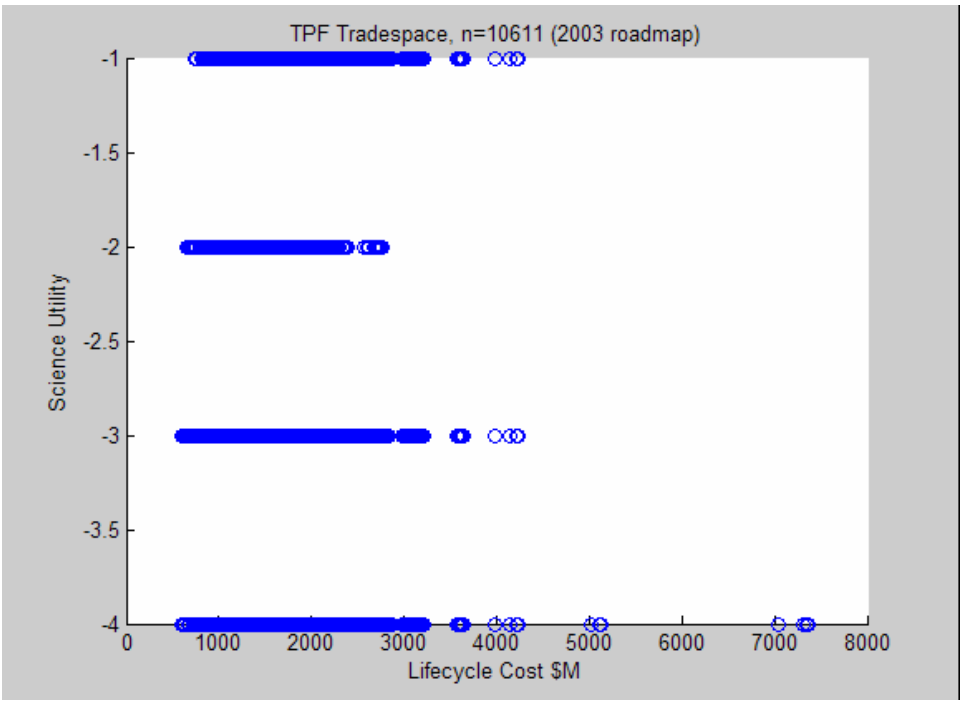


Figure 188 TPF Tradespace for 2003 Origins Roadmap, indicating number of unacceptable attributes

It is interesting to note two features over time. First, counter to usual system design where a tradespace is narrowed down to a point for further consideration, the design space appears to be *increasing* over time, with the addition of more concepts in each successive roadmap. Second, the number of objectives appears to be increasing over time as well, with the inclusion of an admission that TPF will "be able to collect… data on many targets of general astrophysical

interest" in addition to its primary mission of detecting and characterizing Earth-like planets. The addition of the new mission objective can be inferred from a realization that the cost of the originally conceived mission would be too high relative to the size of the benefiting community. The new mission objective makes TPF more appealing to a broader community, possibly increasing the political palatability for the system.

Dynamic MATE analysis can explicitly consider the effect of increasing both the attributes for the system and the interested decision makers. System designs robust to these types of preference changes will be more likely to survive cycles of requirements revision as budgets fluctuate to reflect the political will in Washington.

10.4.2 Design Changeability

In order to create active value robustness, the TPF designers should consider design for changeability. Several possible change mechanisms are mentioned in
Table 31 and restated in Figure 189. In particular, the changing baseline and increasing the number of apertures allows for scalability of mission attribute performance (an increase in the rate and sensitivity of observation modes). In order to achieve these change types, three types of path enablers should be considered: reconfigurability, modularity, and extra apertures. Reconfigurability is the explicit ability to reposition or rearrange the physical orientation of the system, enabling the system to change its baseline. Modularity reduces the time and technical effort needed to incorporate or remove system elements. Having extra apertures reduces the dollar cost and time needed to add to the apertures in the system.

Given the model used for the preceding analysis, rules 1 and 2 can be automatically checked across all designs. Since the schedule was not varied, assessing rule 3 is not possible at this time. If TMAS is rerun with a variable schedule, rule 3 will reveal promising transition paths in terms of increasing value as perceptions change over time. Rule 4 was not assessed since the design variable for design life was likewise held fixed. Future analyses should look at the trades involving mission extension across the fuller range of operational life, especially since the operation life is a potential unarticulated value.

Rule-Effects Matrix			Design Variables											Path Enablers			Change	
TPF			OT	NA	WI	IT	AT	AR	AS	IB	Sc	DL		Mod	+Ap	Rc	Origin	
			DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	DV1	DV1	IV1	IV2	IV3	Flx	Adp
Rule	Change baseline	R1								↑↓						X		X
	Increase NA	R2		↑										/	/		X	
	Change schedule	R3									↑↓						X	
	Extend life	R4										↑					X	
		RK																

Figure 189 Proposed TPF transition rules

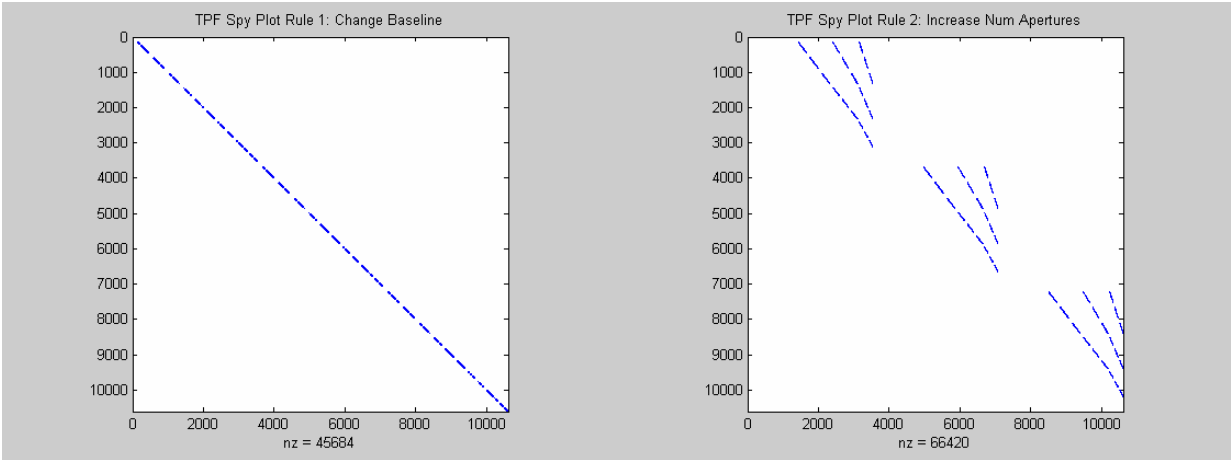


Figure 190 Spy plots for TPF transition rules 1 and 2, indicating allowed transitions between designs i and j

Figure 190 shows the density of allowable paths out of all possible for rules 1 and 2 applied to the TPF tradespace. This plot is equivalent to the accessibility matrix determining allowed paths in a tradespace network. A dark mark in row i, column j indicates a transition from design i to design j is allowed for that rule. According to the plot, 45684 transitions are allowed out of a possible 10611^2, leading to a density of 4.06×10^{-4}. Likewise, for rule 2, 86420 transitions are allowed out of a possible 10611^2, leading to a density of 7.68×10^{-4}.

The original Pareto Set designs are repeated in Figure 191 below. These designs will be specifically compared in terms of their changeability as assessed by the first two rules above.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
ID num:	**5669**	**5646**	**5647**	**5650**	**5641**	**5654**	**5676**	**5655**	**2118**	**5683**	**5684**	**5686**	**6499**	**2962**	**6505**	**2968**
OT	LO	LO	LO	LO	LO	LO	LO	LO	L2	LO	LO	LO	LO	L2	LO	L2
NA	6	6	6	6	6	6	6	6	6	6	6	6	8	8	8	8
WI	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
IT	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi	ssi
AT	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir	cir
AR	const	multi	multi	multi	multi	multi	const	multi	multi	const	const	const	const	const	const	const
AS	2	mid	mid	mid	min	max	3	max	max	4	4	4	3	3	4	4
IB	60	50	60	90	80	50	60	60	60	60	70	90	70	70	70	70
LC	816.6	842.1	853.5	873.1	941.4	985.7	1001.1	1031.5	1053.9	1185.7	1187.0	1191.2	1217.1	1261.0	1495.6	1520.0
U(orig)	0.7378	0.7897	0.8129	0.8138	0.8214	0.8806	0.8844	0.8856	0.8856	0.9320	0.9322	0.9322	0.9368	0.9368	0.9671	0.9671

Figure 191 TPF original Pareto Set designs

Figure 192 below shows the outdegree for the original Pareto Set designs compared to the other designs in the tradespace.

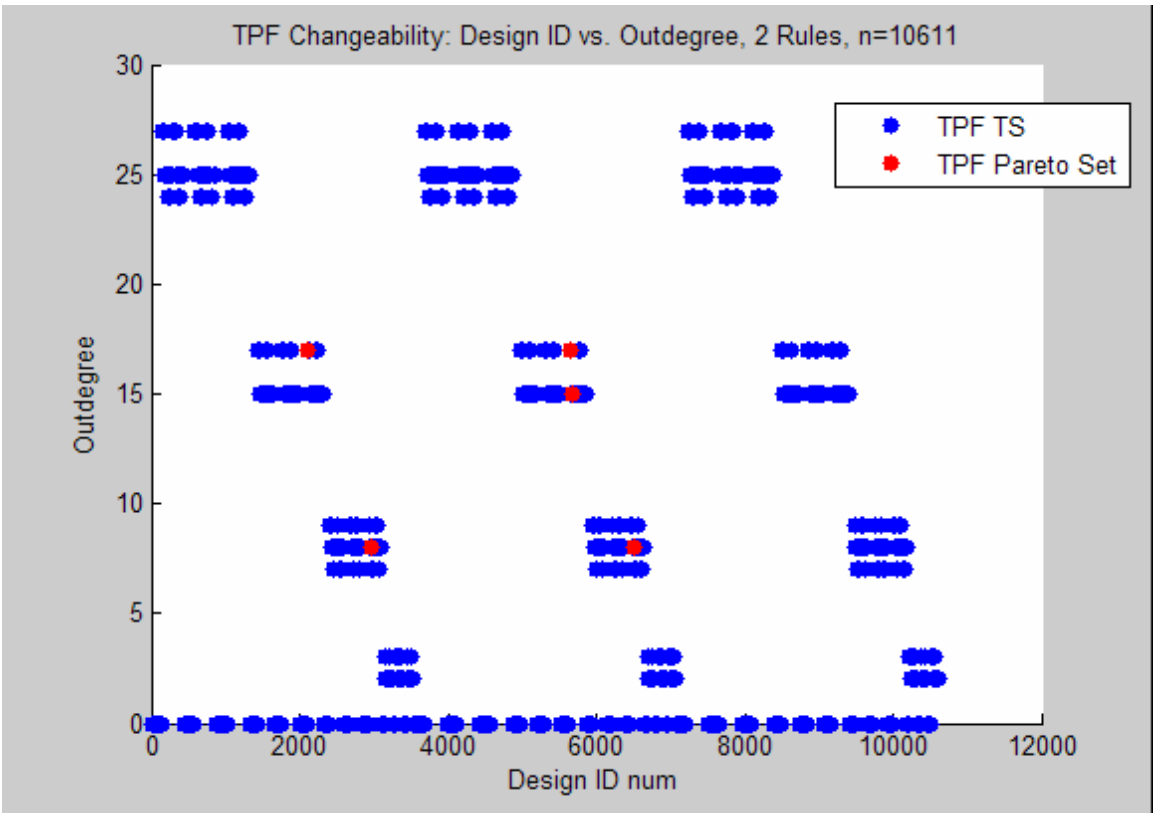


Figure 192 TPF outdegree vs. design number, with Pareto Set designs indicated

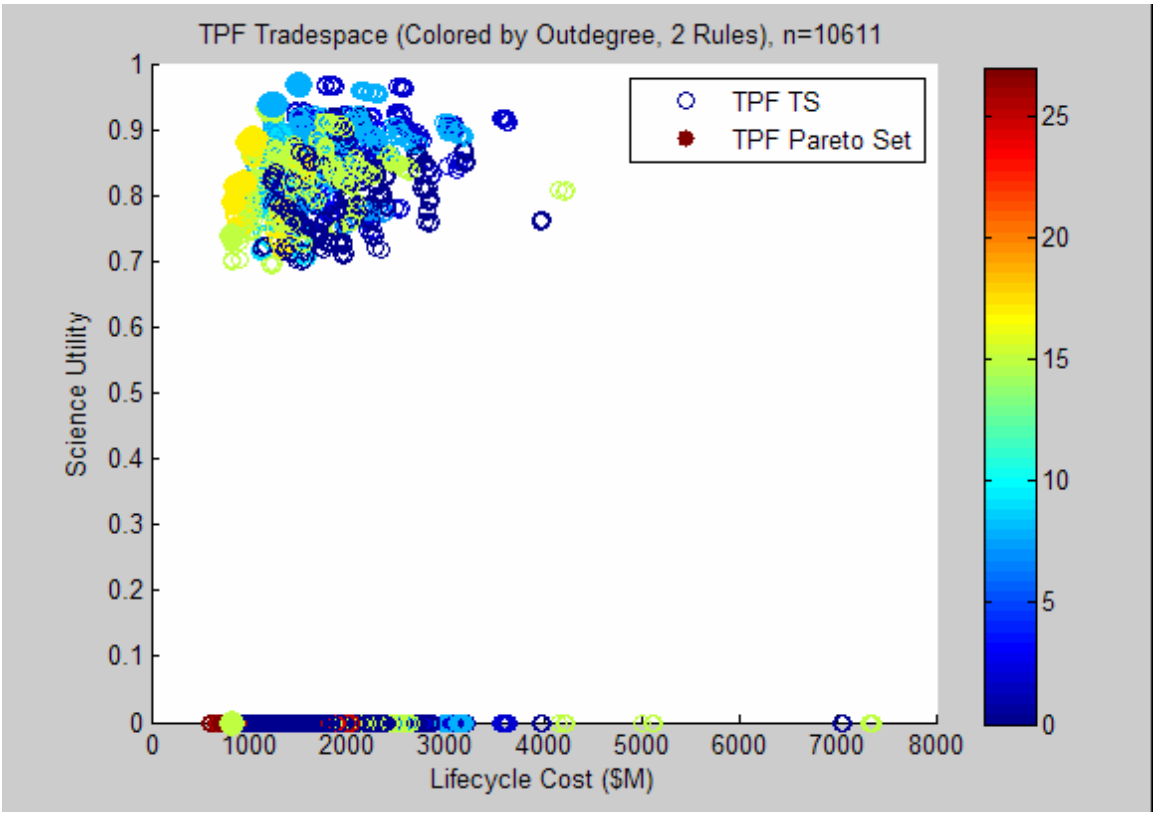


Figure 193 TPF Cost-Science Utility tradespace, colored by outdegree, with Pareto Set designs indicated

Figure 193 shows the full tradespace colored by outdegree. For all of these calculations, it is assumed that the cost threshold is beyond $\hat{C}_\infty$ and $\hat{t}_\infty$ (the OD is the MaxOD) and is the "best case" estimate for changeability for the TPF tradespace.[221] It is interesting to note that for this particular study, the most changeable designs give no science utility. In fact the Pareto Set designs are not the most changeable designs either. In other words, the most changeable designs are not Pareto efficient, likely because changeability is not captured in the utility function as an attribute of value.

Looking only at designs costing less than $1B, per the Agency requirements, results in Figure 194 below. The most changeable designs are not necessarily the most expensive. In fact these designs tend to be less expensive. The most likely cause is the fact that the smallest interferometers in terms of number of apertures has the largest number of potential end states for adding apertures, given the limit of 10 apertures in this study. The small interferometers also tend to perform poorly, thus the zero science utility in Figure 193 for the most changeable designs.

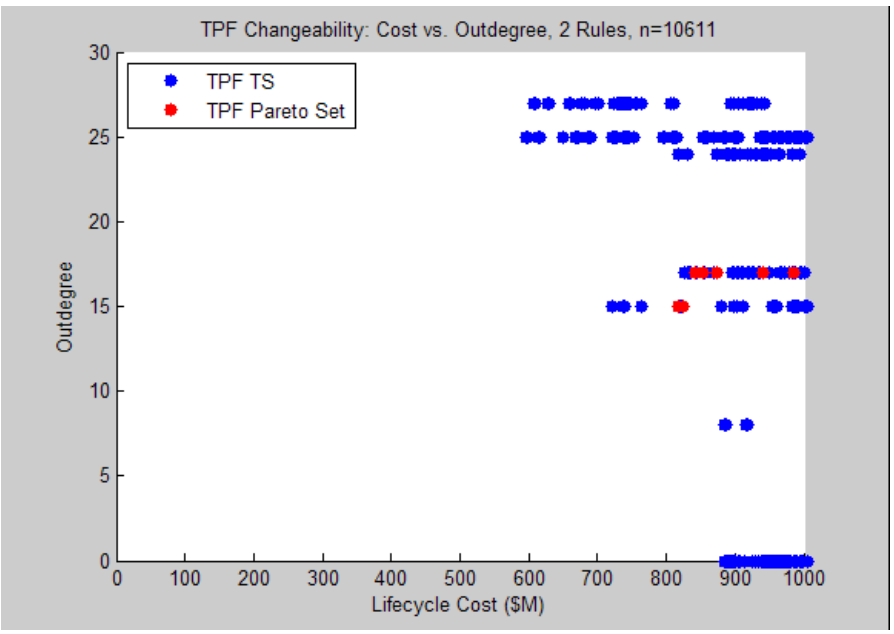


Figure 194 TPF Cost vs. Outdegree for cost less than $1B, indicating Pareto Set designs

Since outdegree is a function of both rules and the size of the tradespace, as more transition path rules and enablers are proposed, the changeability of the design options will increase.

10.5 Discussion

The TPF architecture tradespace study results in (Makins 2002) were displayed on four separate plots, each with a different "performance metric" vs. cost. Deciding the best architecture from these plots relies upon the analyst to aggregate across the tradespaces to determine the relative importance of each performance metric. The Generalized Information Network Analysis (GINA) approach used in that study simplified the exploration of a large TPF tradespace, but gave no

[221] $\hat{C}_\infty$ and $\hat{t}_\infty$ are the cost thresholds which result in no filtering of the outdegree since all paths "cost" less than that amount.

guidance on how to simplify the results to aid in discovering "best value" solutions, an aim proposed by Makins as the goal of systems engineering.[222] The usage of a multi-attribute utility function allows for aggregation across these performance attributes and facilitates the discovery of "best" designs.

In addition to allowing for simplified decision making, the current chapter added to Makins model by incorporating a mission schedule optimizer that sought to maximize expected utility over the lifetime of the mission, rather than assuming the proposed fixed observing schedule from the JPL TPF book.[223] Makins recognized the inherent flaw in a static schedule, made without consideration of the system's specific technical abilities, and pointed to the need for adding an optimizer.[224] This work contributes fundamentally in that area.

According to one of the TPF JPL system engineers, Chris Lindensmith, the actual TPF architecture has remained relatively stable over time due to the fundamental physical relationship between wavelength, resolving power and telescope diameter.[225] As long as a particular wavelength and resolution of interest drive the mission objectives, the system must have a certain "size" imager. The technology to achieve the "size" has changed over time, enabling the reduction of mass and cost for deployment of the system. The overarching science goal of TPF coincides with one of the most fundamental questions in astronomy: "are we alone?" where "alone" refers to the existence of Earth-like planets with life. Mr. Lindensmith points out that the concept of a TPF has existed for decades but until recently the expected cost for the system has vastly exceeded the interest by those with adequate resources. While the technology is being developed by precursor missions, such as the Kepler and Space Interferometry Missions (SIM), the TPF technology proposed in this and other case studies is still at least a decade off.

Even though the scientific rationale for the TPF mission has remained relatively stable over time, the specific requirements levied on the system have not. An inspection of the evolution of the Origins roadmap suggests a trend towards increasing emphasis on the telescope as a general purpose astrophysical observatory in addition to its more specific task of surveying and characterizing extrasolar planets. If the additional role of the telescope becomes a driving requirement, it is possible that the mission will be pulled in two, possibly conflicting directions. A detailed assessment of how the technical architecture relates to a broad spectrum of performance expectations should be done to understand if the system will end up being a "compromise" system that does something for "everyone" but nothing particularly well.

The trend towards creating value to the larger scientific community may be the result of seeking political support for the system development effort. Increasing the number of beneficiaries is one tactic to make the system appear more beneficial to a Funder decision maker, who may not

[222] pp 58. Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission.
[223] JPL TPF 1999 Book pp.88, adapted from Table 9.1
[224] Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission. pp. 230 calls specifically for a "multi-objective, mission time-line optimization." The multiattribute utility function provides a single objective for mission optimization.
[225] C. Lindensmith, private communication 7/2005.

directly derive benefit from the system itself.[226] Cost incurred and benefit accrued to each decision maker would make the tradeoff negotiation between the two decision makers more meaningful since the costs and benefits would be perceived on the same scale.[227]

Recent events in Washington have led to a paradigm shift within NASA: instead of being primarily a science-driven agency, with human spaceflight conducting construction efforts on the Space Station, the new NASA direction is pushing human spaceflight to the moon and beyond. With limited resources, NASA administrator Michael Griffin has been forced to scale back space science missions in order to fund development of new human spaceflight vehicles and heavy lift rockets to carry payloads into space. The TPF program has been put on hold, delaying program start by at least five years, while the human spaceflight effort ramps up. As financial obligations to the aging Shuttle program and construction of the International Space Station decrease, monies, in theory, will again be freed for application to space science.

Even with consideration of various Epochs for TPF, the current MATE study cannot suggest an architecture robust to cancellation due to political forces independent of the system itself. Consideration of decision makers of the larger space program, however, may give TPF managers insight into how to create value outside of its traditional user base. One problem with TPF is that the decision makers satisfied by the mission are not the same as those funding it. A disproportionate distribution of benefit and cost (or value and resources) can lead to tremendous instability in a program.[228] TPF could benefit from this insight by adding human spaceflight stakeholders into the value proposition of the program. While the observation mission itself may not be of direct value to human spaceflight, it is conceivable that the technology for formation flying and advanced optics could be relevant. Such alignment could reduce the cost for future TPF development, while creating goodwill between space science and human spaceflight communities. The problem with this compromise is that human spaceflight would view it as a loss since it is expected that they would get all of the money even without TPF cooperation. Space science and TPF in particular, would have to present non-monetary benefit for gaining resources at the expense of human spaceflight. Such considerations do not come out of a MATE study per se, but could be informed by taking a dynamic value-centric perspective.

10.5.1 Problems

One drawback with the currently applied model is the lack of consideration for the masked coronagraph telescope, which was specifically cited as an architecture under consideration by the 2003 Origins roadmap. Another problem is the inability to capture the important attributes of the

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[226] More research should be done to better understand the forces driving the science requirements and whether a better compromise can be found that does not sacrifice performance for resource support, but rather better distributes the costs and benefits of the system.

[227] This point of cost and benefit being on the same scale directly relates to the problem of comparison of interpersonal utility, an impossible task due to its inherently subjective nature. If both costs and benefits are internalized, they can be compared *intrapersonally*, leading to a more meaningful and efficient negotiation for "best" designs.

[228] Since the Funder does not derive benefit directly, the Funder could pull resources and put them elsewhere where similar or more value could be realized. For Congress, as the Funder for NASA, the benefit does not derive from the science itself, which benefits the science community (User). Since the President has elevated human spaceflight to a higher priority than space science, Congress can derive political benefit from aligning with the President's priorities and be better off funding human spaceflight instead of space science.

non-science community. The politics of space agency funding is particularly relevant today and without including such considerations, discussions on the value of the program is critically incomplete.

Identification of change/transition paths requires a domain expert in space-based telescopes, beyond the capabilities of this research. Further work should be done investigating change mechanisms, with the ability to model hybrid concepts in particular.[229][230]

The addition of coronagraphs and hybrid concepts directly relates to the current architecture under consideration by JPL. According to the official TPF website:

> During almost 20 years of study, design concepts have alternated between interferometeric arrays and coronagraphs. In recent years alternative architectures have emerged with the potential to achieve similar science goals. These opened up the possibility of new mission concepts and additional precursor missions.
>
> In May of 2004, NASA announced it would fly two separate missions with distinct and complementary architectures to fully realize the goals of Terrestrial Planet Finder. These goals are explicit in the nation's new vision for space, which directs NASA to "conduct advanced telescope searches for Earth-like planets and habitable environments around other stars."[231]

The decision to fly both mission types is an attempt to diversify the risk of planet detection and characterization, as well as the technology development risk for the program. Unfortunately, the overall cost of such a dual mission is also higher, thereby raising the profile of the program further and increasing the likelihood of political attention. The added constraints of additional resources and attention can make a multi-decision maker preference set more constricted and result in a design that is mediocre in many aspects as opposed to excellent in a few. The system designers will have to be diligent to understand the relationship between the preference structures of the decision makers and the technical architecture in order to bring the system to fruition.

10.6 Conclusion

Discovering value robust TPF systems may be a difficult proposition. With the trend towards increasing the imaging “requirements” in may be possible that current concepts are unable to meet the requirements. The Joint Pareto Set for Science and Agency may be the null set, as the technology and resources available are unable to meet the minimum acceptable attribute levels set forth. The model used in this analysis showed no designs with nonzero utility for the 2000 and 2003 Origins roadmap. Either the model is incorrect, or new concepts should be considered. Better still, the stakeholders making up the “Science” decision maker, should fully understand the technical implications of their preferences and how it may lead to a null set.

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[229] pp. 217 of Makins. Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission. describes the need to model SSI-SCI hybrid concepts, plus the addition of collector/combiner spacecraft to increase system reliability.

[230] The questions raised over the course of this case application suggest ample work for a follow-on case study to develop more detailed and holistic TPF models.

[231] http://planetquest.jpl.nasa.gov/TPF/tpf_what_is.cfm cited 3/22/06

As for changeability, TPF has several transition paths open to it, including the addition of apertures or a change in baseline. For the concepts considered, the separated spacecraft interferometer (SSI) has higher changeability than the tethered spacecraft interferometer (TSI), which itself has a higher changeability than the structurally connected interferometer (SCI). A key path enabler, however, appears to be the scheduling. By varying the schedule appropriately, the performance of the system can be readily scaled at low cost, though a tradeoff between image types must be made in the process.

Looking at the trend towards the consideration of more concepts, while the expressed preferences drift more towards general astrophysical observation suggests the program is unstable, or at least heading towards a period of increased ambiguity. It is critical that the system designers understand the effect changing preferences will have on system feasibility.[232] It may be the case that new technological developments will either vastly improve performance, or at least reduce the cost, in order to close the cycle of design-value changes. If discovery of the unstable value-design loop is not made, TPF may never have a chance to answer that age old question: "are we alone?"

Key References

Beichman, CA, D.R. Coulter, et al. (2002). "Summary Report on Architecture Studies for the Terrestrial Planet Finder." Pasadena, CA, Jet Propulsion Laboratory**:** 161.

Beichman, CA, N.J. Woolf, et al. (1999). "The Terrestrial Planet Finder (TPF): A NASA Origins Program to Search for Habitable Planets." T. T. S. W. Group. Pasadena, CA, JPL**:** 158.

Makins, Brian J. (2002). Interferometer Architecture Trade Studies for the Terrestrial Planet Finder Mission. Aero/Astro. Cambridge, MA, MIT**:** 270.

[232] Changing attribute priorities or sets may require modifications of the concept, which may require new technology. Since the cost of the system is born by Congress, and does not reside with the beneficiary (scientists), it may be difficult to justify added costs for an ambiguous mission. It appears the "science" needs to be important enough to warrant funding from Congress, however, aggregating enough preferences to appear to be "important" may result in technical infeasibility.

Chapter 11: Discussions

The principal goals in the development of this research were to determine how to incorporate "unarticulated" value into conceptual design, and to determine how to use flexibility, adaptability, scalability, and robustness as decision metrics when choosing among design options. Throughout the development of dynamic MATE, the author has attempted to build a method from "fundamental" relationships and well-accepted practice from related fields. In use, dynamic MATE is intended as a prescriptive tool to aid in making decisions during design. Additionally, descriptive models have been referenced in order to prepare practitioners for the differences between what *is* and what *should be*.

11.1 Method-inspired Issues

The following sections are a few of many issues that can be considered using the framework discussed thus far.

11.1.1 The Nature of Open-ended Transition Types

Changeability in dynamic MATE is assessed in terms of the filtered outdegree from a node in a tradespace network specified by transition rules. In order to increase perceived changeability as defined, it is necessary to 1) increase the size of the tradespace (number of potential destination nodes), 2) increase the acceptability threshold (maximum acceptable cost to count a path), or 3) increase the number of paths from a given node (number of arcs specified by transition rules). Transition rules specified how a design can change into a different design. Clearly the granularity of the tradespace will change the absolute magnitude of a calculated outdegree. To gain insight into the "true" changeability of a design, it is necessary to remove the tradespace enumeration bias.[233] Bias aside, how does the nature of the transition type affect a design's apparent changeability?

Given the tradespace-centric formulation of the changeability metric, how does one assess transition rules that do not specify a destination node assessed by the tradespace? Specifically, this question addresses change mechanisms that alter non-design variable specifications of a design. For example, the ability to update software should make a design more changeable. If software is not a specified design variable, however, following a transition rule that alters software would not result in transition to a new node in the tradespace, and therefore no increase in the outdegree measure. Such a transition rule is called an open-ended transition type if it results in movement to an unspecified node in the tradespace.[234] Designers could create new design variables to enumerate such destination nodes, and that would remove the problem, but such straightforward approaches may not always be feasible, especially under constraints.

One approach to the problem, when considering only a few number of designs, is to use the semi-quantitative calculation of changeability used in the JDAM study. In the approach, designs are listed along the top row of a matrix, while proposed transition rules are listed down the left column. No destination nodes are explicitly considered while the analyst proposes expected costs and times to follow each rule for each node. (Qualitative measures, such as "low, medium, and

[233] See Appendix E for discussion of outdegree calculation and removal of tradespace sampling bias.
[234] In a sense open-ended transitions are "paths to the unknown," but paths nonetheless.

high" can be used as in the JDAM example, or other indicators of magnitude such as 1, 3, and 9 used in QFD.) The rules whose costs are less than the threshold set by the decision maker are summed down the column for each design. The resulting number is an indicator, albeit lower fidelity, of the filtered outdegree. Figure 195 gives an example from the JDAM case application in Chapter 9.

OD Assessment		Design ID number																	
W/o MOD, w/COTS		1		2		3		4		5		6		7		8		9	
		$	t	$	t	$	t	$	t	$	t	$	t	$	t	$	t	$	t
Refit strakes	R1	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L		
Upgrade GPS	R2	M	H	L	M	L	M	L	M	L	M	L	M	L	M	L	M		
Upgrade INS	R3	M	M	M	H	L	M	M	H	L	M	L	M	L	M	L	M		
New software	R4	H	L	H	L	H	L	H	L	H	L	H	L	H	L	M	L		
Refit for new AC	R5	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H		
Refit for new Warhead	R6	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H		
Replace tail section	R7	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L		
Add IC	R8	M	H	M	H	M	H	L	M	L	M	L	M	L	M	L	M		
Add LS	R9	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		
Add wings	R10	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		
Add term guide	R11	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		
	MaxOD	11		11		11		11		11		11		11		11			
	OD(<C,t): (M,M)	**6**		**6**		**7**		**7**		**8**		**8**		**8**		**9**			

Figure 195 Qualitative changeability assessment for JDAM Pareto Trace designs, incl. COTS path enabler

This type of analysis will give a good indication of the relative changeability through various transition types, both closed and open-ended. One aspect of transition rules on which qualitative changeability analysis will not give insight is the relative pervasiveness of the transition rule. For example, one transition rule may enable a system to change to one particular destination state, while another transition rule may enable the same beginning system to change to many particular destination states. Quantitative changeability analysis would relate the second type of transition rule to be much more changeability-inducing than the first type. Determining which type is "better" cannot be done without valuing the relative importance of each transition type.

It is important to realize that the relative importance of different types of changes is not considered in the formulation of the changeability metric; all changes are equal in importance. In order to screen for particular types of change, such as flexibility in avionics upgrading, one can simply filter the tradespace network by only counting transition rules that result in the desired change type. In this way, important aspects of changeability, as defined by decision makers at any point in time, can be called out and quantified in addition to the more general changeability measure.

11.1.2 On "Generic" Flexibility

At the end of the analysis, a key question is whether it means anything to say that something is "flexible." The statement is ill-posed, as the definitions described in Chapter 6 point out. In order to "be flexible," a system has to be able to be changed by an external agent. If such a type of change can occur, then one can fairly claim that such a system is indeed flexible. But to answer simply "yes, it is flexible" would be to gloss over important details, such as the assumed or

implied cost for change. In any discussion regarding changeability, be it flexibility, adaptability, scalability, etc, it is important to explicitly communicate the acceptable "costs" for such changes, including dollars, time, and effort. Additionally, it may be the case that the inquirer has particular change types in mind when posing the question. In fact changeability describes the ability of a system to follow multiple and different types of change paths. Explicit communication of the change paths (or transition rules) will also clarify the issue.

Returning to the concept of "generic flexibility," a question naturally arises regarding clever architectures or designs that can readily change along multiple dimensions. Modular and networked architectures come to mind as inherently flexible designs since their cost for a reconfiguring change is often very low and the number of potential configuration states is very high.[235] The upfront costs for developing such systems may not be worth the resulting changeability; however these costs can be explicitly revealed and communicated through a dynamic MATE framework. The expense for modularity will be captured in a Design-Value Matrix, along with which decision makers may be willing to pay for it. Likewise modular and non-modular designs can be compared side-by-side in the same tradespace, colored by changeability, in order to inform decision makers of the costs and benefits. System timeline Era analysis can be used to explicitly show the value of changeable designs using an active value robust strategy over likely future Epochs. (See Figure 196 below for a notional example of utility and cost over time for a changeable versus not changeable system.)

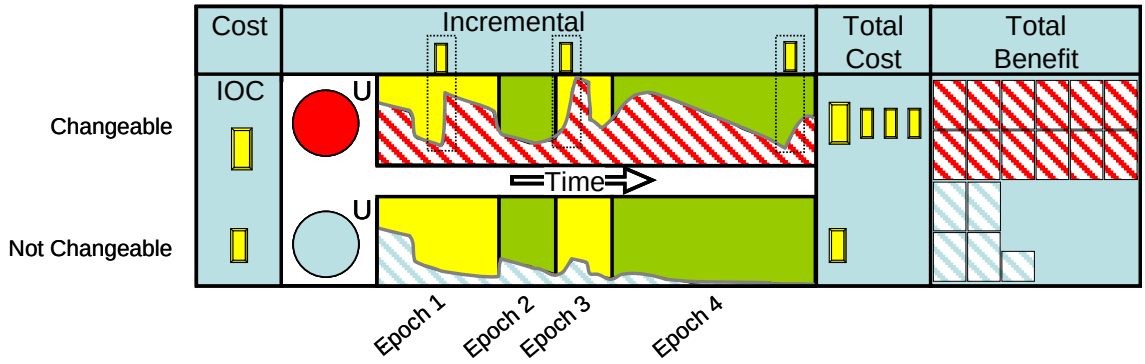

Figure 196 Comparison of notional costs and benefits for changeable versus not changeable systems

11.1.3 Modularity and System Architecture Effects on Accessibility

Modularity and system architecture effects have been discussed in previous sections, but since the topic is of particular relevance to designers, it is again mentioned here. Much work has been done on modularity as it relates to system design (see for example (Baldwin and Clark 2000; Suh 2001; Whitney 2003; Shah 2004; Whitney 2004; Holtta, Suh et al. 2005).) Modularity is a physical arrangement of system components that reduces coupling between "modules," but may increase coupling within modules.[236] By grouping components that are likely to change together, modules can be changed within a modular system with minimal effects on other modules. The

[235] Further work should be done deriving general principals for assessing and recommending generic architectures or patterns that result in natural changeability.

[236] A "module" is a tightly coupled group of components within a system that, when taken together, are loosely coupled to other components.

cost of modular design, both in development time and mass and size, must be weighed against the benefit of increased changeability and passive robustness.[237]

As described in Chapter 9, JDAM chose a mixed architecture approach, using modularity for some aspects of the design and integrality for other parts. System designers made their choice partly based on the organization developing the components; suppliers whose organization were used to developing modules were encouraged to develop modules, especially for components that were expected to be upgraded in the future. For physically constrained parts of the system, such as the fin actuator motor housing on the smaller JDAM variants, an integral motor component was used.[238]

11.1.4 The Role of Standards

Standards are sometimes considered to be both a blessing and a curse. The cost, both in effort and time, to adhere to detailed standards, as well as the reduction in variation of approaches due to the constraints placed by the standards, are the downside of their use. On the other hand, standards reduce uncertainty by specifying technical expectations across systems. In particular, interface standards enable the interoperability of separately developed systems by ensuring compatibility. In effect, good interface standards can form a "wrapper" around systems, similar to the System Mask concept discussed in section 6.4.1. Designers are free to innovate on the other side of the Mask, and the environment can continue to see a fixed "face" for the system.[239]

11.2 Using the Method Descriptively

Descriptive models attempt to represent or predict reality as it really is. No normative perspective on what *should* be is included. Since design is driven by subjective needs, normative processes are typically used. Descriptive use of dynamic MATE is not its primary purpose, though it can be used in that way in order to capture and represent information for better decision-making. Discrepancies between what *is* and what *should be* can motivate improved design.

11.2.1 Comparing Designs

An example of descriptively using MATE is comparing already crafted design in a tradespace format. Since the decisions on the designs are already complete, no normative judgments regarding their configuration are needed. Instead, the designs can be cast in terms of utility and cost within an Epoch, elucidating value. Teams tasked with comparing contract bids can utilize this technique to determine best designs to select.

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[237] A research opportunity exists for formalizing the analysis of modularity and other architecture choices within a MATE framework, in terms of how to assess the costs and benefits of the modular approach. Effects on transition rule cost and time, in addition to the cost to initial operating capability should be considered.

[238] Based on conversation with JDAM system engineer. Modular motor components were used on the larger tail variants.

[239] Ongoing doctoral research by Nirav Shah at MIT will seek to better define "loose couplers" for developing system-of-systems, akin to interface standards for linking systems. The concept of System Mask and Shelter—together the System Shell—may inform such thinking.

11.2.2 Capturing Articulated Value

Another example of descriptive use is filling out the Decision-Maker-Attribute portion of the Design-Value Matrix. Figure 197 below shows this part of the DVM. The DVM provides explicit feedback of the interests, both current and potential for each decision maker, elucidating current and potential value conflicts. Additionally, the articulated values can now become explicit drivers for the design endeavor.

Design-Value Matrix		Value-space										Design-space					
		Attributes										Design		Path		Resources	
		Latent				Cheap		Accessible		Inaccessible		Variables		Enablers			
	Class:	0		1		2		3		4							
	Attribute:	X1	XM	X'1	X'M'	X	X	Y	Y	W	W	DV1	DVN	IV1	IVP	C	t
Decision Makers	DM1																
	DMZ																
Design Variables	DV1																
	DVN																
Path Enablers	IV1																
	IVP																

Figure 197 DVM highlighting the decision maker-attribute submatrix

11.3 Using the Method Prescriptively

Prescriptive use, determining which designs *should* be developed, is the primary intent of dynamic MATE analysis. The attributes *should* be used to drive creation of design variables. Consideration of how the designs can change *should* drive creation of transition rules and path enabling variables. Once decision maker preferences are captured in utility functions and subjective change cost acceptability thresholds determined, MATE can point out the best sets of designs that *should* be considered as delivering best value.

11.3.1 Proposing Dynamic Strategies

Dynamic MATE analysis can be used to create a set of potential system contexts, in the form of Epoch sets, which can be used in timeline analysis. Each Epoch can be analyzed to create "best" strategies according to decision maker-specified strategic goals. Example transition strategies include minimum cost, or maximum utility, or minimum time, or some combination of above, plus others. The ability to explore various strategies and their effect on transition paths through an Epoch will reveal prescriptive design considerations in order to enable value over time. Various combinations of Epochs strung together can form potential system Eras, which provide long run prescriptive advice on transition strategies. In fact, as more information becomes available, or uncertainties are resolved, the Epochs can be readily modified and strategies adapted to the new potential contexts for the system.

11.3.2 Finding "Good" Transition Rules

Another application of dynamic MATE analysis is investigating the relationship between transition rules and transition cost. In practice, application of a transition rule will require

varying combinations of resources (e.g., spend a little time, spend a lot of money, or spend a lot of time, spend a little money, up to some constraint). Understanding the trade-off between time, money, and other resources for each design rule can enable motivation for new technologies, or clearly superior change strategies (those which provide value regardless of other parameter values). Identification of these rules can provide the motivation for the creation of value-enhancing "hooks" or real options.

11.3.3 Generating Path Enablers

As discussed in the JDAM case application, modularity, use of COTS parts, and simple, excess capacity interfaces all increased the changeability for the system. The TPF case application added the concept of reconfigurability, while the X-TOS example suggested serviceability, tugability, and refuelability as path enablers. A reasonable question to ask is whether these path enablers are part of a set of generic path enablers that would be applicable across a large range of systems. Having such a set would not only simplify a designer's efforts, but also reveal insight into the relationship between architecture and structural and operational strategies and changeability in general. (Holtta and Otto 2005) discusses specific types of modularity that increases product flexibility (read: changeability). Other research, such as (Baldwin and Clark 2000) can be used to better understand the cost lowering or path increasing properties of modularity.[240] The potential exists to unify an analysis that can address *why* modularity, simple interfaces, network architectures, independence, and other path enablers increase system changeability.[241,242]

11.3.4 Finding "Best" Dynamic Designs

With quantification of system properties comes the ability to use them as decision metrics when comparing designs. The changeability (filtered outdegree) or robustness (Pareto Trace number) of a design can be used as explicit attributes in decision maker utility functions and thus treated as articulated value. Conversely, strategies for value robustness can be pursued, either seeking options that remain high value over time (passive value robust), or options that can be readily changed to match changing value perceptions in order to be high value over time (active value robust). If quantitative data or models are unavailable, dynamic MATE also encourages designers to think qualitatively about how potential change mechanisms or system designs affect the number of change paths available or the cost of following change paths for a particular design.

11.3.5 Achieving Value Robustness

Two strategies for achieving value robustness have been discussed: passive and active. Passive robustness is achieved by choosing the "best" system that remains high value in various contexts,

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[240] Further research for proposing general sets of path enablers should be conducted, focused by the changeability framework proposed in this thesis.

[241] See Fricke and Schulz. "Design for Changeability (DfC): Principles to Enable Changes in Systems Throughout Their Entire Lifecycle." for example of principles to increase changeability. Principles include the pursuit of modularity and Axiomatic Design's Independence of the design parameter-functional requirements relationship.

[242] See Holtta, Katja M.M., Eun Suk Suh, et al. (2005). Tradeoff Between Modularity and Performance for Engineered Systems and Products. International Conference on Engineering Design, Melbourne, Australia. for a discussion on the possible physical limits of modularity and their relation to physical systems, especially space systems.

or Epochs. Figure 198 below depicts these two strategies. The teal design follows the passive value robust strategy, while the green design follows the active value robust strategy. The top portion of the figure shows utility versus time across two Epochs, while the bottom portion shows utility versus cost at the beginning of the first Epoch and the end of the second Epoch respectively. Comparing the utility-cost tradespaces show both value robust strategies result in "constant" utility across changing context, though the active strategy results in a different end design than the passive strategy.

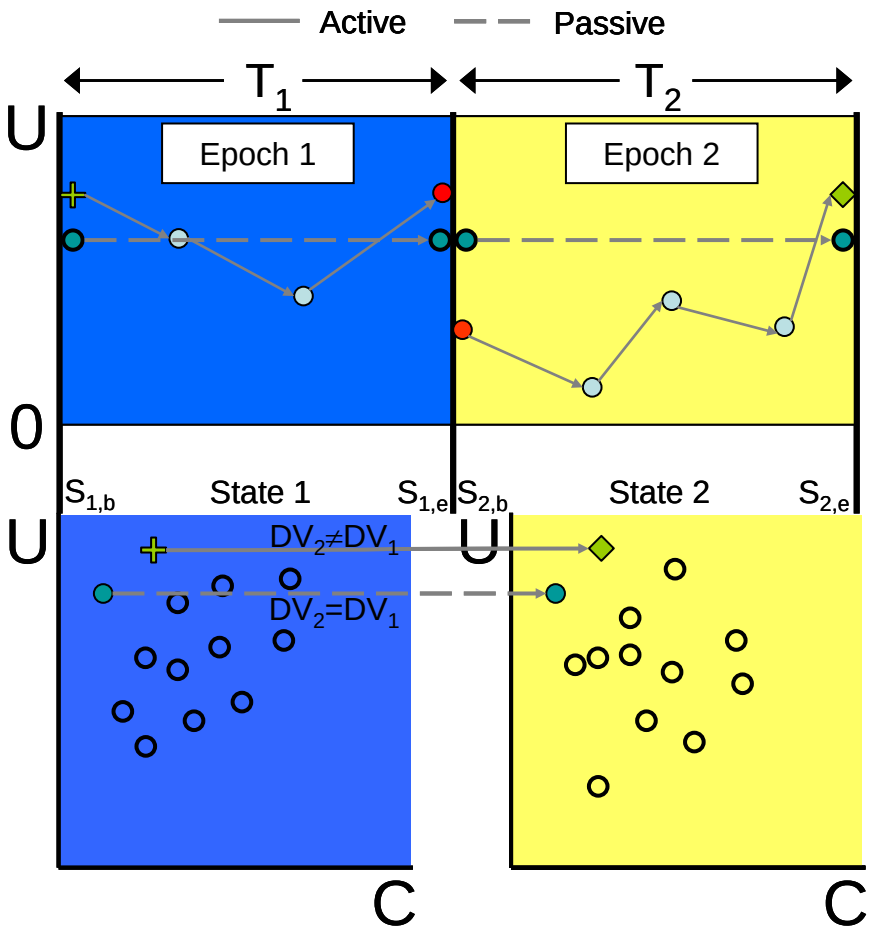

Figure 198 Active versus passive value robustness across two Epochs

Of the two value robust strategies, seeking passive value robustness is akin to proposing "clever" designs. Achieving passive value robustness can be accomplished through having excess capability, insensitivity to the propagation of change within the system, independence of components, or local stability within the tradespace (the "physics" of the problem).

As an example to insensitivity to change, consider Figure 199 below. Value robustness at a conceptual level means "continuing to perceive high value" in spite of changes upstream of the value perception. Upstream influences include the shape of the utility function, the value of the attributes, the value of the design variables, the shape of the design variable to attribute mapping, the value of the context, and the shape of the context to design variable mapping. Shown at far right in the figure is the functional dependence of design variables to context in a "locally flat"

region. A large change in context results in a small change in design variables. Choosing a context value that falls within the flat part of the relation is one way to achieve design variable robustness. Likewise inside the box, the middle mapping shows the relationship between design variables and attributes, in a locally flat region. Large changes in design variable values result in small changes in attribute values.

Selecting a functional relation between design variables and attributes that is flat is similar to the design parameter (DP)-functional requirement (FR) insensitivity goal for robustness in Axiomatic Design.[243] Selecting a design variable value so that the system falls within the flat region of an already existing DV-X mapping is similar to parameter design in Taguchi robust design.[244] The third mapping in the figure relates attributes to utility values and is the utility function. Typically the designer does not have freedom to select the shape of the utility function, as it is elicited from the decision maker and reflects his preferences. For a particular decision maker, flat regions of the utility function may exist and in those regions changes in attribute values will result in smaller changes in utility. One region of the utility function that is predictably flat is above the best acceptable value for an attribute; in that region the utility is defined to always be one, its best value. In this way, over design is robust since changes in the attribute value have no effect on the decision maker's perceived value: it is always good. A danger in all of this "flat" or "stable" region seeking is the risk of "falling off the edge" into a steep region of the functional mapping.

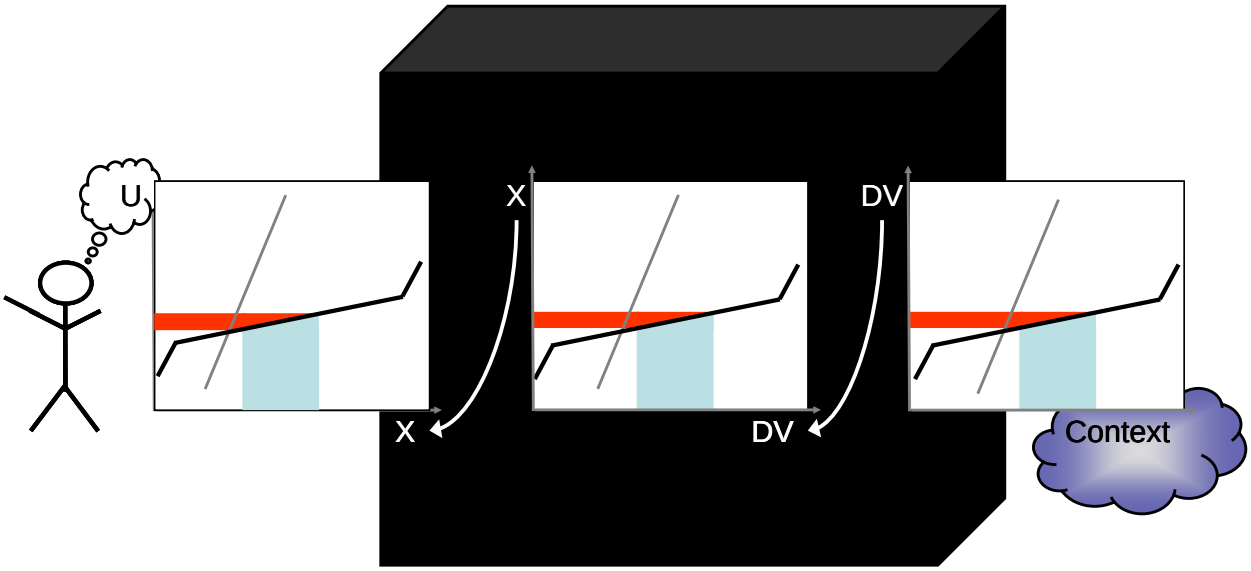

Figure 199 Passive Value Robustness achieved through insensitivity to changes in Context, Design Variables, Attributes, or Utility

A visualization of the insensitivity of parameters due to local flatness is depicted in Figure 200 below. Two flat regions of the utility function are shown: below the "worst" or least acceptable attribute level and above the "best" or most acceptable attribute level. In the case where the system attribute level is above the "best" level, the system has excess capability and up to a point, is robust to changes in that attribute level. Once the attribute level moves below the "best" level,

[243] Suh, Nam Pyo. (2001). Axiomatic Design--Advances and Applications. New York, Oxford University Press.
[244] Park. Robust Design and Analysis for Quality Engineering.

robustness is lost. Care must be taken in this approach as the decision maker has control over the shape of the utility function, including defining the “best” and “worst” levels. Changes in the shape will affect the system robustness.

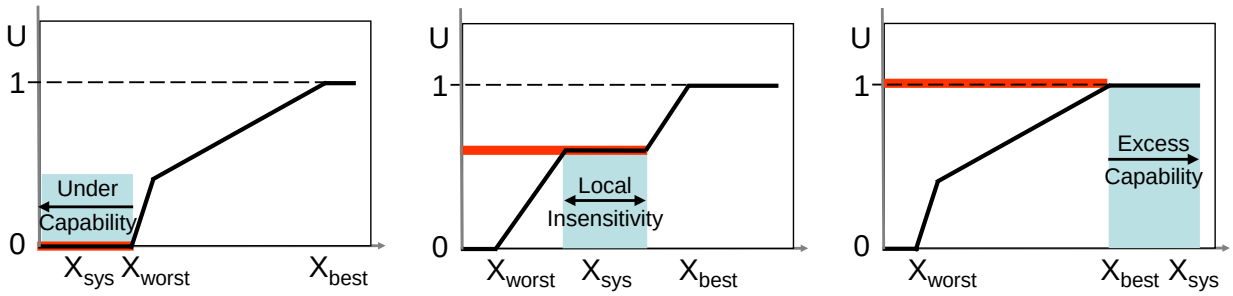

Figure 200 Example of robustness due to parameter insensitivity: Utility function "shape"

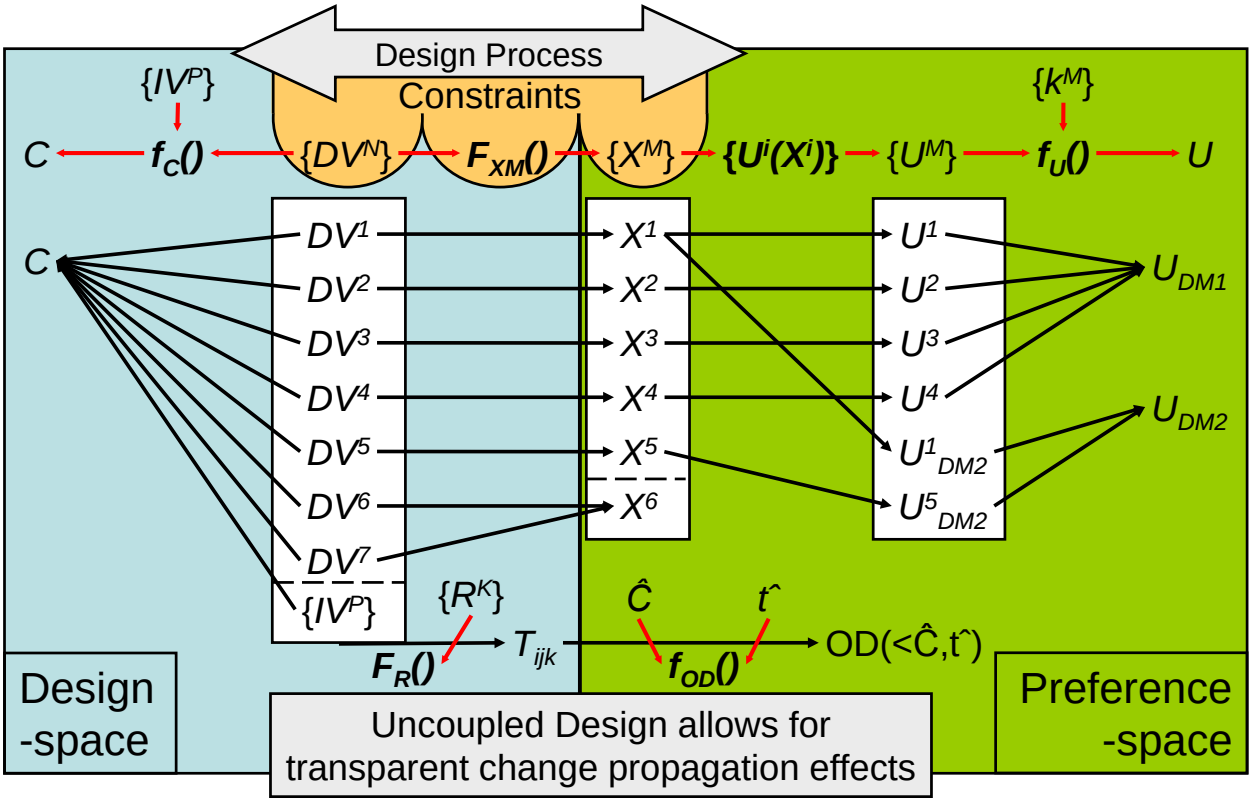

Figure 201 Dynamic MATE function and variable mapping, with uncoupled design

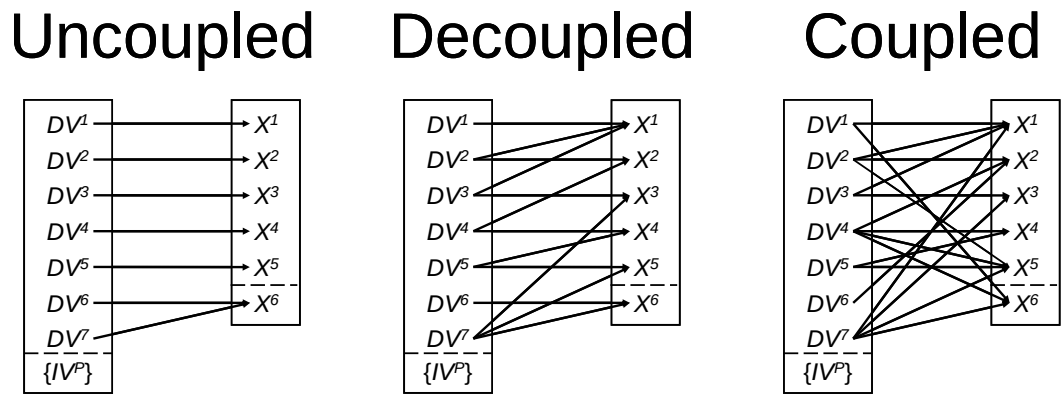

Figure 202 Design-attribute functional mappings for uncoupled, decoupled, and coupled design

Figure 201 shows the important variables and functions in dynamic MATE analysis. Change propagation can be inferred by tracing paths connecting variables in the diagram. For example, a change in DV^1 will result in a change in cost, C, attribute X^1, single attribute utilities U^1 and U^1_{DM2}, and multi-attribute utilities U_{DM1} and U_{DM2}. This particular figure shows an uncoupled design relationship in the design variable-attribute mapping. Two other design relationships could exist and are shown in Figure 202: decoupled and coupled. Real systems, characterized by high levels of complexity, tend to be of the coupled variety. The Independence Axiom of Axiomatic design suggests the selection of design parameters (variables) such that the design relation is uncoupled, or at least decoupled. The more uncoupled the design, the better, meaning more robust, it is. The fewer the couplings, the more likely a change in a design parameter will have a small effect on the value. In practice, seeking decoupling does not necessarily result in smaller changes in utility.[245]

Pursuing "local stability" of the tradespace through the "physics" of the problem is yet another approach to robustness. (Clausing and Frey 2005) give an example of using a failure mode to fix itself due to the physics of the failure. (When the system fails, the change in the output feeds back to the system, altering its input to move the performance back into an acceptable range.) Creation of this type of robustness requires creativity and knowledge of the "physics," or structure of the uncontrollable factors, in order to create an effective control mechanism to create robustness.

A different strategy for achieving value robustness is to seek active robustness through increased changeability. The active strategy is dynamic and requires the system to continually change in order to deliver high value for the particular context in which the system finds itself. Changeability can be increased through the generation of transition rules and path enabling

[245] The magnitude of the relationship between design parameter and attribute may be more important than the number of design variables that affect a given attribute. System Design in Taguchi's method is the phase where designers seek to select design variables that have nonlinearities that result in small changes in the output for large changes in the input. Independence does not guarantee the dampening of effects on the outputs. As an example consider the following possible attribute-design variable choices: $X^1=(DV^a)^2$, or $X^1=DV^a$, or $X^1=DV^a+DV^b$. The second case would be preferred since changes in DV^a would have a potentially smaller effect on the attribute level than the other two. The Independence Axiom suggests that the third choice would be least preferred since it couples two design parameters to the attribute level (getting two design variable levels "right" is harder than getting one design variable level right, thereby increasing the chance for getting the "wrong" attribute level.)

variables. Designs with a high filtered outdegree will be the most attractive. As Epochs are defined, designers can custom tailor new transition rules that will increase the system changeability for the expected contexts. Investment in new technologies or concepts is one approach to targeted changeability enhancement. Embracing path enablers such as modularity, reconfigurability, use of COTS parts, and simple excess capacity interfaces, will increase the changeability of a design as well.

Figure 203 below shows the potential paths from the baseline design to a design with high utility. The higher the changeability, or filtered outdegree, of a design, the more potential paths exist. Since the cost of the paths change over time, as new technologies are developed, and the acceptability threshold for the decision maker changes, seeking high outdegree designs as a general strategy should be sound. In fact, the changeability analysis suggested in this thesis provides a foundation by which designers can discover which paths are most useful for cost reduction measures (those that are "close" to the decision maker threshold, whose cost reduction will result in a significant increase in the apparent changeability of the system).

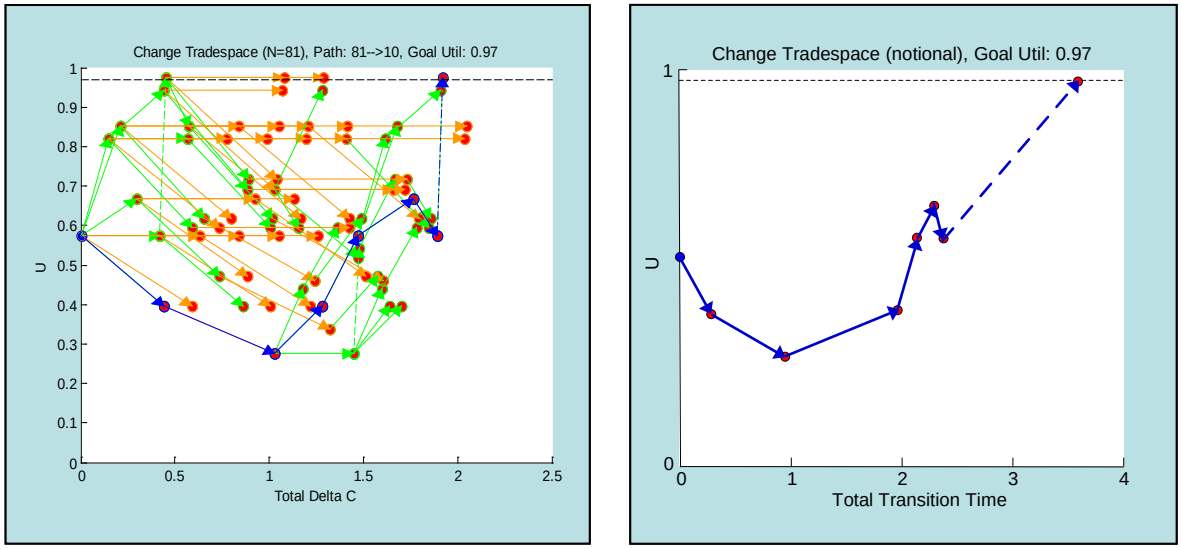

Figure 203 Changeable designs have many potential change paths to achieve high value

11.4 Relationship to Prior Research

The dynamic MATE process proposed should, as a special case, be able to reproduce the findings in (Diller 2002; Weigel 2002; Chaize 2003; Derleth 2003; Roberts 2003; Ross 2003; Spaulding 2003; Shah 2004). The goal of the present work was precisely to generalize the insights contained in these works, so the applicability is not a coincidence. While not incorporated explicitly, the multiobjective optimization strategies outlined in (Jilla 2002) could be beneficial if only Pareto Set Tracing is desired. The rapid, computationally frugal method would result in efficient determination of static "value robust" options. Likewise, no explicit Monte Carlo modeling with uncertainty propagation was conducted during this particular research Even so, as proposed in (Walton 2002), such analysis can be readily wrapped around the existing models of a MATE study. The creation of portfolios of options, ranked by changeability, could be a potential strategy for hedging against future uncertain Epochs.

11.4.1 Comparison to Select MIT Theses

(Nilchiani 2005) proposes a generalized six element framework for defining flexibility. Those six elements are mapped to changeability described in this thesis in Table 35.

Table 35 Nilchiani 6E Flexibility vs. Dynamic MATE Changeability

Element in Nilchiani 6E Flexibility	First order concept(s) in MATE Changeability
1. System boundary	1. System boundary
2. Time window of change	2. Epoch or Era duration, time for transition
3. System aspect	3. Parameter to be changed (attribute or DV)
4. Type of uncertainty	4. Δcontext/Epoch, timeline strategy
5. Response to change in value delivery	5. ΔUtility or Δattribute w.r.t. Δcontext
6. System accessibility	6. Cost/time for change: transition rule "cost"

The Nilchiani framework is derived from a very extensive literature synthesis on definitions of flexibility. MATE changeability captures the same key elements, although it does not rely on uncertainty per se, but rather on the expectation of change (which may be considered to be analogous to the implications of uncertainty).

(Suh 2005) proposes a flexible product platform design process. That process is mapped to dynamic MATE analysis in Table 36.

Table 36 Suh Flexible Product Platform Design Process vs. Dynamic MATE Analysis

Step in Suh Flexible Product Design Process	First order concept(s) in Dynamic MATE
1. Identify market, variants and uncertainties	1. Market~{DM}, Variants=Concepts, Uncertainties=Contexts/Epochs
2. Determine uncertainty related attributes and design variables	2. Desired attribute change for flexibility mapped back to needed DV change
3. Optimize product family and platform bandwidth	3. Perform tradespace analysis and exploration (not optimization)
4. Identify critical platform elements	4. Perform sensitivity analysis (ΔDV→ΔAtt)
5. Create flexible design alternatives	5. Find designs with high filtered outdegree
6. Determine costs of design alternatives	6. Costs calculated in both static and dynamic tradespace analysis
7. Uncertainty analysis	7. Uncertainty/sensitivity analyses layered on system timeline analysis

One key difference between the two approaches is that Suh assumes a market class, due to the thesis application to mass-produced products. Additionally, the transition rules for changing the system are implicit in the analysis, instead of being explicitly defined as in dynamic MATE.

(Smaling 2005) proposes an architecture selection framework using tradespaces. That framework is compared to the dynamic MATE framework in Table 37 below.

A key difference between Smaling and dynamic MATE is the former assumes a well-defined, or at least static, objective function, which enables optimization. The concept of Fuzzy Pareto Set

would be useful for inclusion in further MATE work, though it is an approximation to the tradespace exploration approach used in MATE.[246]

Table 37 Smaling Architecture Selection Framework vs. Dynamic MATE Framework

Smaling Architecture Selection Framework	First order concept(s) in Dynamic MATE
1. Limited to technology insertion	1. No such limitation
2. Fuzzy Pareto Optimal Set	2. Changeable objective functions…
3. Solution-Design Space linked filtering	3. No filtering used in analysis, though DOE could be used if TS converged for OD(<C,t)
4. ΔDSM change propagation due to technology insertion	4. No DSMs used in analysis, though could be used to aid model development
5. Aggregate System Arch Analysis: Risk and Opportunity	5. System timeline analysis through Epoch scenarios, finding value "robust" options
6. Design diversity vs. optimization, tuning filter and fuzziness factor K	6. Tradespace exploration knowing value metrics will change (cannot optimize for life)

(Chaize 2003; de Weck, de Neufville et al. 2004) describe the concept of a tradespace path through the staged deployment of satellites. The Chaize tradespace path framework is compared to dynamic MATE path framework in Table 38.

Table 38 Chaize Tradespace Path Framework vs. Dynamic MATE Path Framework

Chaize Tradespace Path Framework	First order concept(s) in Dynamic MATE
1. Partitioning of DV to flex and nonflex	1. No partitioning (any DV can change)
2. Evolution Rules (assumes constraints and Capacity objective value change)	2. Transition Rules (no limit). No assumption on objective change effect.
3. Cost for transitions (Initial Dev. Cost, Evolution Cost, Ops/Maint Cost), plus discounting	3. Cost to IOC, path cost, recurring cost. Currently no discounting (could be added).
4. Strategy assumes minimization of Lifecycle Cost	4. No strategy assumption (could be min f(cost), min f(time), max f(util), etc)
5. Families are {DV} subset where nonflex DV values are same	5. No {DV} partitioning, so families not defined a priori, can be identified ex post

The Chaize tradespace path application is similar to the dynamic MATE tradespace framework, though represents only a subset case: assumed transition rules and transition strategy. The idea of identifying system families by grouping designs with identical non-changing design variables is intriguing and could be applied in a MATE study during tradespace exploration. Platform systems could, in theory, give insight into where to focus changeability generating efforts.[247]

[246] The goal of making the Pareto Set "fuzzy" is to include designs "close" to the optimal set, which may still be of high value, especially when considering tradespace uncertainty. Such considerations are already taken into account in a tradespace exploration study since the structure of the "full" space is better understood. When objective functions change, there is no guarantee that the Fuzzy Pareto Set designs will remain in the new Fuzzy Pareto Set.

[247] More study should be done applying the concept of platforming to dynamic MATE case studies.

11.5 Valuing "Ilities"

While the identification and quantification of the ilities was explicitly undertaken in this work, valuation of the ilities was intentionally excluded from consideration. Valuation of ilities is an additional layer of analysis that can be put on top of the proposed dynamic MATE methodology. The reason valuation was excluded is that all valuation techniques rely upon specific assumptions regarding how to collapse time, utility, and cost into a single metric. Layering such assumptions into the MATE process would obfuscate the interesting trades which exist among these three quantities. In effect, the ilities are being valued through the decision process itself. If additional metrics are desired, the MATE output can be used as input into the valuation method of an analyst's choice, without biasing the MATE methodology in the process.

11.6 Applying Real Options

As pointed out in (Roberts 2003), the ability to change the onboard delta-v for the Space-based Radar system represents a real option for the system. In dynamic MATE terms, this same capability is described by the existence of a "path-enabling" variable. Real options and path-enabling variables are similar in that both factors allow for a system change, and may not contribute to system value if left unused. Valuation of path-enabling variables can be done utilizing real options analysis, and likewise, identification of real option opportunities can benefit from the definition of path-enabling variables. The present work is considered to be both preceding and complementary to traditional real options analysis. The ongoing MIT work on defining real options "in" systems tends to focus more on valuation, rather than discovery of the key variables that should be investigated for real options.[248] Dynamic MATE can help discover those key variables.[249]

11.7 Dynamic MATE Implementation Issues

Successful application of dynamic MATE analysis requires access to appropriate training, resources, information, and managerial support. Training includes an understanding of both the MATE philosophy and process implementation. The core concepts of MATE are fairly generalizeable since they derive from basic problem solving theory: define problem, identify goals, propose alternatives, evaluate alternatives, select alternative. MATE analysts must be familiar with the assumptions in the process in order to appropriately apply the analysis to new problems or domains beyond the examples in this and related theses.

The resources required for MATE analysis is principally in terms of time and labor for the application, though access to computational resources may be necessary as well. A MATE analysis can be done at various levels of support, from an informal half-day study if relevant stakeholders and knowledge is accessible, to a full, on-going support analysis throughout a system's lifecycle. The necessary information for a MATE study includes the key variables highlighted in Chapter 8, including decision maker set, attributes, domain and context knowledge, design expertise, modeling expertise, and utility and cost models. Even with training, resources,

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[248] An exception is Bartolomei, Jason E., Daniel E. Hastings, et al. (2006). Screening for Real Options "In" an Engineering System: A Step Towards Flexible System Development--PART I: The Use of Design Matrices to Create an End-to-End Representation of a Complex Socio-Technical System. INCOSE Conference on System Engineering Research, Los Angeles, CA, INCOSE., whose research is trying to discover "hot spots" or key system aspects that should be addressed for leveraging changeability (flexibility)—i.e., identifying real option opportunities.

[249] Further work exploring the parallels between path enabling variables and real options should be done.

and information, a MATE study will not be successful in having impact without managerial support.[250] The role of a good manager is to ensure access to the appropriate training, resources, and information in order to complete the study with good data, conclusions, and impact.

More specific implementation considerations for a MATE analyst will be discussed in the following subsections, mostly relating to incomplete information, access to stakeholders, or resources.

11.7.1 Choosing Appropriate Model Fidelity

Choosing the appropriate level of fidelity for model development can mean the difference between discovering key insights, and glossing over critical decision opportunities. The tradeoff for fidelity selection is accuracy versus effort. Higher fidelity models tend to be more accurate and thus lend more credibility to the results, however, require deeper expertise and often more computation power to execute. The accuracy of any model is only as strong as its weakest assumption. In practice it has been found that a heterogeneous approach to fidelity selection is appropriate. Low fidelity models are used for most analysis, with high fidelity models used for analyzing key attribute relationships. As an example, for the X-TOS project, it was found that orbit simulations were primary drivers for determining most attribute values. High fidelity orbit simulations were used to calculate the important attribute values. For the JDAM study, unit cost was the most important attribute and thus a high fidelity cost model should be used. Since such a high fidelity model was unavailable for the study conducted in Chapter 9, the results are unreliable and are more illustrative than conclusive. Pursuing models with high accuracy for unimportant parameter value calculations is both a waste of resources, and results in a false sense of security on the conclusions. Fidelity matching is about focusing accuracy and effort where it will have the most impact on the important results.

Selecting the appropriate level of fidelity is not yet a science, though some research has been done with respect to space-based telescope design. [251] In general, a modular software architecture has been employed for MATE studies, with low fidelity models used in the first iteration. As analysts gain insight into the important relations, higher fidelity models can be substituted for their low fidelity predecessors, thereby achieving a learning process, conservative in its commitment to excessive modeling effort.[252]

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[250] Managing a successful MATE study is similar to managing any successful team task. For a research-grounded text on leading successful teams see Hackman, J. Richard. (2002). Leading Teams: Setting the Stage for Great Performances. Boston, Massachusetts, Harvard Business School Press.

[251] Deborah Howell in the MIT Space System Lab is conducting PhD research addressing the appropriate tuning of model fidelity. Her PhD abstract proposes the following hypothesis: "1) certain aspects of each system impact system performance more than others, 2) that these aspects are unique to each type of architecture and 3) that by concentrating modeling efforts on these aspects, a more accurate model will result. This would facilitate a higher fidelity model overall, while still retaining the flexibility appropriate for Engineering Systems analysis (multi-objective design optimization, pareto-front, sensitivity analysis, etc)."
(web.mit.edu/deweck/www/students_current_files/HowellAbstract.html as cited on 4/12/06)

[252] See Chapter 5 of Ross. MATE-CON as Value-centric Framework for Space System Architecture and Design. for discussion of model fidelity effects on the TOS projects

11.7.2 Model Tractability

Development of the models in a dynamic MATE analysis requires knowledge of both the relationship between design variables and attributes and a mechanism for extracting that information. Either causal relationships, or data-based relationships can be used for extracting attribute values from a particular design. The best types of models are those that reflect the underlying causal relationship, or "physics" of the design-to-attribute mapping. In absence of that knowledge, or if pursuit of "physics"-based models would require too many resources to implement, a data-based, or even semi-quantitative approach could be used, with a requisite increase in uncertainty. Complex, engineered systems may not be describable by causal relationships and only expert opinion or a small sample size dataset may be available. In any case, the dynamic MATE framework at least informs the analyst of the necessary information for determining attributes from designs. Regardless of the model type, a dynamic MATE study can still be conducted, though it is important to at least capture the highest-level cost-benefit tradeoffs within the causal structure of the problem even for qualitative analysis.[253]

11.7.3 Qualitative vs. Quantitative

A key question in the development of a MATE model, or in fact any of the analysis, is the necessity of using "hard" numbers. For a technical audience, numbers convey a sense of concreteness and believability that words or images seem to lack. Numbers are in fact a concise means of communicating information, especially when derived from a rigorous mathematical framework. But the reliance on quantification can be both misleading and dangerous. In fact anything, from fictional to nonfictional, and from concrete to fuzzy, can be quantified. For example, colors can be quantified by their wavelength, and happiness can be quantified on a scale from 1-10.

The key results from a MATE study are not the numbers per se, but rather the insight into the structure of the design for value problem. The numbers help to make better decisions, but in themselves mean little. A rigorous qualitative MATE study is superior to a shabby quantitative MATE study. The analyst must make appropriate use of qualitative versus quantitative approaches based on client community expectations and the availability of accurate data and models.

11.7.4 Availability of Expertise

The expertise needed for effective MATE implementation falls into two categories: process and content. Process expertise relates to understanding the MATE process and its underlying assumptions and applicability. Such expertise is necessary for any rigorous MATE study. Content expertise relates to the information for the study, including constraints, contexts, domain-specific knowledge, decision maker preferences, design knowledge, modeling knowledge, etc. Availability of content expertise is necessary to some extent, though complete access is not necessary, but the more the better. A MATE analyst confronted with the problem of insufficient expertise can rely upon past projects, analogy, and clever assumptions.[254]

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[253] Shishko, Robert, Ed. (1995). NASA Systems Engineering Handbook, PPMI. warns of models that imply benefit without cost due to incorrect, incomplete, or inappropriate model assumptions.

[254] "Clever" assumptions refers either to building in the ability to easily revise the assumptions at a later point in time when such information becomes available, or to minimizing the negative effect the lack of information will

11.7.5 Availability of Decision Makers

Having access to the key system decision makers is one of the most important parts of the MATE approach. Without their input, the results may be invalidated upon their eventual inspection. Sometimes access to decision makers is limited or delayed. In those cases, proxy decision makers may be used, preferably by those most familiar with the true decision maker preferences and thinking frame of reference.

Often the designer or analyst must assume decision maker preferences, especially during preliminary attribute brainstorming with no access to decision makers. The process can be done in this way, but it may be useful for a person (or people) to play the role of decision maker, rather than designer, in order to better characterize the potentially very different thinking style. The caveat of this decision maker absent approach is the need to validate the attributes with the decision maker or proxy at a later point in time. The designers and analysts run the risk of having to repeat effort if the attributes are incorrect. Additionally, the analyst must take care to not impose artificial preferences on the decision maker.[255]

11.7.6 Computational Constraints

Since MATE embraces tradespace exploration and not optimization, it necessarily requires more computation effort than a more traditional multi-dimensional optimization exercise. The size of a tradespace increases very rapidly with number of design parameters. Coupled with the multidimensional objective structure of multiple decision makers over time, the tradespace exploration analysis requires access to computers and efficient computation algorithms to ensure feasible calculation time. The MATE analyst may have to scope the tradespace size for consideration to the available computational resources. An implication of insufficient tradespace enumeration is reduced confidence in the convergence of the node outdegree metrics, which is directly related to the number of possible destination nodes.[256] On the upside, a resulting benefit from computational constraints is the encouragement of efficient algorithm design and clever tradespace sampling techniques.

11.7.7 Schedule Constraints

A common problem confronting up-front design work is lack of resources commensurate with the impact of the analysis. Figure 204 below shows the small cost incurred relative to cost committed at the conceptual design stage in a system development lifecycle. In such cases a fidelity-improving spiral approach should be taken, with low fidelity, quick analyses done at first and as resources permit, higher fidelity models done later. Using the spiral approach allows the analyst to generate insights, perhaps qualitative at first, under tight schedules. An experienced MATE analyst may be able to perform a simple MATE study in less than a week, though deeper

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have on meaningful results. Recasting the problem in different terms, or identifying causal structures that remain "true," independent of parameter values, are two examples of the latter type of clever assumptions.

[255] Decision analysis and support is primarily intended to help decision makers make better decisions through formalization or facilitation of the decision making process. Imposing preferences, if temporary in its effects on the decision maker, will result in transitory bias of the decision making process and render unstable some of the MATE results. Care must be taken between informing, instructing, and imposing preference information and structure on the decision maker(s).

[256] Further work should be done merging insights from the DOE and computation communities into prescriptive advice on sampling and computation time.

and more rigorous insights would be possible with more time (See prior sections on other implementation issues that directly relate to scaling the MATE effort in response to constraints on resources or expertise.)

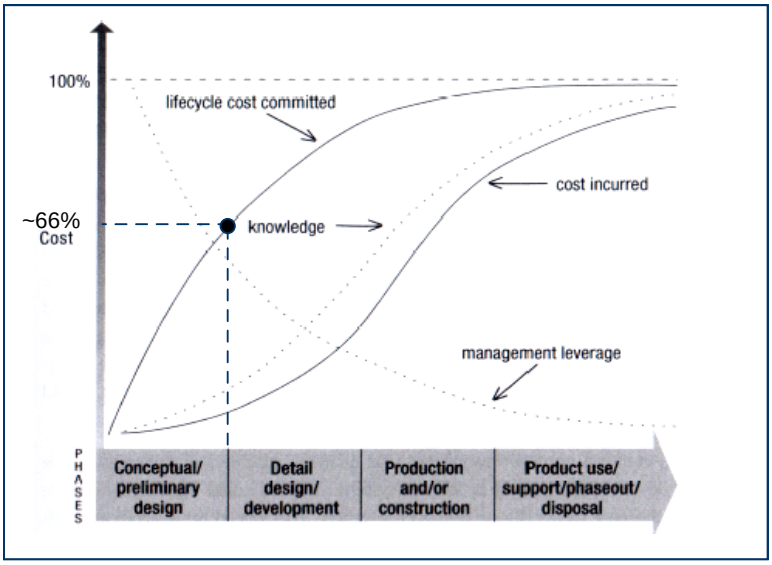

Figure 204 Cost committed versus cost incurred across product development phases show Conceptual/Preliminary Design is a potentially under-funded part of development process (Fabrycky 1991)

11.8 Potential Application Areas

As illustrated in the JDAM case application in Chapter 9, dynamic MATE can be used to make concrete the definition of flexibility. JDAM was found to both be flexible in itself due to use of the path enablers of modularity, COTS, and simple, excess-capacity interfaces, as well as enabling a flexible mission through its ability to change mission targets and high accuracy, freeing up more available pilot time. If used as a framework during design, the changeability analysis approach introduced in this thesis could inform designers how to increase the flexibility of a design.

Epoch analysis can give useful insights in the context of spiral development, a use and learn product development process with successive system generations informed by experienced utility of the user in practice. The analysis of spiral development of small-diameter bomb (SDB) in (Derleth 2003), has been extended as a retrospective analysis of the development of JDAM variants, including JDAMASK (terminal seeker), JDAM-ER (extended range), and JDAM Laser (laser targeting). Systems embracing change and value feedback can benefit from the structured approach to predicting higher value designs in Epoch analysis.

The TPF case application in Chapter 10 reveals a different important insight capable through dynamic MATE analysis: the structure of value-space to design-space mappings. It was found that the temporal trend of the system value proposition (i.e. requirements) may be pushing the overall system to value infeasibility (inability to meet minimum acceptable attribute levels, or excessive costs). A natural discussion arises regarding the distribution of system costs and benefits and the problems caused by interpersonal comparison of utility. Development of any complex engineering system would benefit from knowledge of the structure of stakeholder

preferences, especially whether desired attributes conflict to the point of rendering a system infeasible or mediocre. Additionally, insight from such analysis can recommend technology development efforts that will best increase the likelihood of designs moving to high value regions of a multi-stakeholder tradespace.[257]

Determining appropriate application areas for dynamic MATE requires the potential MATE analyst or designer to be aware of its limitations, both in terms of underlying assumptions as well as costs for implementation (time, effort, knowledge, etc). As a general rule, MATE analysis requires some minimum amount of resources and the scaling of the analysis effort must be commensurate with the expected benefits of the analysis. For dynamic, complex, and expensive systems, such as found in aerospace, dynamic MATE analysis could prove very valuable. For static, simple, and inexpensive systems, dynamic MATE analysis may be cumbersome or unjustifiably expensive and inappropriate. Ultimately, like any analysis in use, the applicability of dynamic MATE will be first dictated by available resources, and second by its appropriateness.

[257] For example, mass or power decrease may reduce launch or test costs, or improved technical performance and resulting attribute performance may move a design from an unacceptable to more acceptable region of the tradespace.

Chapter 12: Conclusions

The ending of the thesis is more like a beginning. It seems that more questions exist at the end than the beginning, so more work remains to be done. The effort to incorporate dynamic aspects of value and system change has been begun and framed for future researchers and analysts to further develop and apply. To remind the reader of the progress made during the current work, it is necessary to return to the beginning.

12.1 Research Findings

12.1.1 Research Questions Revisited

The questions that motivated the work are revisited here, along with the answers generated in the current work.

Q1. What are the relationships between flexibility, adaptability, robustness, and scalability for aerospace systems and how do they relate to unarticulated value?

A1. The ilities relate to the changeability mapping of design variables $\{DV^N\}$ to attributes $\{X^M\}$ through a transition rule set $\{R^K\}$; unarticulated value can be captured as classes of attributes, motivating the transition rules.

Q2. How can these ilities be quantified and/or used as decision metrics when exploring tradespaces during Conceptual Design?

A2. Changeability can be quantified using tradespace network-derived Filtered Outdegree, OD($<\hat{C},\hat{t}$), passive robustness using Pareto Trace number; together these can be used in System Era tradespace path analysis to determine "best" dynamic strategies to achieve value robustness.

12.1.2 Changeability and Robustness Revisited

One of the benefits of taking a value-centric perspective on the system design problem is that it focuses attention on what is important and what can be done in order to achieve it: value-space and design-space. Flexibility and adaptability are the two types of design-space change, in terms of externally motivated and internally motivated change, respectively. Scalability and modifiability are the effects of the change on the tradespace, in terms of level of a tradespace parameter and membership in the tradespace parameter set, respectively. (In general the tradespace parameters of interest are the attributes since they drive value. Attributes can be design variables if the decision maker derives value from the design variables themselves.) Each of these ilities are aspects of changeability, which captures both objective (whether can change) and subjective (acceptable "cost" for change) aspects. Value robustness is the perception that a system continues to deliver value in spite of changes in its context or design parameters.

Unarticulated value is wrapped into the MATE framework in terms of classes of attributes. When analyzing the system, both articulated, or class 0, attributes and possible unarticulated, or class 1-3, attributes are calculated and mapped into the changeability analysis. Movement of attributes from class 1-3 to class 0 represents articulation of value and the designer can take steps to reduce the cost of the system change response to the new value perceptions. Designs

quantified as having high outdegree are those which are most changeable. The subjective cost and time thresholds, however, reduce the actual perceived outdegree of a design for a particular decision maker.

One of the goals of a system designer is to maximize value delivery at efficient levels of resource expenditure. Pareto Tracing provides a mechanism for the analyst to discover and quantify designs that are passively most value robust. A design with high Pareto Trace is one that appears in many Pareto Sets across various Epochs, or change scenarios. These designs can become "attractors" for future scenarios, as a goal state for change pathways. Additionally, real-space analysis of the Pareto Trace gives system designers insight into the most value-delivering and efficient combination of design parameters in the face of changing contexts. Figure 205 and Figure 206 below give examples of the quantified changeability and robustness for several X-TOS designs, respectively.

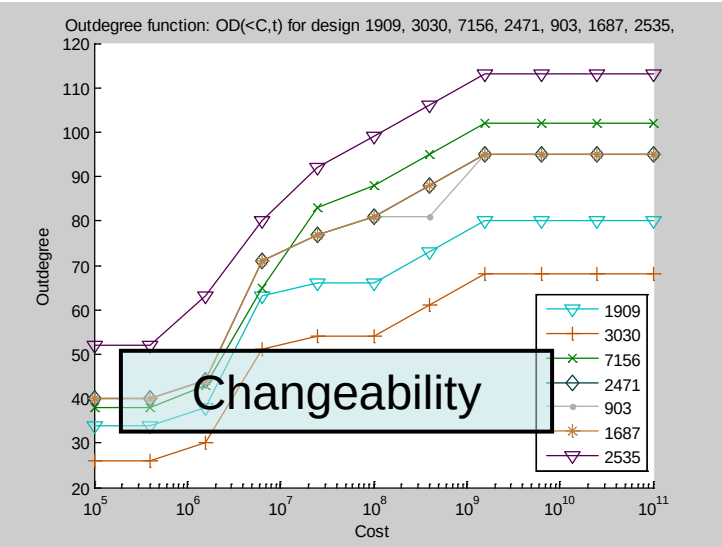

Figure 205 Changeability for selected X-TOS designs (including 2471, 903, 1687, 2535)

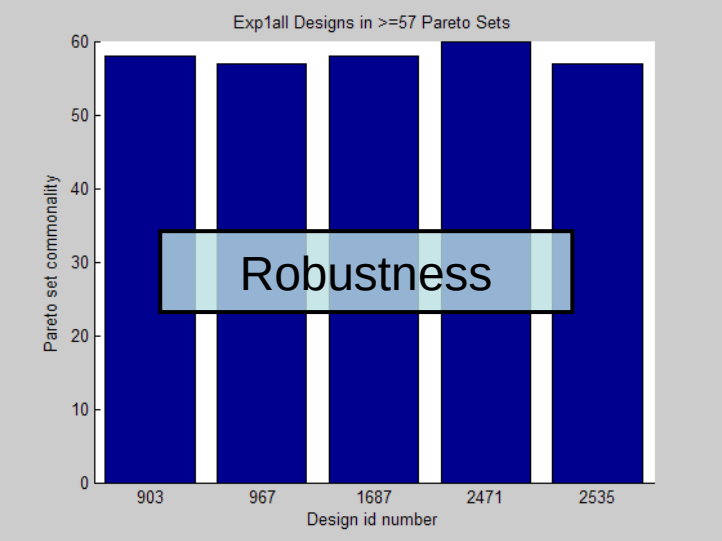

Figure 206 Passive value robustness for selected X-TOS designs (including 2471, 903, 1687, 2535)

12.1.3 Corollary Concepts

Two corollary concepts were derived from the defined changeability concepts in Chapter 6: the **System Shell**, and **Fundamental Attributes**. The concept of System Shell decomposes into two parts: the System Mask and the System Shelter. The System Shell is a mechanism to change the problem confronting designers by altering the interaction between a system and its context. The Mask alters the interaction from inside-out; it changes how the system is "seen" by the environment. The Shelter alters the interaction from outside-in; it changes how the system sees the environment. The System Shell concept can be used to conceive buffers and mechanisms for systems to cope with changing contexts. As an example, clothing for humans can serve either or both purposes (as Shell and/or Mask), protecting people from variations in the environment, as well as altering their appearance. (Specialized clothing, such as outdoor gear and high fashion, may seek to serve one purpose more than the other.)

The concept of Fundamental Attributes relates to the decomposability of attributes. Constructed by analogy to physics units, which are all derivable from seven "fundamental" quantities, Fundamental Attributes form the basis from which all other attributes can be derived. The Principle of Fundamental Attributes suggests that a system displaying more fundamental attributes will be more modifiable than one with fewer. The reason is that the "cost" for adding new attributes to the system will be simply a recombining of existing fundamental attributes (articulation from class 2, meaning most potential attributes are latent to the system). GPS is an example system displaying the fundamental attributes of position and time information, relevant to all physical entities, and therefore is a system having tremendous latent value.

12.1.4 Summary of Key Research Contributions

The key contributions of this research can be summarized into six main categories.

1. **A unified definition of six system properties (ilities)**
   The six ilities considered in this thesis are shown to be different aspects of the same concept: changeability. (Figure 207 below reviews the concept of changeability.) Flexibility and adaptability relate to the origin of the change agent: external or internal to the system boundary, respectively. Scalability and modifiability relate to changes in levels or sets of system parameters, respectively. Robustness cast as "value robustness" relates to maintaining value delivery in spite of changes within or without the system. Robustness can be pursued either through passive robustness (choosing a good design that does not need to change), or active robustness (choosing a design that can be altered to continue to deliver value over time).

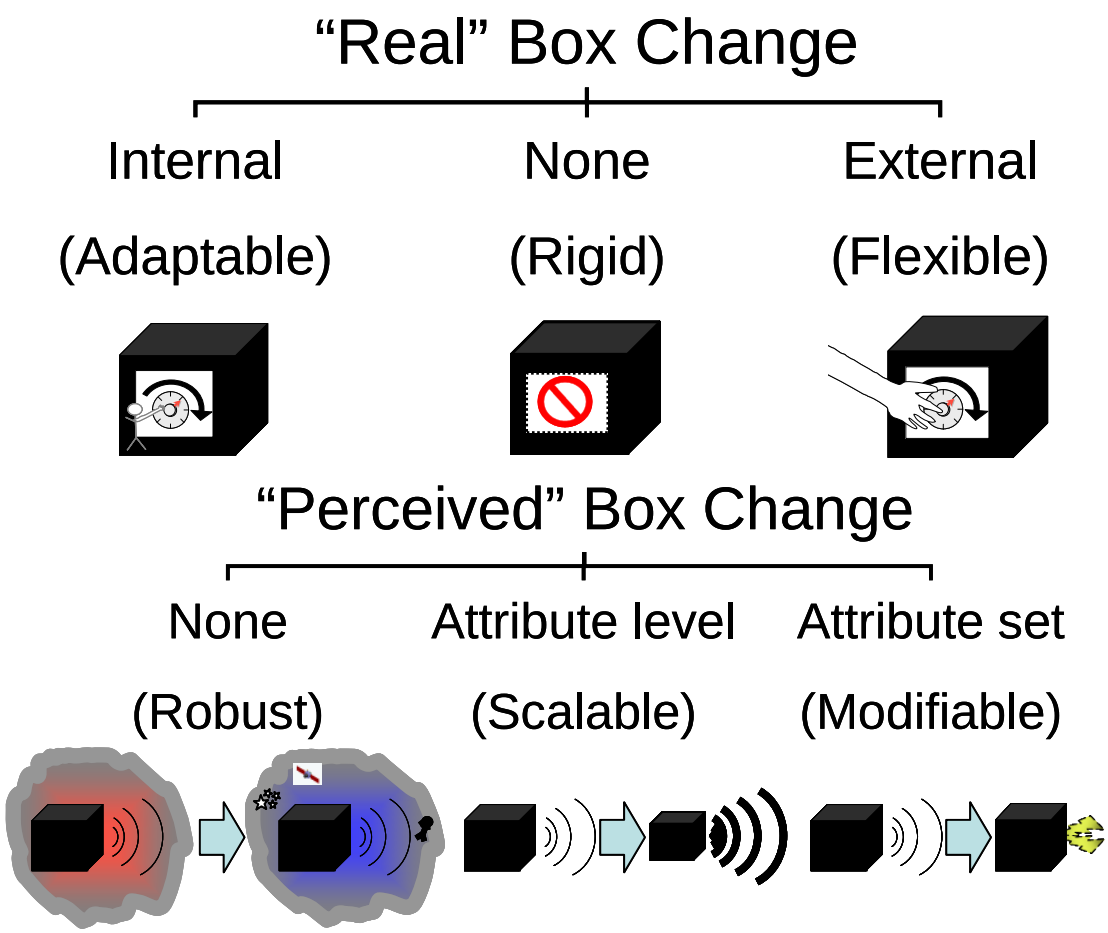

Figure 207 Aspects of changeability: adaptability, rigidity, flexibility, robustness, scalability, and modifiability

2. Quantification of flexibility/adaptability/robustness/scalability/modifiability

As aspects of changeability, flexibility/adaptability/scalability/modifiability can be quantified as the Filtered Outdegree of a particular design in a tradespace network generated by transition rules (see Figure 208 below for review). The outdegree reflects the number of possible change paths from a design's current state to possible future states. The filter is the subjectively set acceptability threshold that varies from decision maker to decision maker, capturing the inherent subjectivity of changeability perception. Only paths "costing" less than the acceptability threshold are counted when determining the Filtered Outdegree. A change in subjective perceptions, increases in change mechanisms (transition rules), or decreases in cost for change all can increase the perceived changeability of a system.

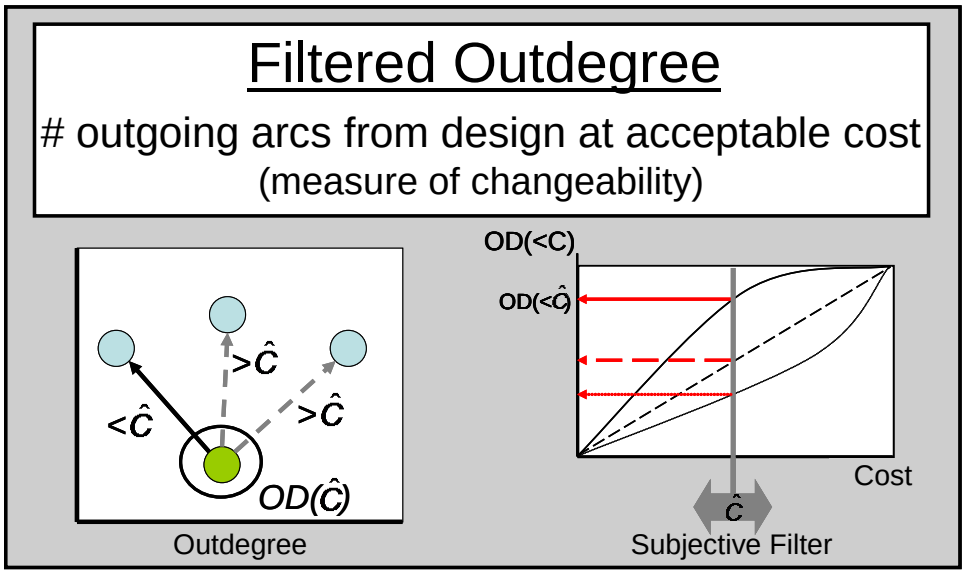

Figure 208 Filtered Outdegree definition

Passive value robustness can be quantified as the Pareto Trace number, which is the number of Epochs (or scenarios) whose Pareto Set contains that particular design, reflecting the designs that have the most efficient utility for a given level of resource expenditure (see Figure 209 below for review). A relatively large Pareto Trace number implies a high passive robustness factor for a particular design and can be a function of excess capability, insensitivity to the particular change scenario, or a locally stable region in a tradespace.

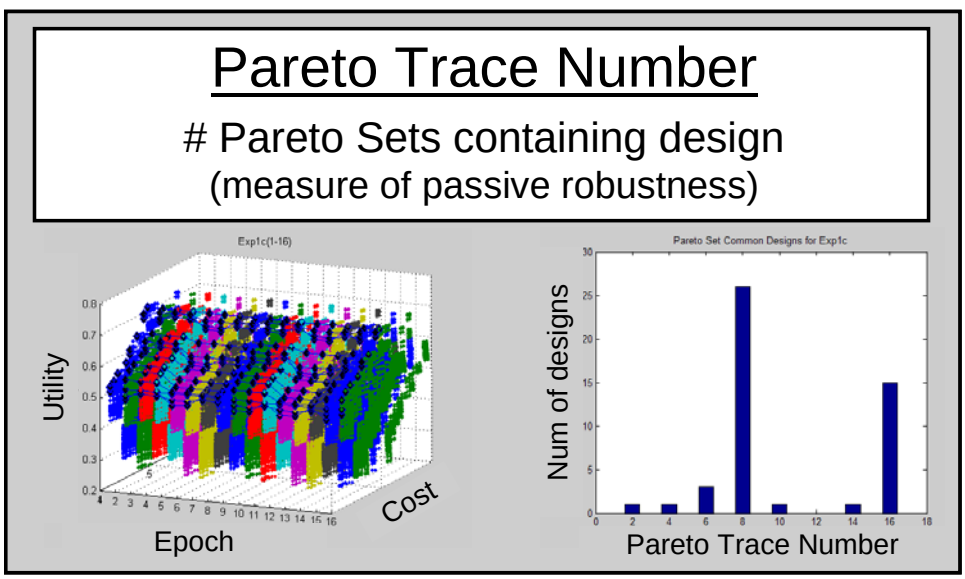

Figure 209 Pareto Trace Number definition

3. Framework for representing unarticulated value

In addition to the typical articulated value, captured in explicit communication between decision makers and system designers, a spectrum of value exists. Unarticulated value includes those current and potential aspects of a system that result in value to a decision

maker, but have not been explicitly communicated. Differentiating between the articulated and unarticulated value in terms of "cost to display" in the system results in five attribute classes (see Table 39 for review). The "display" of an attribute means that the system "is" or "does" the attribute.

Table 39 Attribute class definitions

Class	Name	Property of Class	Cost to Display
0	Articulated Value	Exist and assessed	0
1	Free Latent Value	Exist, not assessed	0
2	Cheap Latent Value	Can exist by recombining class 0 and/or 1	Small
3	Accessible Value	Can be added through changing {DV} (scale or modify)	Small→large
4	Inaccessible Value	Cannot be added through changing {DV} (system too rigid)	Large→infinite

Class 0 attributes are the "articulated value" and include those value metrics that are explicitly used to design the system. These attributes are "free" to display since the system already addresses them. The rest of the classes are types of unarticulated value. Class 1 attributes are "free latent" value, representing aspects of a system already being displayed, but not asked for by the decision maker. If that attribute becomes value generating, it is "free" for the system to display it. Class 2 attributes are "cheap latent" value, representing aspects of the system that can be created through a simple recombination through an interpretation mechanism. The system itself does not require change, only the interpretation of the existing displayed attributes. Class 3 attributes are "accessible" value, representing attributes that could be displayed through a change to the system. The cost for the articulation of class 3 attributes ranges from cheap to expensive. Class 4 attributes are "inaccessible" value, representing attributes that cannot be displayed by the system due to excessive cost or the existence of constraints. These attributes are better displayed in a different system.

4. Framework for discovering "efficient" solutions for multi-stakeholder negotiations

The multi-decision maker tradespace exploration proposed in dynamic MATE results in a set of designs that can be used as the basis for negotiation. The single decision maker Pareto Set solutions represent the most "efficient" usage of resources for creating value for that particular decision maker. The Joint Pareto Set is the multi-decision maker analogue and captures the individual Pareto Set solutions as well as "compromise" solutions that trade between the decision makers. (Figure 210 below gives the Joint Pareto Set example from X-TOS analyzed in Chapter 7.) Knowledge of the structure of the tradespace, as well as the Joint Pareto Set enables decision makers to understand the key trades between their value propositions and whether an acceptable compromise solution can be found. The distribution of costs and benefits (resources and utility) can also be illustrated through this process, helping decision makers to discover key tensions in the interpersonal comparison of utility, which cannot be done in an arbitrary fashion.

(See Figure 211 below for a notional example of using the Design-Value Matrix for capturing the distribution of costs and benefits as discussed in Chapter 8.)

Designs in Joint Pareto Set

DM1 Pareto Set DM2 Pareto Set Compromise Pareto Set

903	919	920	933	935	936	951	952	965	967	981
982	983	984	997	1687	1703	1735	1749	1751	1765	1767
1781	2471	2487	2501	2503	2519	2533	2535	2549	2551	2565
4511	4515	4531	4535	4536	4539	4540	4555	4556	4559	4560
4563	4564	4579	4580	4583	4584	4587	4588	4603	4604	4607
4608	4611	4612	4627	4628	4631	4632	4633	4707	4708	4727
4728	4747	4748	4771	4773	4795	4796	4797	5687	5691	5707
5711	5715	5731	5735	5739	5755	5759	5779	5783	5787	5803
5807	5809	5883	5903	5923	5947	5949	5971	5973	6863	6867
6883	6887	6891	6907	6911	6915	6931	6935	6939	6955	6959
6963	6979	6983	6985	7059	7079	7099	7123	7125	7147	7148
7149										

Joint Pareto size: 122 designs

Figure 210 Example Joint Pareto Set for X-TOS, including overlapping "best" designs in white

		Value-space										Design-space					
		Attributes										Design Variables		Path Enablers		Resources	
		Latent				Cheap		Accessible		Inaccessible							
	Class:	0		1		2		3		4							
	Attribute:	X1	XM	X'1	X'M'	X	X	Y	Y	W	W	DV1	DVN	IV1	IVP	C	t
Decision Makers	DM1																
	DMZ																
Design Variables	DV1																
	DVN																
Path Enablers	IV1																
	IVP																

DV DM "willing to pay" for

Figure 211 Design-Value Matrix used for analyzing cost-benefit distribution among decision makers

5. Framework for considering "Design for Changeability"

The usage of Design-Value Matrices, Rule-Effects Matrices, and Outdegree Assessments help focus the attention of designers on the effects of change on the value propositions of decision makers, as well as the effect on the system design parameters. (Figure 212 below reviews the Design-Value Matrix.) Explicit attention to the creation of "Path Enablers" reveals design choices intended to create value not through their effect on attributes, but rather through their effect at enabling change (through the generation of additional change paths, or their reduction in cost for following a change path). The effect of the Path Enablers can be traced through their effects on design parameters to attributes and subsequently to the decision makers. In this way, designers can better understand "who might care about modularity" and therefore be willing to pay for it. The change enabling nature of these concepts can also be used as a strategy

for reducing long run change costs within an organization, as shown in the JDAM case application.

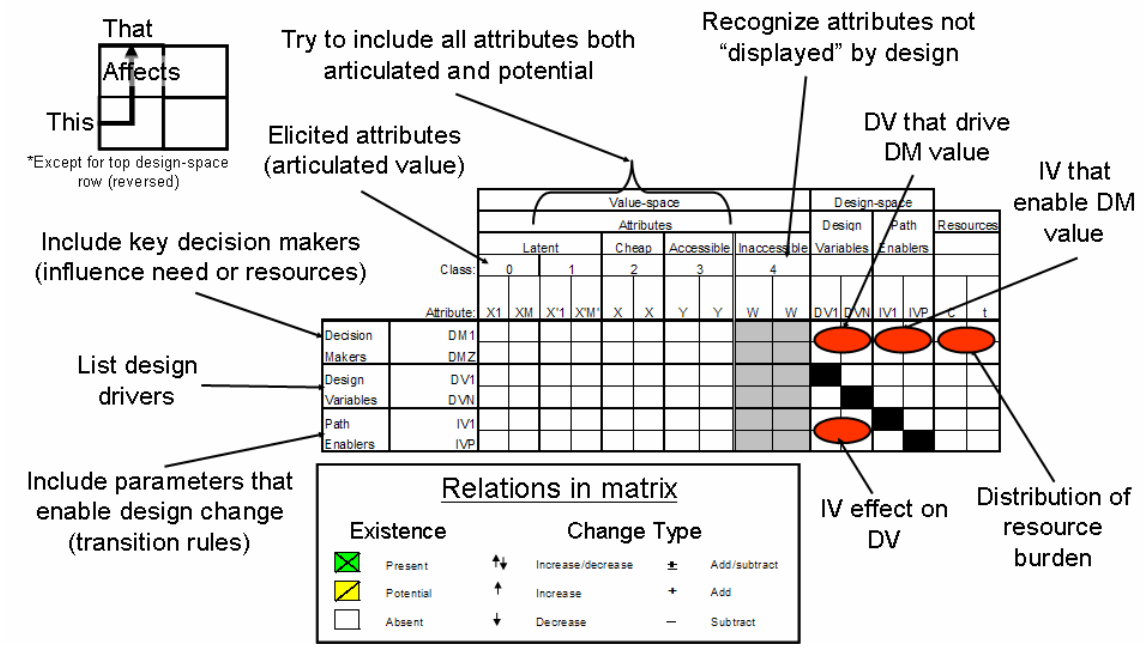

Figure 212 Design-Value Matrix defined

6. Application of dynamic MATE to two real systems

The Joint Direct Attack Munition (JDAM) and the Terrestrial Planet Finder (TPF) were studied through the dynamic MATE lens and shown to address changeability in very different ways. (See Figure 213 below for example tradespaces.) JDAM, as an actual system in use, was shown to be a highly changeable system due to its use of three key path enablers: modularity, commercial off-the shelf (COTS) parts, and simple, excess capacity interfaces. Along with its simple design, these path enablers have allowed the system developers to continuously upgrade and refit the system over time, offering several "accessories" to customize the system to customers, all while maintaining a high level of program success. The JDAM was shown to not only be a changeable system itself, but also a path enabler to flexible and adaptable missions.

TPF, a major space-based astrophysical observatory seeking to characterize extrasolar planets for their potential for life, is aiming for deployment early next decade. The conceptual design phase for this system is ongoing and the architectures under consideration have slowly changed with time, as have the requirements. Since the science aims may change with time, the system itself must be able to change, or have excess capability in order to meet the various demands placed on it. Finding a passively robust TPF architecture may not be possible, as the current set of requirements may not be readily met with a single architecture considered by this study.

The pressure to combine science goals of distinct communities may result in a reduction in the feasible space of design options to a null set. Coupled with detector technological progress, the TPF mission may benefit from waiting before further development as

system designers seek to better understand the key tensions between science goals, available resources, and technical capabilities.

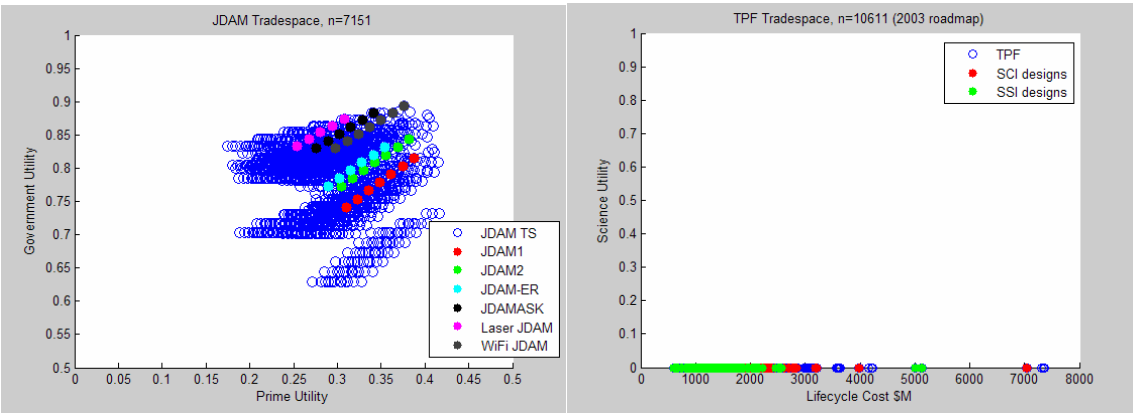

Figure 213 JDAM and TPF tradespaces

12.1.5 Application to Engineering Systems

Engineering systems are typically systems with diverse stakeholder needs, complex relationships between inputs and outputs, and uncertain, dynamic contexts. Dynamic MATE analysis can be readily applied to these systems, helping to answer such salient questions as the following:

How do decision maker value propositions relate to one another?
How do decision maker value propositions change over time?
How do system design drivers relate to stakeholder value?
How can the system respond to dynamic contexts?
How can the system be "value robust"?
How can a designer create a "flexible" system?
How can a complex system be represented objectively to assist in negotiation?
How can a designer cope with poorly defined or changing needs?
How can a designer compare qualitatively diverse options in a single framework?

Building off of (Whitney 2004), the current thesis contributes fundamentally to concepts and techniques for the development and evaluation of engineering systems. The need for considering changeability and managing unarticulated value are key problems facing engineering systems, and will directly benefit from insight generated by dynamic MATE.

12.2 Further Work

As mentioned earlier, a host of questions arose during the development of the present work. Scoping considerations limited the extent to which these questions could be addressed. Potential avenues for further work are highlighted in context throughout the thesis and are recaptured here for review. Page numbers for the originating research comments are included for easy reference.

Page	Research Opportunity
96	Potential research could apply the temporal theories of utility perception presented here to the domain of aerospace system acquisition.

97 An interesting consideration relates to the case of the Demander with multiple personalities. Such individuals may have multiple or conflicting preferences, with the expression of "dominant" values changing over time. Congress as a single entity can be considered of this class since each individual member may have differing and conflicting preferences, yet the decisions articulated by Congress may or may not remain stable over time as "dominant" Congressmen become the voice for the body. Treatment of Congress as a multiple Demander case may provide insight into the problem as well, but reality lies somewhere in between (has single demander effects, but multiple demander preferences). Further work should be considered in this area.

102 An opportunity exists for applying the four market frameworks presented here to the U.S. Aerospace industry. An historical study analyzing the consolidation of the industry may provide insights into the forces at play in such a market model. Intervention at the market level could be proposed based on the model and desired system offerings and preferences sets.

120 Further work should be done applying the system shell concept to a variety of systems to identify how the concept has been or could be applied to improve system robustness.

121 Further theoretical research should be done defining, validating, and/or proving a complete set of fundamental attributes.

146 Further research should be done across multiple case studies to understand whether the existence of high Pareto Trace designs can be made predictable.

150 Further work should be done to uncover the true cause of the apparent robustness of the four X-TOS designs, including analysis of the utility functional form and mathematical effect of altering k_i and X^i.

182 Further research should be conducted on the best distribution to use in order to minimize the time to remove sampling bias in tradespace enumeration. Application of Design of Experiments (DOE) could be a fruitful path for study.

285 Further work should be done merging insights from the DOE and computation communities into prescriptive advice on sampling and computation time.

198 Lack of temporal modeling hampers time-dependent insights. Potential research could incorporate schedule modeling work such as in (Browning 1998)

231 The key differences between Conceptual Design level and Preliminary Design level analyses are the level of detail and fidelity of models. The fidelity-cost tradeoff for creating models usually precludes the ability to create detailed models during Conceptual Design for all of the concepts being considered. Design for Manufacturability and Assembly (DFMA) and component selection to improve affordability may be differentially applicable to different concepts, so insights at the Conceptual Design phase

would be valuable. Further research into incorporating DFMA in Conceptual Design should be done.

252 In the TPF case application, 486 designs out of 10611 had “images long” exceeding the 400 image minimum acceptable level. Of these, none met the other three attribute minimum levels, though they all had over 2000 “images short.” Further model work should be done to enable variable imaging on short and long baselines. The Makins model assumes half of imaging time is spent on short baseline images and half on long baseline images. The science requirements suggest interest in being able to tune the interferometer to a particular planetary system.

266 More research should be done to better understand the forces driving the TPF science requirements and whether a better compromise can be found that does not sacrifice performance for resource support, but rather better distributes the costs and benefits of the system.

267 The questions raised over the course of the TPF case application suggest ample work for a follow-on case study to develop more detailed and holistic TPF models.

271 Further work should be done deriving general principals for assessing and recommending generic architectures or patterns that result in natural changeability.

272 A research opportunity exists for formalizing the analysis of modularity and other architecture choices within a MATE framework, in terms of how to assess the costs and benefits of the modular approach. Effects on transition rule cost and time, in addition to the cost to initial operating capability should be considered.

272 Ongoing doctoral research by Nirav Shah at MIT will seek to better define “loose couplers” for developing system-of-systems, akin to interface standards for linking systems. The concept of System Mask and Shelter—together the System Shell—may inform such thinking.

274 Further research for proposing general sets of path enablers should be conducted, focused by the changeability framework proposed in this thesis.

281 More study should be done applying the concept of platforming to dynamic MATE case studies, leveraging insights from (Suh 2005).

282 Further work exploring the parallels between path enabling variables and real options should be done.

349 The discussion of completeness and tradespace outdegree convergence is relatively simplistic and would benefit from a rigorous application of real analysis techniques. Concepts such as countably and uncountably infinite sets are readily applicable, as well as convergence and DOE sampling techniques. Given the power of the network model of tradespaces, application of more network theory concepts should be considered as well.

These research ideas are not intended to be complete, but merely the obvious ones suggested by a first reading of the thesis. Many other potential research avenues most certainly exist and are encouraged by the author.

12.3 A Final Word

Dynamic MATE, as developed herein, seems to make progress addressing the motivations outlined in the first chapter. Not only can the precursor MATE work each be seen as special case applications of the generalized dynamic MATE approach, but also system properties, the "ilities," have been defined within a unifying framework for their consideration during Conceptual Design. It is the hope of the researcher that the contributions made in this thesis are extended and deployed to deliver value, both fiscally and pedagogically. It is only when designers have a good grasp of the dynamic flow of value that they can develop truly long-lasting valuable systems. From the mind of the decision maker through a system in its context and back through the eyes of the decision maker, perception of value passes through many phases and transformations. The role of a good designer is not about technical achievement, but about value creation and sustainment.

On a personal note, the concepts introduced in this thesis have had a profound impact on the author's world-view. Change is no longer seen as the enemy of happiness, but as a means for continuous improvement and opportunities for success.

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Notation Glossary

$\{DV^N\}$	Design vector with N elements, in general
N	Number of elements in design variable set, or vector
DV^i	Design variable element i, in general
DV_i	Specific design vector i
DV_1^2	Design vector 1, variable element 2
f_c	Cost function, scalar function
$f_c(\{DV^N\})$	Cost function, maps $\{DV^N\} \rightarrow C$
f_c^{-1}	Inverse cost function: ill-defined, Design Process
C	Cost scalar
$\{X^M\}$	Attribute set with M elements, in general
$\underline{X}$	Attribute vector (same as set)
X^i	Attribute element i, in general
X_i	Specific attribute set i
X_1^2	Attribute set 1, attribute element 2
$\{R^K\}$	Rule set with K rules, in general
K	Number of rules in rule set, (also different definition, see below
R^k	Rule k
$R^k(DV_i \rightarrow DV_j)$	Rule k, connecting DV_i to DV_j
F_{XM}	Attribute function, vector function. System Simulation
$F_{XM}(\{DV^N\})$	Attribute function, maps $\{DV^N\} \rightarrow \{X^M\}$
F_{XM}^{-1}	Inverse attribute function, ill-defined, Goal Process
f_U	Utility function, scalar function
$f_U(\{X^M\})$	Utility function, maps $\{X^M\} \rightarrow U$
$U^i(X^i)$	Single attribute utility function on attribute X^i
$U(\underline{X})$	Multi-attribute utility function, MAUF, on attribute set $\underline{X}$
U	Utility scalar, either single or multi-attribute derived
k_i	MAUF weight for attribute X^i
K	MAUF normalization constant (not same as size($\{R^K\}$))
T_{ijk}	Transition matrix, elements "cost" of $DV_i \rightarrow DV_j$ using R^k
${}_i\Delta_j$	Difference operator: state i to state j
n	Number of nodes in tradespace network, also enumeration size
m	Number of arcs in tradespace network
D^i	Number of values of DV^i enumerated, complete
d^i	Number of values of DV^i enumerated, actual
$\mathcal{D}$	Span of $\{DV^N\}$, same as set $\{DV^N\}$
$\mathcal{d}^k$	Subset of $\{DV^N\}$ to which R^k applies
α^k	Theoretical fraction of tradespace accessible through R^k
$\bar{\alpha}^k$	Actual measured fraction of tradespace accessible through R^k
OD^k	Theoretical outdegree due to R^k
$\overline{OD}^k$	Actual measured outdegree due to R^k
$\hat{C}$	Cost threshold for acceptable changeability

$\hat{t}$	Time threshold for acceptable changeability
$OD(<C,t)$	Outdegree function
$OD(<\hat{C},\hat{t})$	Filtered outdegree

<u>Example</u>

Let a design vector = {num sats, altitude}
$\{DV^N\} = \{DV^1, DV^2\}$, where DV^1:num sats, DV^2:altitude
DV_4 = {3 sats, 1150 km}, is a specific design vector, and DV_4^2=1150

Let an attribute set = {coverage, latency}
$\{X^M\} = \{X^1, X^2\}$, where X^1:coverage, X^2:latency
X_6 = {80%, 30 min}, is a specific attribute set, and X_6^1=80%

Appendix A: Pre-interview Survey

Assessing Usage of System Property Metrics during Conceptual Design Trade Studies

ID#_____

- **PURPOSE OF THE STUDY**

This survey is designed to assess whether system properties are addressed during Conceptual Design trade studies and the applicability of MIT's Engineering System Division definitions of system properties. It is intended as a precursor to a follow-up interview that will investigate more fully the Conceptual Design trade study process.

- **PARTICIPATION AND WITHDRAWAL**

Your participation in this study is completely voluntary and you are free to choose whether to be in it or not. If you choose to be in this study, you may subsequently withdraw from it at any time without penalty or consequences of any kind. You may decline to answer any or all questions. Your identity will only be used in preparation for a follow-up interview. Your confidentiality is assured.

The definitions given below are directly or derived from the Massachusetts Institute of Technology (MIT) Engineering Systems Division (ESD) working paper ESD-WP-2002-01: ESD Terms and Definitions (Version 12).

Please read the following definitions and questions, marking your choice with an 'X' on the 1 to 5 scale.

12.4 Flexibility

Flexibility is defined as *"the property of a system that is capable of undergoing classes of changes with relative ease. Such changes can occur in several ways: a system of roads is flexible if it permits a driver to go from one point to another using several paths. Flexibility may indicate the ease of 'programming' the system to achieve a variety of functions. Flexibility may indicate the ease of changing the system's requirements with a relatively small increase in complexity and rework."*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.5 Agility

Agility is *the ability of a system to be both flexible and undergo change rapidly*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.6 Robustness

Robustness is defined as *"the demonstrated or promised ability of a system to perform under a variety of circumstances, including the ability to deliver desired functions in spite of changes in the environment, uses, or internal variations that are either built-in or emergent."*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.7 Fail-safe

Fail-safe is *the ability to be guided to a safe state, if the system cannot deliver the full desired function due to failure(s).*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.8 Adaptability

Adaptability is defined as *"the ability of a system to change internally to fit changes in its environment," usually by self-modification to the system itself.*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.9 Scalability

Scalability is *the ability of a system to maintain its performance and function, and retain all of its desired properties when its scale is increased greatly without having a corresponding increase in the system's complexity.*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.10 Modularity

Modularity is *the degree to which the components of a system can be designed, made, operated, and changed independently of each other.*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.11 Safety

Safety is *the property of being free from accidents or unacceptable losses.*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.12 Durability

Durability is *the ability to deliver a specified level of function for a specified length of time.*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.13 Sustainability

Sustainability has two scopes: *Broad: maintaining economic growth and viability while meeting concerns for environmental protection, quality of life, and social equity; narrow: a property of an engineering system having optimal resource preservation and environmental management over time.*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.14 Quality

Quality is *the ability to deliver requirements at a "high" level, as perceived by people relative to other alternatives that deliver the same requirements.*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.15 Reliability

Reliability is *the probability that a system or component will satisfy its requirements over a given period of time and under given conditions.*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.16 Reparability

Reparability is *the ability to be returned to the original state of function when some function is lost.*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.17 Maintainability

Maintainability is *the ability of a system to be kept in appropriate operating condition; the system should also possess the property of reparability.*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.18 Manufacturability

Manufacturability is *designing for ease of manufacturing, which is the processes by which materials are made, parts or components are fabricated from materials, and products are assembled from parts; software is implemented rather than manufactured*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.19 Testability

Testability is *designing for ease of component and system testing, which is the process by which the components and systems are verified and validated to perform as intended*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.20 Operability

Operability is *designing for ease of system usage in performing desired functions, which includes simplicity in human-machine interfaces, maintainability, and reparability.*						
Q1	*Given above definition, how well is it addressed in Conceptual Design trades?*					
Not at all	1	2	3	4	5	**Very well**
Q2	*Given above definition, how important is it to address in Conceptual Design trades?*					
Not important	1	2	3	4	5	**Very important**

12.21 Comments

Are there any comments you wish to make regarding the questions above?

Are there any issues you wish to discuss during the interview?

Thank you for your participation.

Please return completed survey to adamross@mit.edu or the mailing address below.

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Please feel free to contact the Associated Investigator above if you have any questions or concerns about the research.

Appendix B: Semi-structured Interview

Interview Assessing Aerospace Industrial Practice in Conducting Concept Design Trades Studies

Draft Version 05.27.04a Adam Ross

Semi-structured: Choose ordering as time and interest allow. Skip questions as necessary.

12.21.1 Outline

- Introduction
- Trades
- Stakeholders
- Metrics
- Constraints
- Modeling
- Flow
- Conclusion

12.21.2 Introduction

1. Intent of interview?
2. About me (Background)
3. About you
    a. Job title
    b. Years experience in field
    c. Number of trade studies/projects participated in <Ranges?>
        i. Names of projects?
        ii. Scale/scope/success?

12.21.3 Trades

1. Is there a formal process for tradespace exploration?
    a. Yes: what is it?
    b. No: how is process developed?
        i. Autonomy – experience-based?
        ii. Structure
        iii. Repeatability
        iv. Documentation
2. How much of a tradespace is explored?
    a. Point design
    b. Optimal set design
    c. DOE

12.21.4 Stakeholders

1. For whom are the designers designing the system?
    a. Is there a formal representation of system stakeholders?
    b. How are stakeholder needs represented?

        i. Requirements
        ii. Utility function
        iii. Other
2. What is composition of team (from org and technical perspectives)?
    a. What technical disciplines are represented in trade study?
    b. Who creates trade models?
    c. Who runs trade models?
    d. Who makes decisions based on trade results?
3. How are decision-makers included in process?
    a. How are models selected?
    b. How are team participants selected?
    c. How are concepts selected?
    d. How are stakeholder needs verified against system performance?
    e. When are decisions made?

12.21.5 Metrics

1. What are the metrics utilized for determining **value**?
    a. Is there a formal definition for value?
        i. Yes: what is it?
        ii. No: how is value defined?
            1. Autonomy – experience-based?
            2. Consistency?
2. How is **utility** addressed?
    a. Value metric?
3. How is **uncertainty** addressed?
    a. Definition
    b. How addressed?
        i. Representation
        ii. Effect on metrics
4. How is **risk** addressed?
    a. Definition
    b. How addressed?
        i. Representation
        ii. Upside v. downside
        iii. As metric?
5. <u>System Properties</u>: How are "ilities" addressed?
    a. Follow-up from pre-interview survey

12.21.6 Constraints

1. What is a typical schedule for tradespace exploration?
    a. How much time is allocated to concept exploration? (alternative generation)
    b. How much time is allocated to conceptual design? (low fidelity system/performance estimation)
    c. Does the schedule limit the extent/depth of tradespace exploration?
2. What are constraints for such analysis? (dollars, politics, process, etc)
    a. Are models computationally constrained?

b. Is tradespace exploration limited by available person-hours?
c. By politics? (e.g. options not considered)
d. Does the development process itself limit tradespace exploration?

12.21.7 Modeling

1. What level of fidelity is utilized?
    a. How is model fidelity determined?
    b. How are model assumptions matched?
    c. How are models updated in light of new information?
2. How is analysis verified?
    a. How are model output verified?
    b. How are analysis results verified against previous analyses?
3. How is analysis validated?
    a. How are model and analysis assumptions validated?
    b. How is analysis validated against true needs of stakeholders?
    c. How are analysis results validated against existing systems?
4. What tools are utilized for modeling?

12.21.8 Flow

1. Where does tradespace knowledge go after complete?
    a. How does tradespace knowledge flow to downstream system development?
    b. How does downstream development flow back into conceptual design?
        i. Models (fidelity improvement?)
        ii. Process
        iii. Knowledge
        iv. Tools
    c. How are tradespace studies reused in new studies?
        i. Models
        ii. Process
        iii. Knowledge
        iv. Tools
        v. They're not
2. How are studies perceived by rest of organization?
    a. Is there "buy-in" from down-stream stakeholders into analysis
    b. How much of analysis is redone downstream?
    c. Are concepts brought to fruition?

12.21.9 Conclusion

1. What issues are most important for inclusion in conceptual design trade studies?
2. What issues do you think cannot be included in conceptual design and why?
3. Suggestions
    a. People
    b. Issues
    c. Research
    d. Etc

Appendix C: Epoch Template

Epoch name:	X-TOS Initial operating scenario	Modified: 10.04.05
Similar to:	N/A	
Epoch duration:	Five years, or until system context change	
Epoch goal:	Find maximum utility design at $S_{i,e}$	

Constraints

Resource: Must spend less than $100M over 5 years
Political: Must not use foreign launch vehicle
Market: N/A
Physical: Must use
Operational: Must provide less than 5 Gbps downlink data rate
Other: Must have a catchy acronym

Constants

Constant variable set, {*CON*}:
Controllable:
Uncontrollable:

Preference-space

Decision Maker set, {DM)}: User
Number of DM, size({DM}): 1

For Decision Maker i

Attribute set$_i$, {X^{Mi}}: {Data Lifespan, Latitude Diversity, Equator Time, Latency, Sample Altitude}
Attribute Priorities, {k^{Mi}}: [0.3,0.125,0.175,0.1,0.425]
Single att utility curves, $U^j(X^j)$: See attached
Multi-att utility function, $f_U(k_j,U^j)$: MAUF
Changeability Cost threshold, $\hat{C}$: 50$M
Changeability Time threshold, $\hat{t}$: Depends 30 min short term, 6 mos long term

Design-space

Design variable set, {DV^N}: {Inclination, Apogee Altitude, Perigee Altitude, Communication Arch, Total DeltaV, Propulsion Type, Power Type, Antenna Gain}
Baseline design, DV_{base}: None; new design
Path-enabling variable set, {IV^P}: None; changeability not considered
Transition rule set, {R^K}: R1: Plane Change (Adapt), R2: Apogee Burn (Adapt), R3: Perigee Burn (Adapt), R8: Add New Sat (Flex)
Cost function, $f_C(CON,DV,IV)$: SMAD CERs

Model-space

Model to be used, $F_{XM}(CON,DV,X)$: 16.89 developed X-TOS code version 1.1

Appendix D: Single Decision Maker Experiments Results

This Appendix contains the results of the single decision maker computer experiments discussed in Chapter 7. For an outline of the experiments, please refer to section 7.1.1.3, "Experiments Outlined."

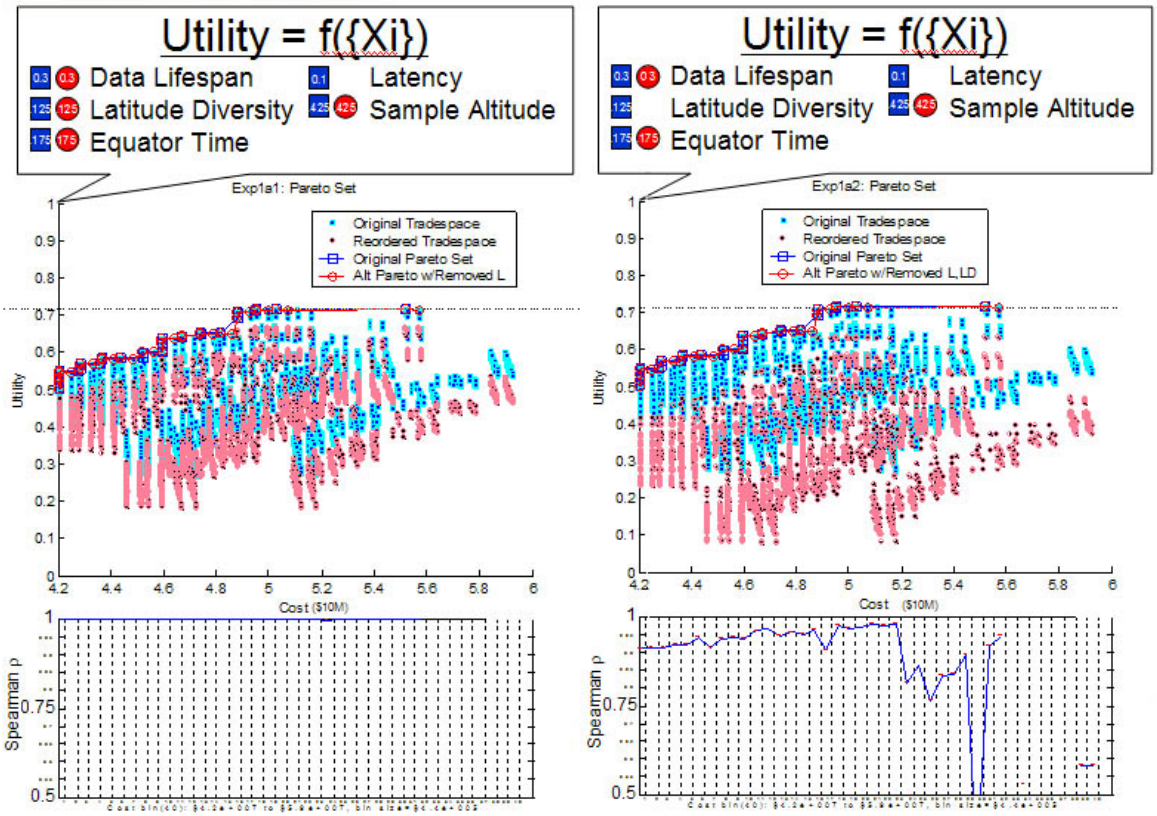
Experiment 1a: Major change case

Exp1a:	1	2	3	4	5	6	7
DL	0.3	0.3	0.3			0.3	0.3
LD	0.125				0.125	0.125	0.125
ET	0.175	0.175			0.175	0.175	0.175
L					0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425	0.425	0.425
SM						0.2	

Figure 214 Exp1a runs: varying attribute sets

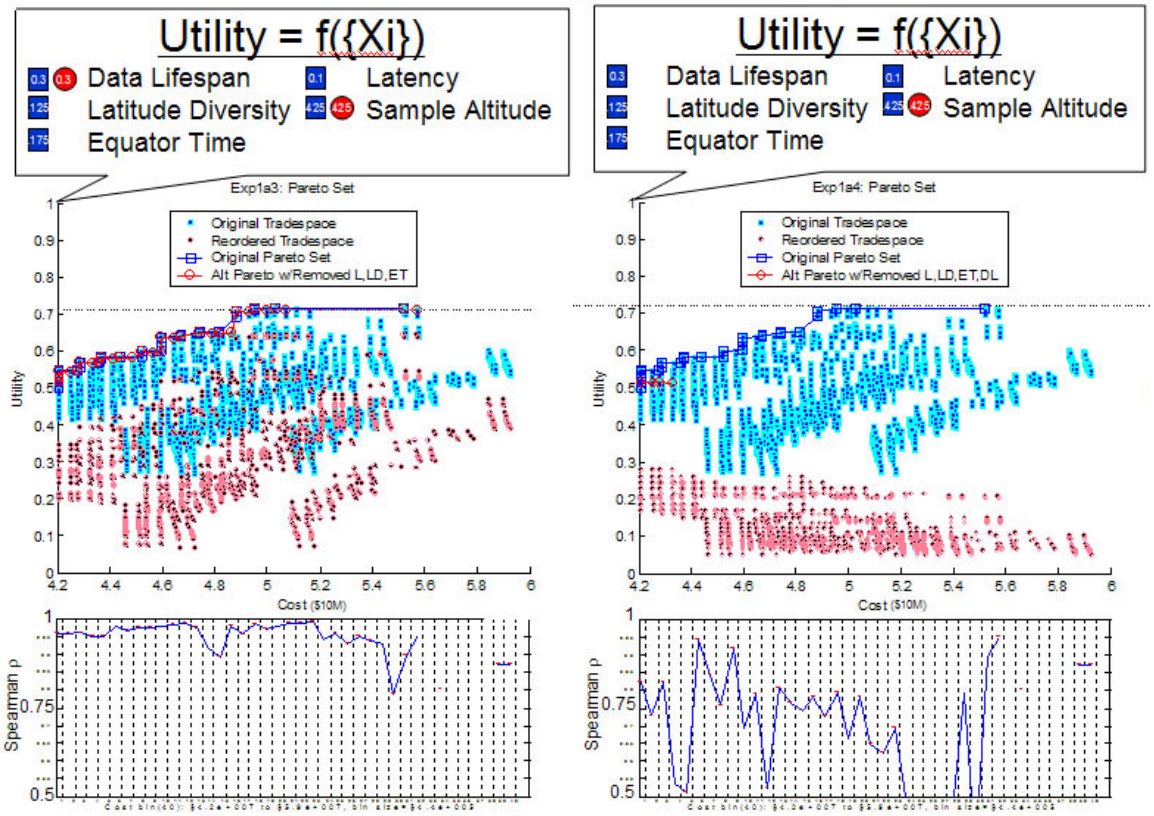
Experiment 1a varied the attribute set as shown in Figure 214 and the results of this experiment are shown in Figure 215 through Figure 217 below. The original tradespace is shown in small blue boxes, with the reordered tradespace shown in small red circles. The components of the attribute set for each tradespace is shown above, and the Spearman's Rho statistic is plotted along the bottom. In order to get a sense of the Spearman statistic, the maximum and minimum Spearman values are included, as is the size of the Pareto Set. (Note: cost bins that do not have a Spearman value shown have fewer than 10 items and the statistic is not valid and has been excluded.[258])

[258] See Spaulding. Tools for Evolutionary Acquisition: A Study of Multi-attribute Tradespace Exploration (MATE) Applied to the Space Based Radar (SBR). for discussion on Spearman Rho statistic applied to tradespace comparisons and statistical validity.



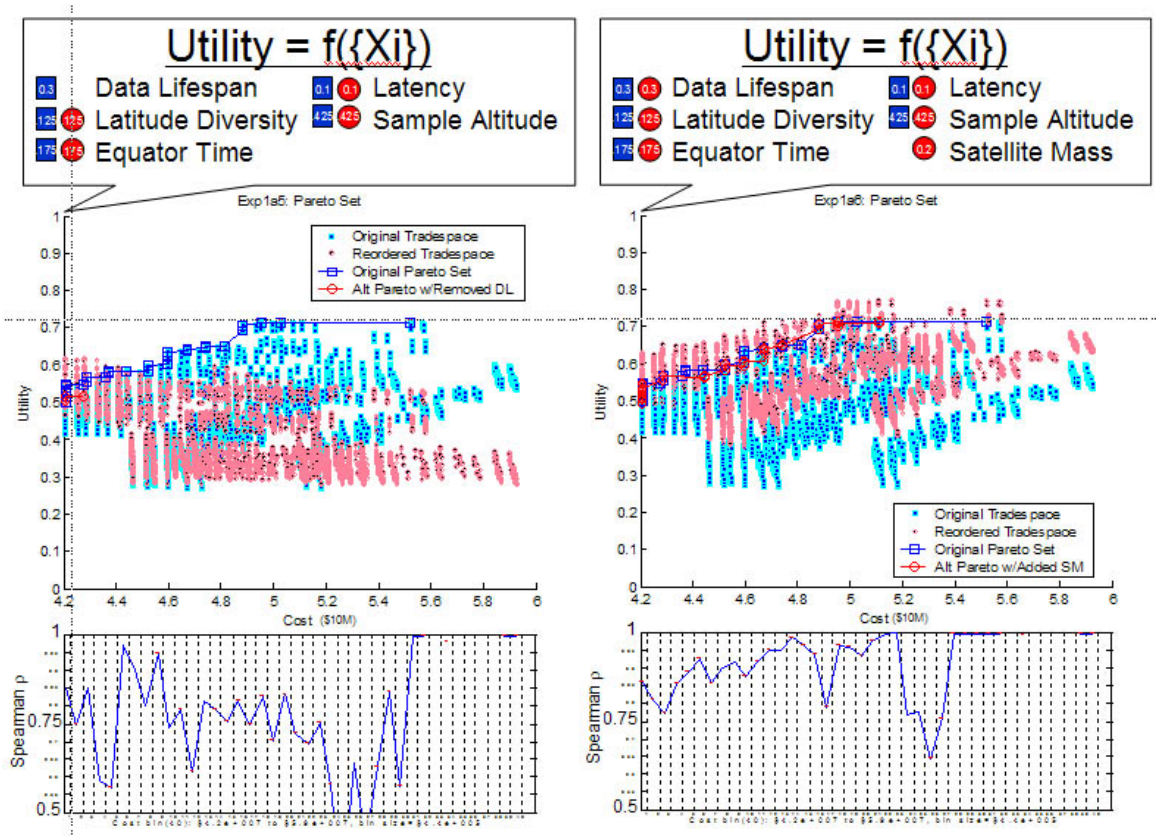
Max Spearman	1.0	Max Spearman	0.9806
Min Spearman	0.9985	Min Spearman	0.3367
Size Pareto Set	47	Size Pareto Set	35

Figure 215 Exp1a results: tradespace shifts, Spearman Rho statistic, and Pareto Set size (runs 1 and 2)



Max Spearman	0.9915	Max Spearman	0.9525
Min Spearman	0.7904	Min Spearman	0.1936
Size Pareto Set	31	Size Pareto Set	4

Figure 216 Exp1a results: tradespace shifts, Spearman Rho statistic, and Pareto Set size (runs 3 and 4)



Max Spearman	0.9976	Max Spearman	0.9995
Min Spearman	0.2983	Min Spearman	0.6435
Size Pareto Set	4	Size Pareto Set	42

Figure 217 Exp1a results: tradespace shifts, Spearman Rho statistic, and Pareto Set size (runs 5 and 6)

Looking at the changes in the tradespace begs the question of how to select a design in the original tradespace that still delivers value in the reordered tradespace. The question is akin to trying to discover value-robust designs in the face of changing preferences. A simple proxy for value robustness is being a part of the Pareto Set. These designs are the maximum utility systems at a given cost. If a design appears in more than one set, it is robust to that particular change. Upon inspection, four designs appear in four or more Pareto Sets. Design id 2471 appears in all seven Pareto Sets, while designs 903, 1687, and 2535 appear in five sets each. Pareto Set tracing is the practice of following designs across tradespace orderings looking for designs "surfing" the best region in all tradespaces. (Both Figure 218 and Figure 219 below show the Pareto Trace.)

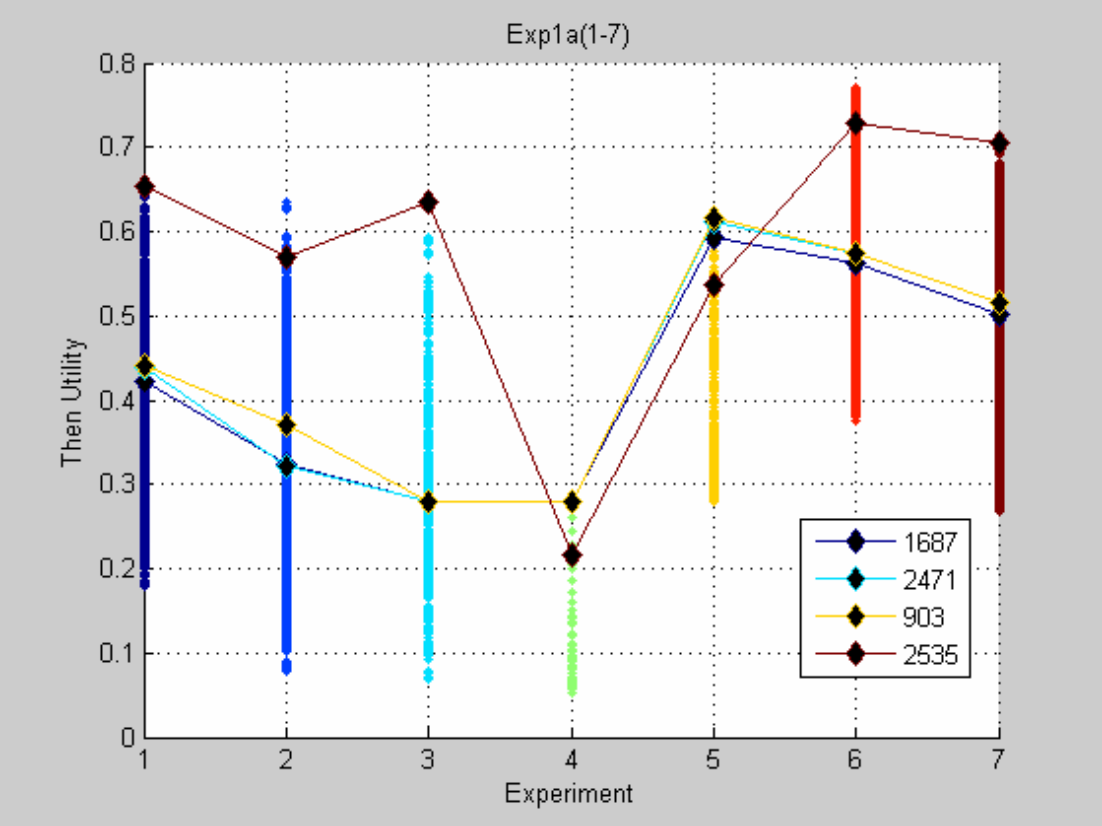


Figure 218 Two dimensional Pareto Set Tracing for Exp1a (Experiment-Utility). Four designs appear in four or more Pareto Sets across the experiments.

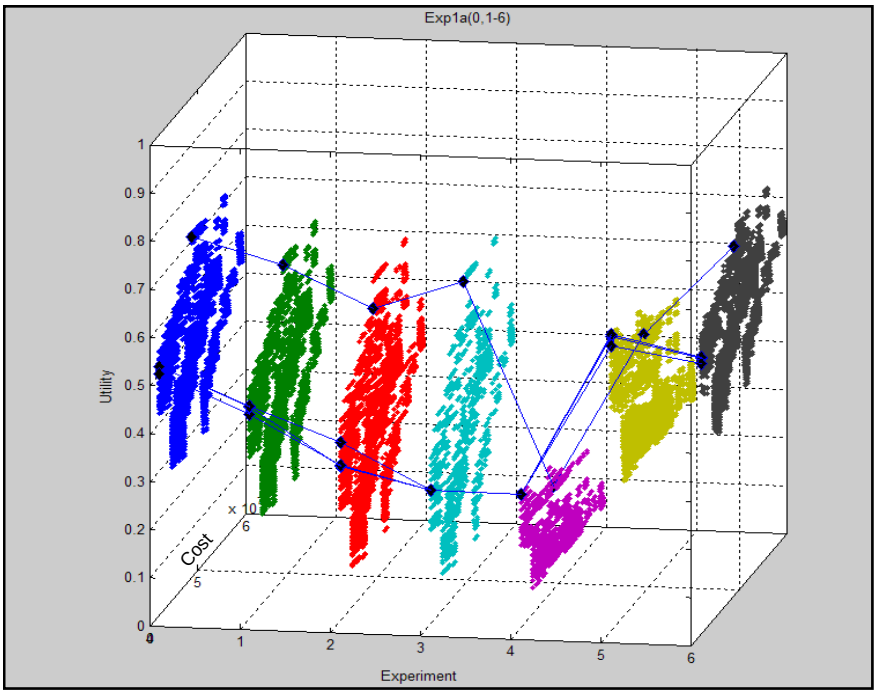


Figure 219 Three dimensional Pareto Tracing for Exp1a (Experiment-Cost-Utility). Exp1a0=Exp1a7 (Original, unaltered preferences)

The concept of Pareto Set tracing can be taken farther by generating Figure 220, which shows the distribution of Pareto Set commonality (Pareto Trace number) versus number of designs. Designs appearing in a large fraction of Pareto Sets are more value robust than other designs. For this experiment, one design appears in 7 sets, none appear at 6, 3 more appear at 5, and 16 appear at 4, as shown in Figure 221 and Figure 222 below.

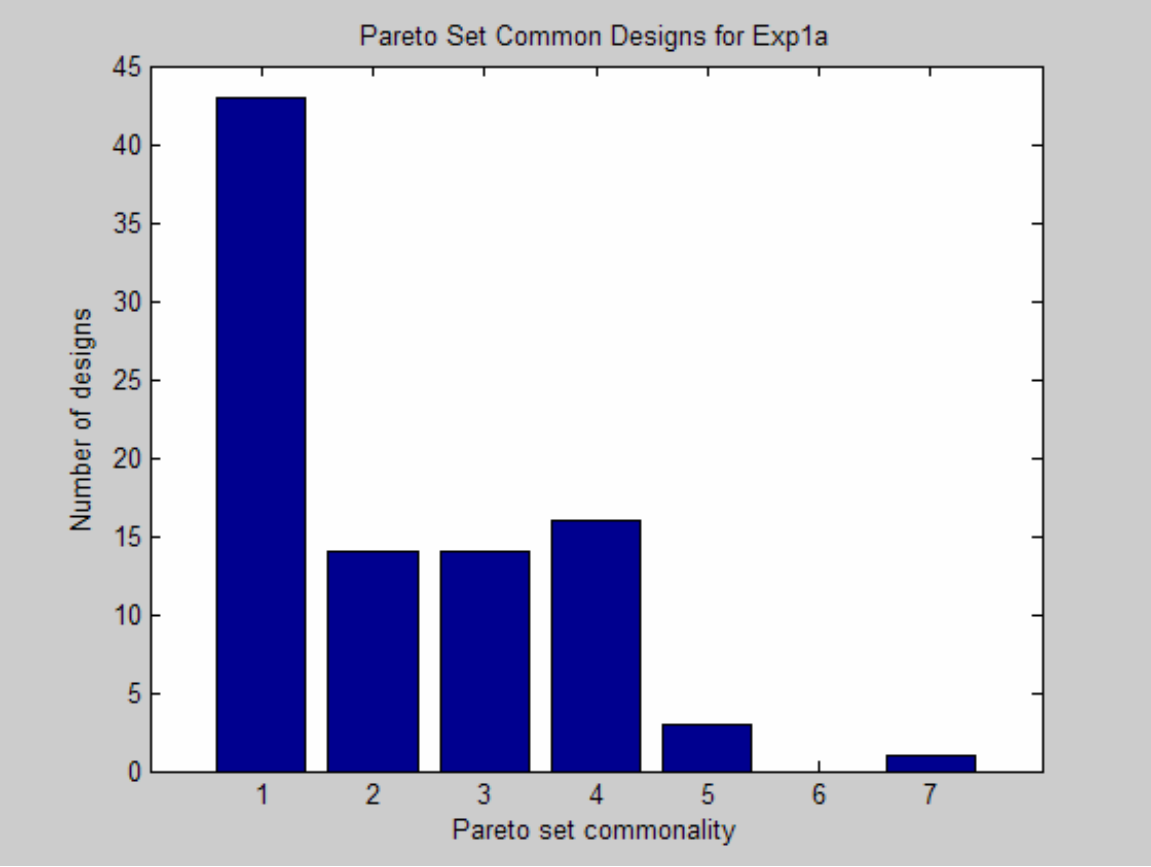


Figure 220 Distribution of Pareto Set commonality (Pareto Trace number) for Exp1a

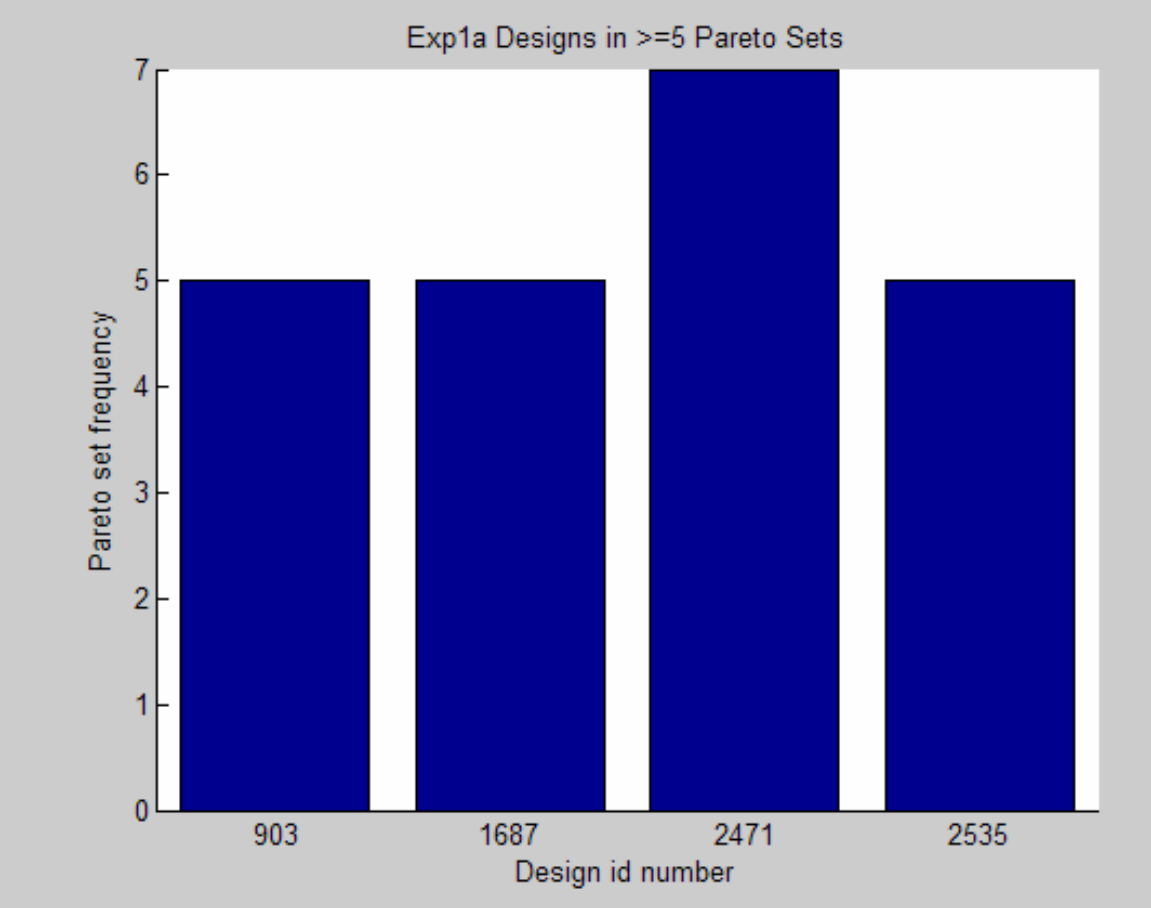


Figure 221 Design ID number versus Pareto Trace number for Exp1a (only Pareto Trace >=5)

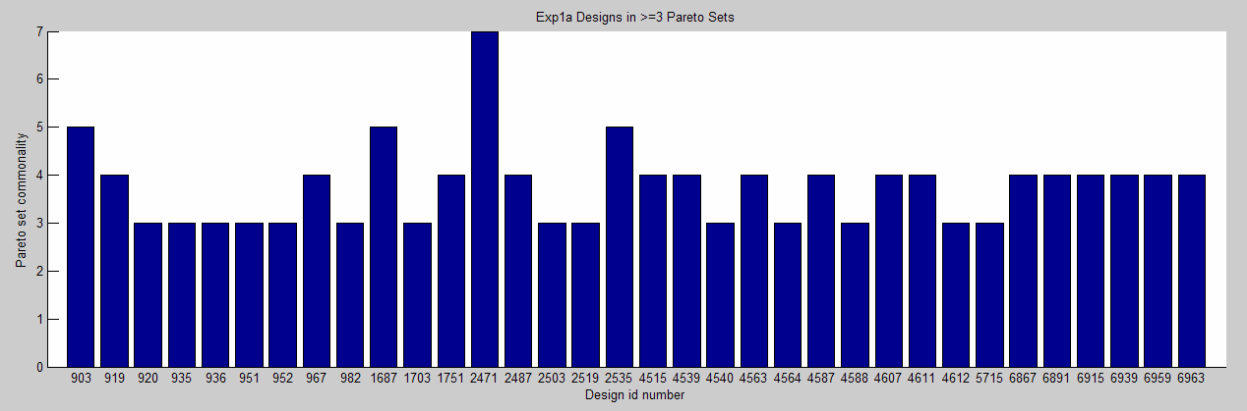


Figure 222 Design ID number versus Pareto Trace number for Exp1a (only Pareto Trace >=3)

After locating the existence of designs that remain value robust, the designer can inspect the particular properties of the designs to look for common features. Figure 223 lists the four value-robust X-TOS designs, highlighting their similarities and differences. More discussion about the reason for robustness is done in Section 7.2, “Discussion.”

DV	2471	903	1687	2535
Inclination	90	30	70	90
Apogee	460	460	460	460
Perigee	150	150	150	290
Com Arch	TDRSS			
Delta V	1200			
Prop Type	Chem			
Pwr Type	Fuel Cell			
Ant Gain	Low			

Figure 223 X-TOS Exp1a robust design variable comparison

Recognizing the properties of value-robust designs may suggest strategies to the designer for achieving the robustness, either through initial design, or through changeability at a later point in time (changing a system to a value-robust configuration may be more cost effective than continually changing a system to maintain high value delivery).

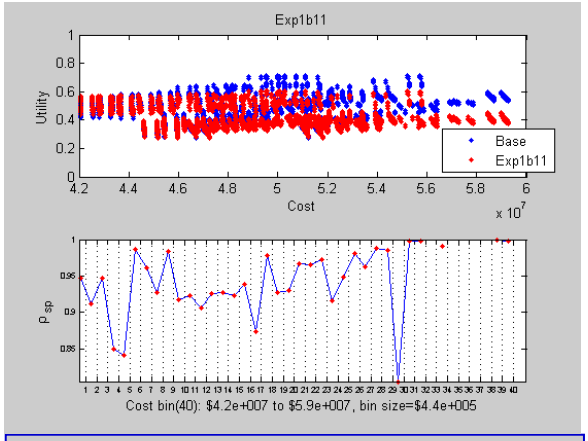
Experiment 1b: Moderate change case

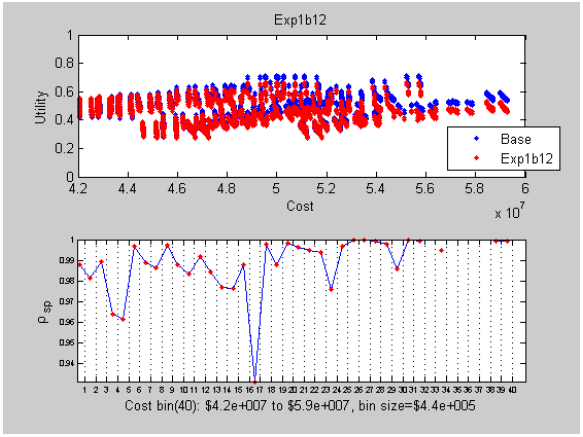
The results of this experiment were surprising in that the Spearman Rho statistic displayed a greater range than in Experiment 1a, meaning that the "Major" and "Moderate" labels should be swapped. While the results of this particular experiment cannot be generalized without further study, it is suggestive that variation in k_i will have a larger effect on value determination than the change of an attribute set.

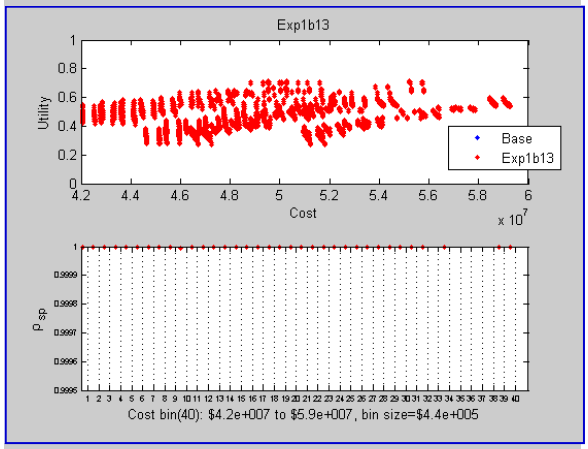
Experiment 1b1 varied the k_i value for Data Lifespan, enumerated in Figure 224, and the resulting tradespaces and Spearman Rho statistics are shown in Figure 225.

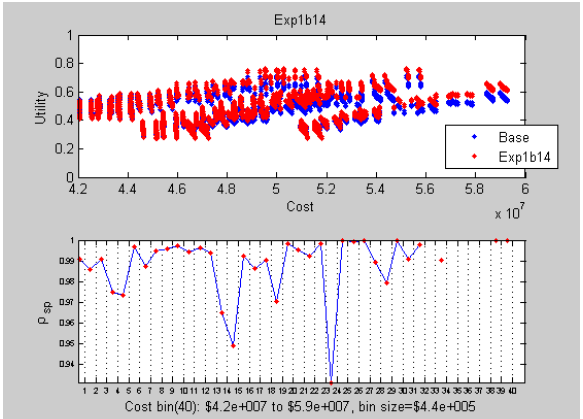
Expb1:	1	2	3	4	5	6	7	8	9
DL	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LD	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175
L	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425
SM									

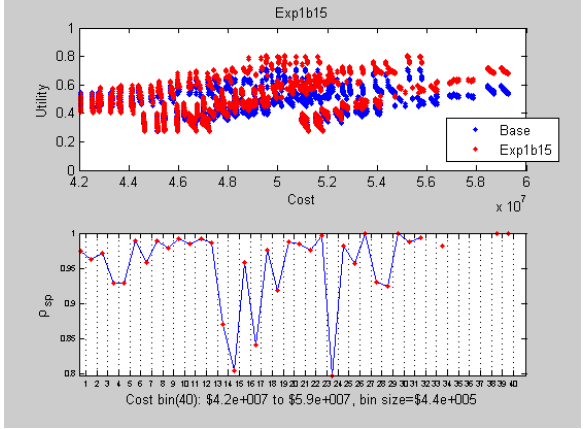
Figure 224 Exp1b1 run enumerations

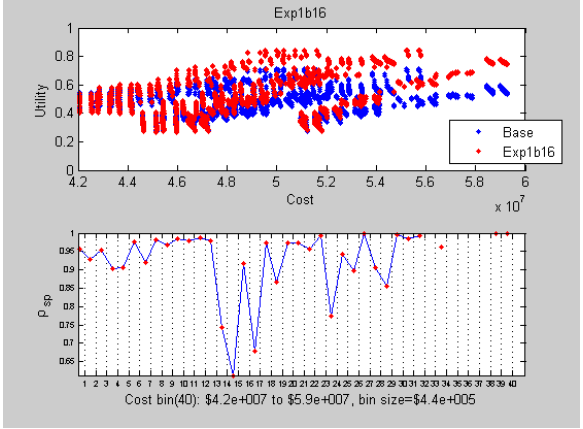

Exp1b11
Utility
Cost
x 10^7
Base
Exp1b11
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005

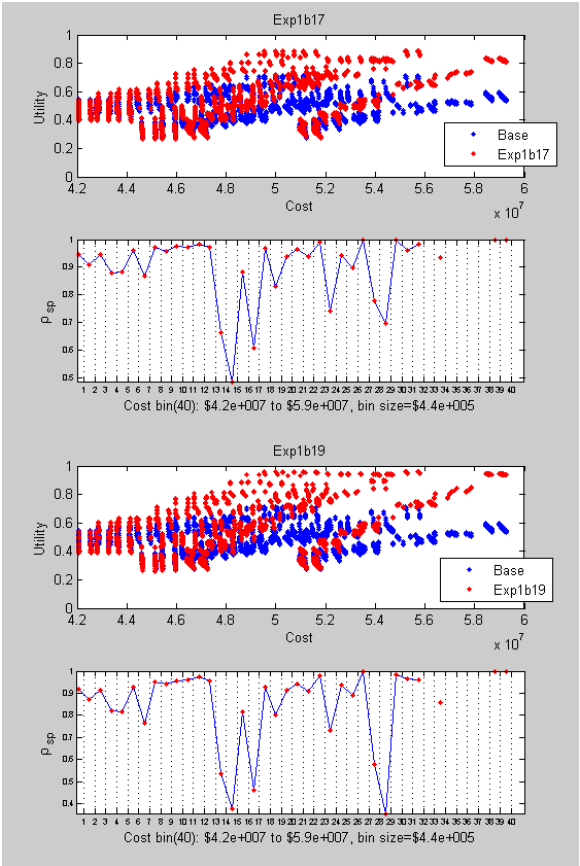

Exp1b12
Utility
Cost
x 10^7
Base
Exp1b12
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b13
Utility
Cost
x 10^7
Base
Exp1b13
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b14
Utility
Cost
x 10^7
Base
Exp1b14
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b15
Utility
Cost
x 10^7
Base
Exp1b15
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b16
Utility
Cost
x 10^7
Base
Exp1b16
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005



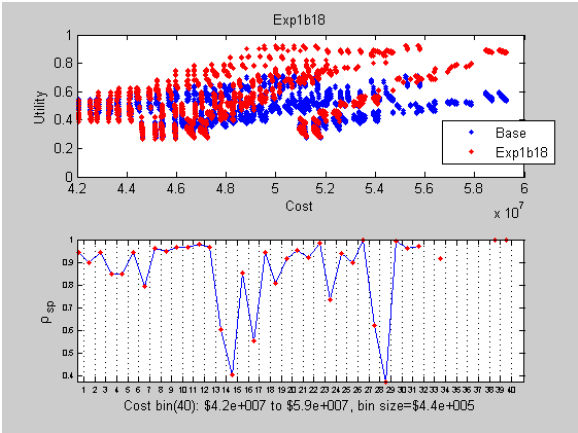
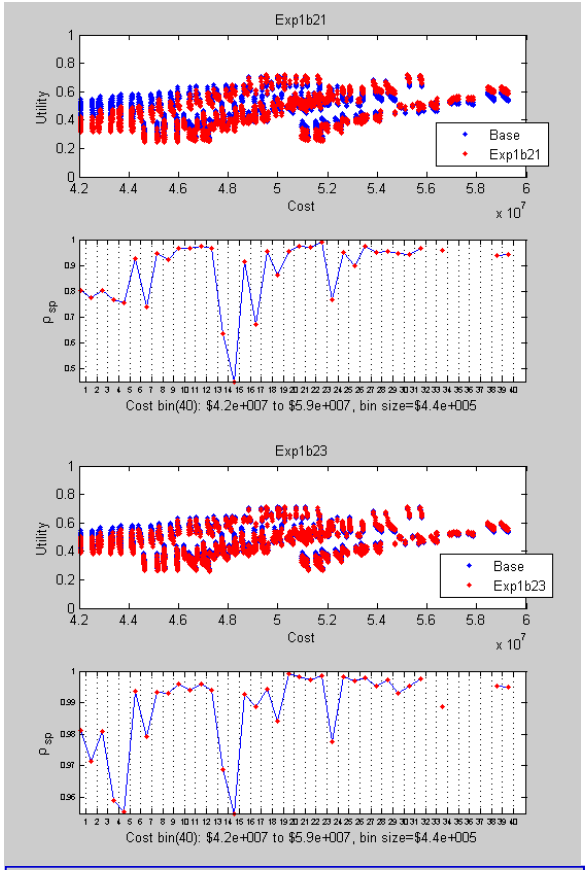


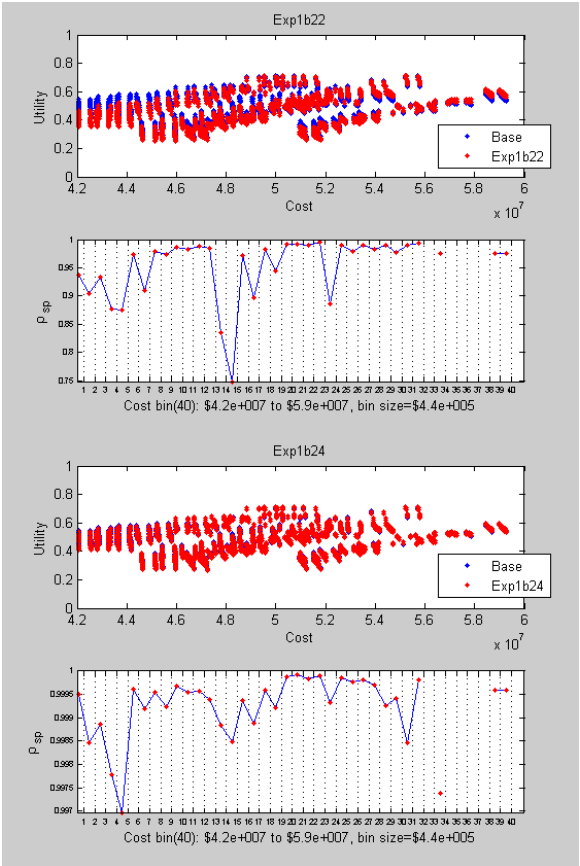
Figure 225 Exp1b1 results: Tradespace shifts and Spearman Rho statistics (runs 1-9)

Experiment 1b2 varied the k_i value for Sample Altitude, enumerated in Figure 226, and the resulting tradespaces and Spearman Rho statistics are shown in Figure 227.

Expb2:	1	2	3	4	5	6	7	8	9	10
DL	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
LD	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175
L	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SA	0.1	0.2	0.3	0.4	0.425	0.5	0.6	0.7	0.8	0.9
SM										

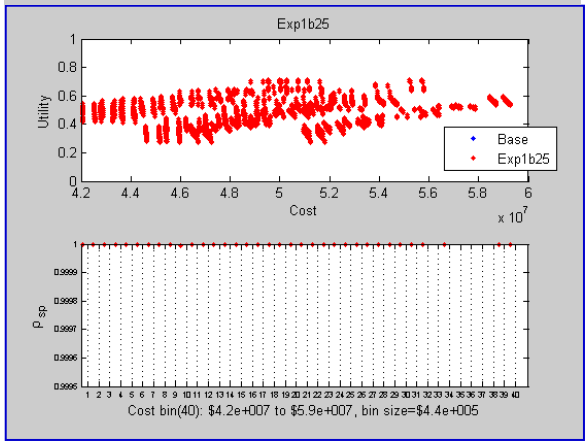
Figure 226 Exp1b2 run enumerations

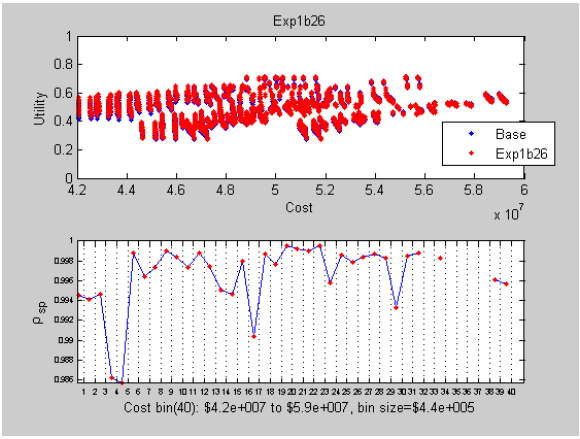

Exp1b21
Utility
Cost
x 10^7
Base
Exp1b21
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b22
Utility
Cost
x 10^7
Base
Exp1b22
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005

Exp1b23
Utility
Cost
x 10^7
Base
Exp1b23
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005

Exp1b24
Utility
Cost
x 10^7
Base
Exp1b24
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b25
Utility
Cost
x 10^7
Base
Exp1b25
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b26
Utility
Cost
x 10^7
Base
Exp1b26
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005

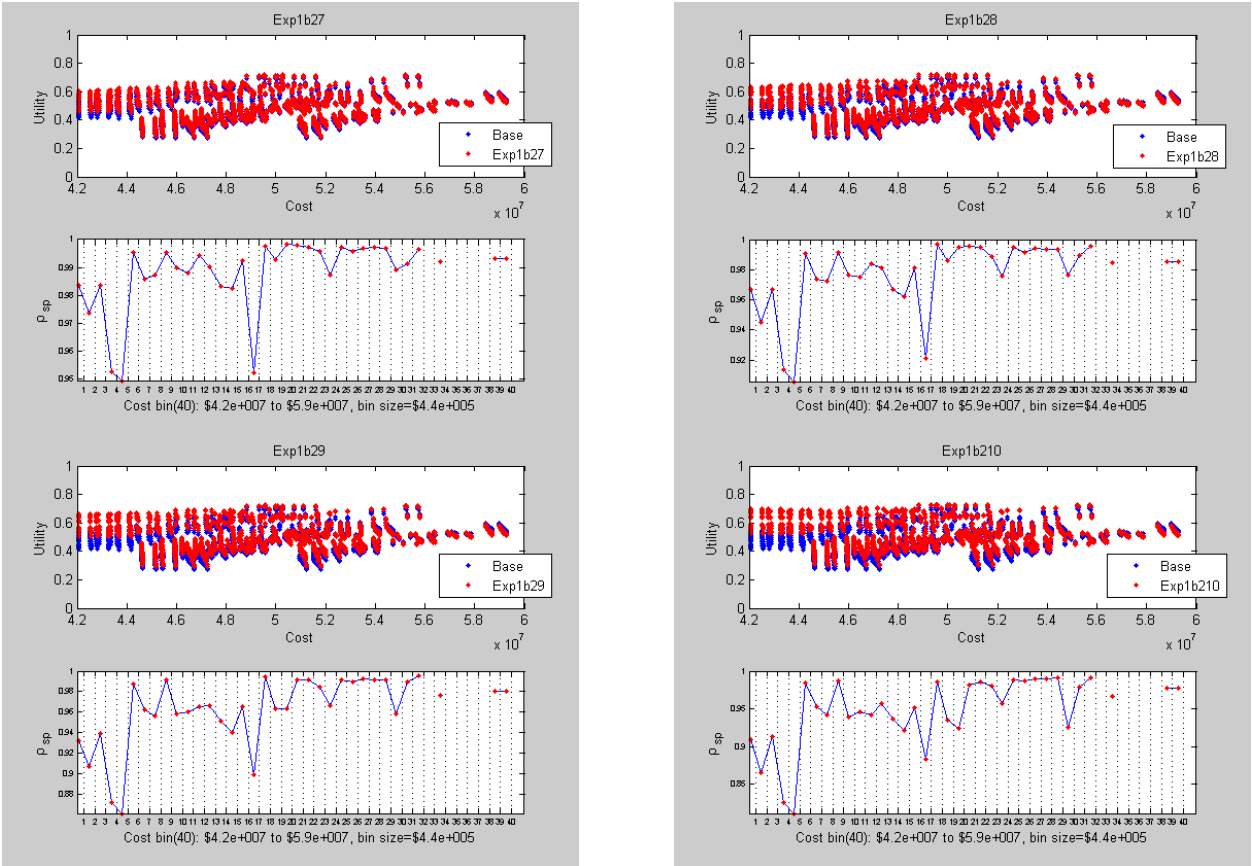
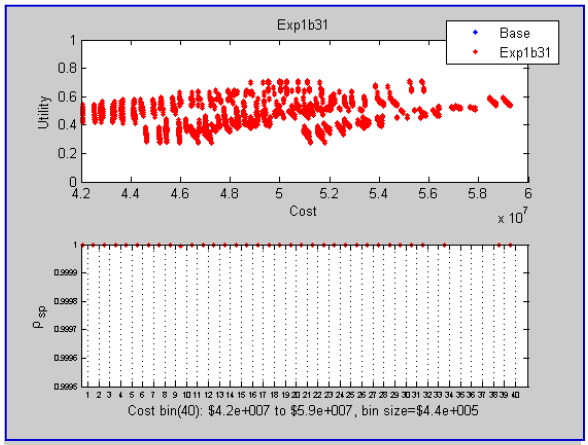


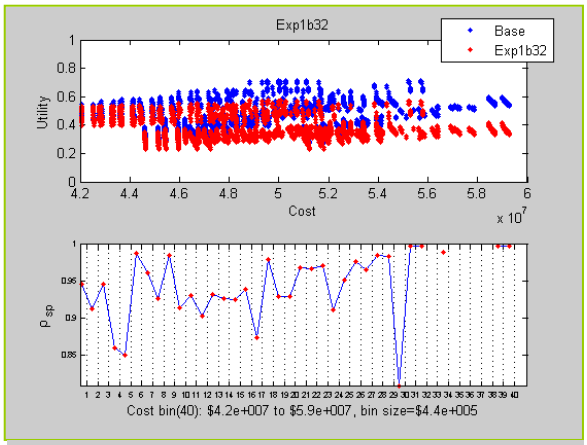
Figure 227 Exp1b2 results: Tradespace shifts and Spearman Rho statistics (runs 1-10)

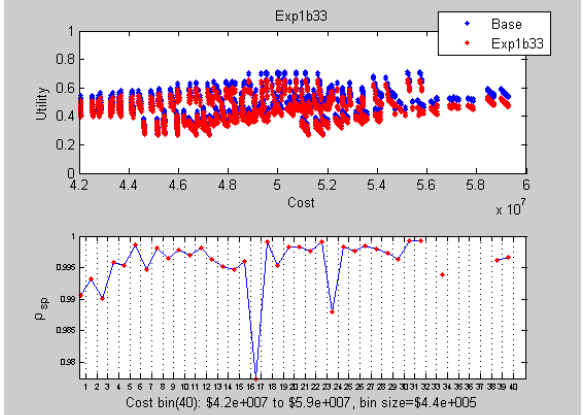
Experiment 1b3 varied the k_i values for both Data Lifespan and Sample Altitude, enumerated in Figure 228, and the resulting tradespaces and Spearman Rho statistics are shown in Figure 229.

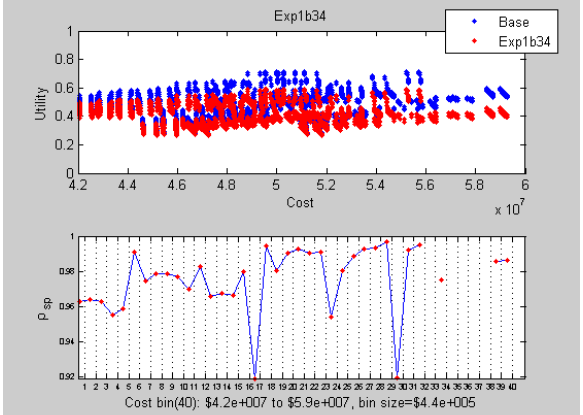
Expb3:	1	2	3	4	5	6	7	8	9	10	11	12	13
DL	0.3	0.1	0.2	0.1	0.4	0.5	0.425	0.4	0.1	0.2	0.1	0.2	0.4
LD	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175
L	0.1	0.05	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.3	0.2	0.3	0.2	0.4	0.1	0.1	0.1	0.3	0.2	0.2
SM													

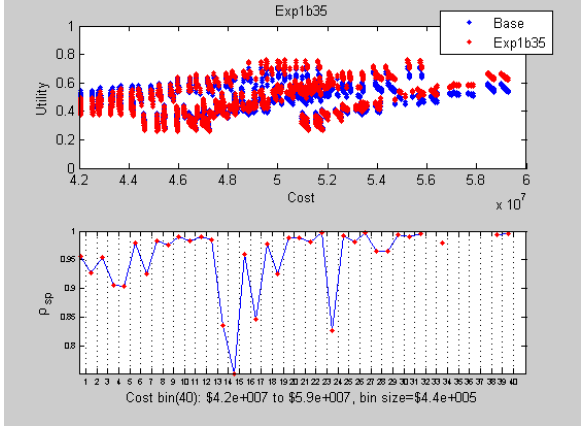
Figure 228 Exp1b3 run enumerations

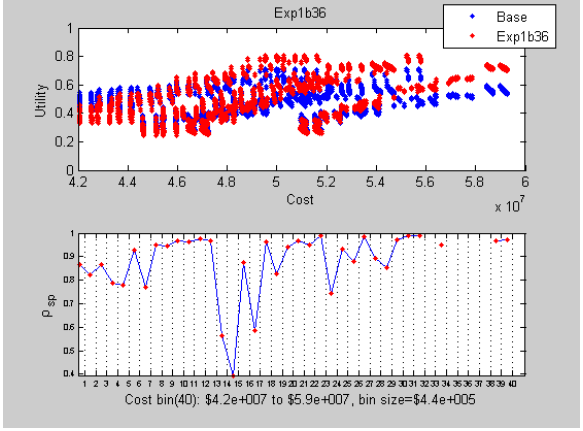

Exp1b31
Base
Exp1b31
Utility
Cost
x 10^7
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b32
Base
Exp1b32
Utility
Cost
x 10^7
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b33
Base
Exp1b33
Utility
Cost
x 10^7
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b34
Base
Exp1b34
Utility
Cost
x 10^7
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b35
Base
Exp1b35
Utility
Cost
x 10^7
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1b36
Base
Exp1b36
Utility
Cost
x 10^7
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005

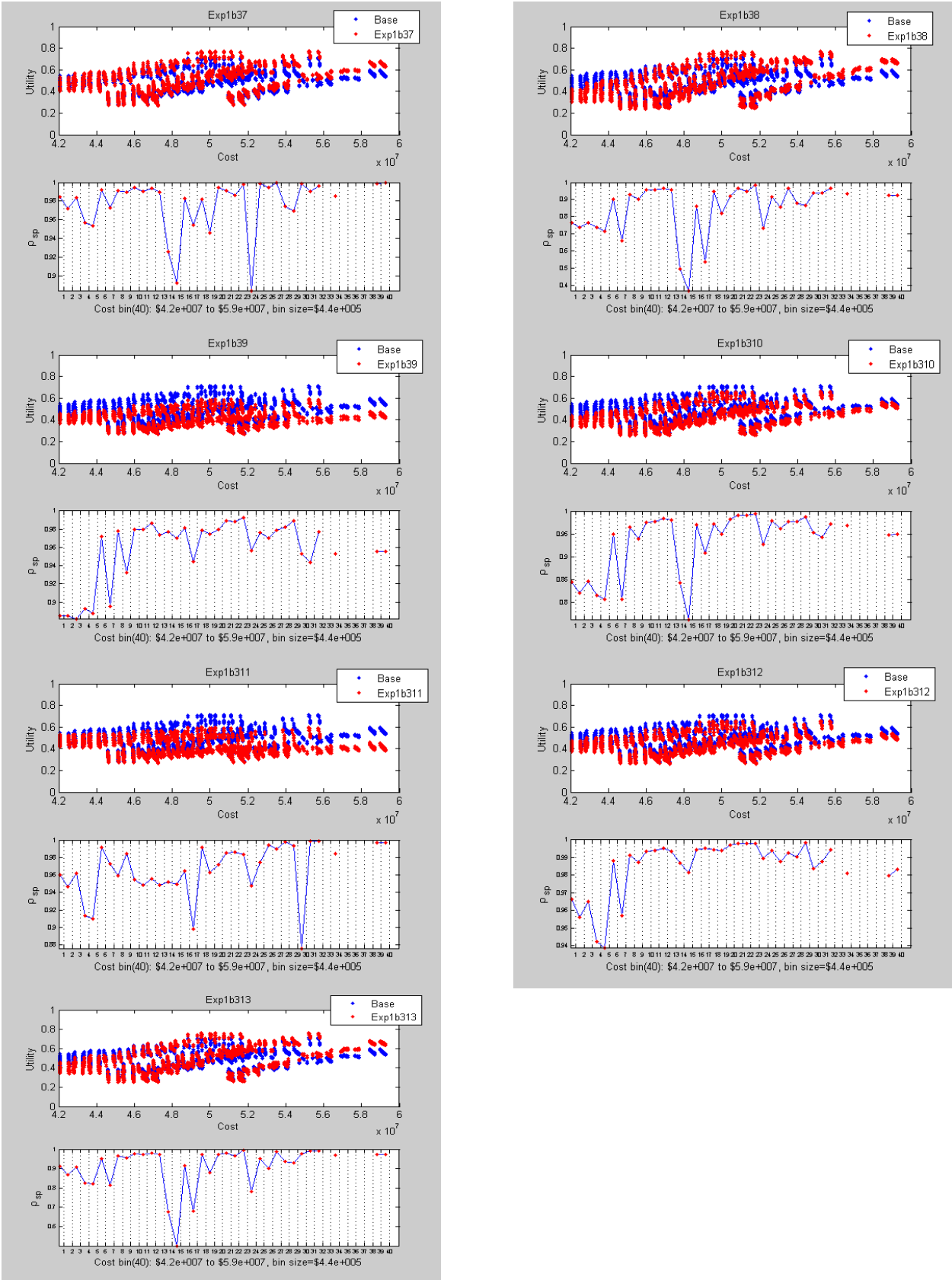


Figure 229 Exp1b3 results: Tradespace shifts and Spearman Rho statistics (runs 1-13)

Pareto Tracing experiment 1b1 reveals 13 designs are in the sets of all 9 cases. 17 more are in the sets of 8 out of 9 cases. Figure 230 shows the distribution of number of designs appearing in different numbers of Pareto Sets. Figure 231 below shows the designs in 9 or fewer Pareto Sets, while Figure 232 below shows the designs in 8 or fewer Pareto Sets. It is interesting to note that designs 2471, 903, 1687, and 2535 all appear in all 9 Pareto Sets. (These designs are then robust to both Experiment 1a and Experiment 1b1 preference variations.)

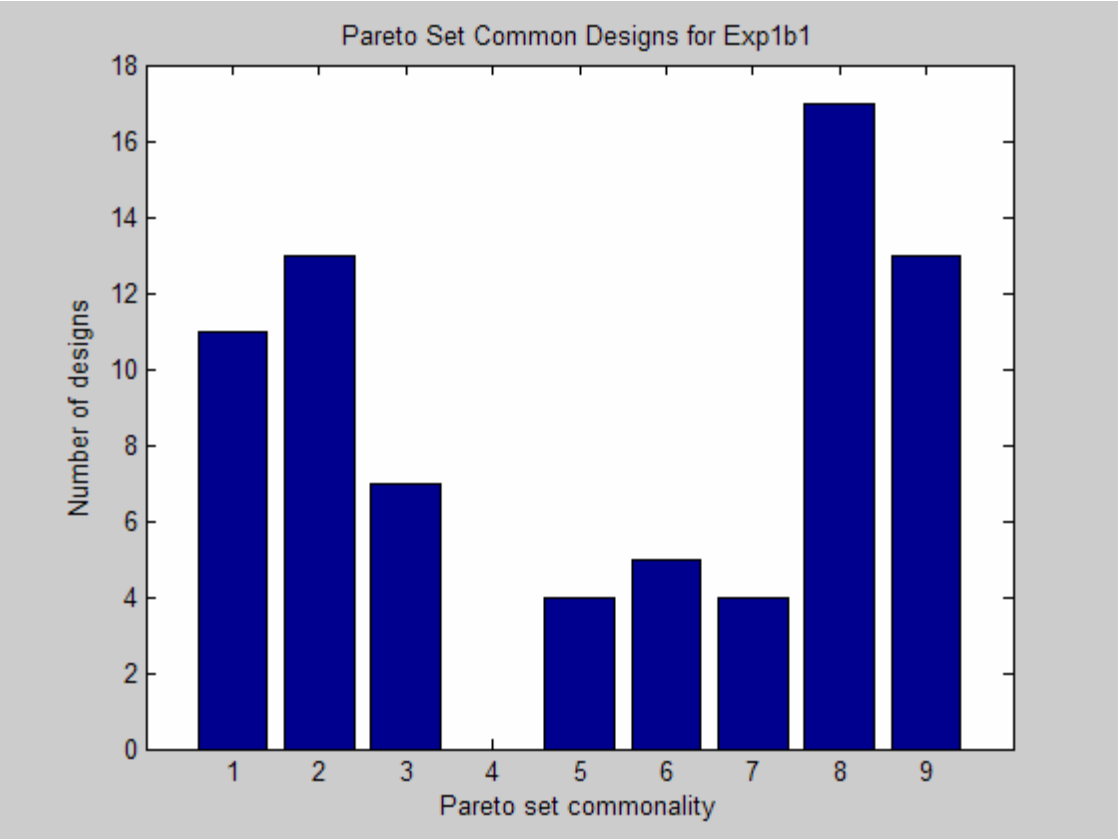


Figure 230 Exp1b1 Pareto Trace number distribution

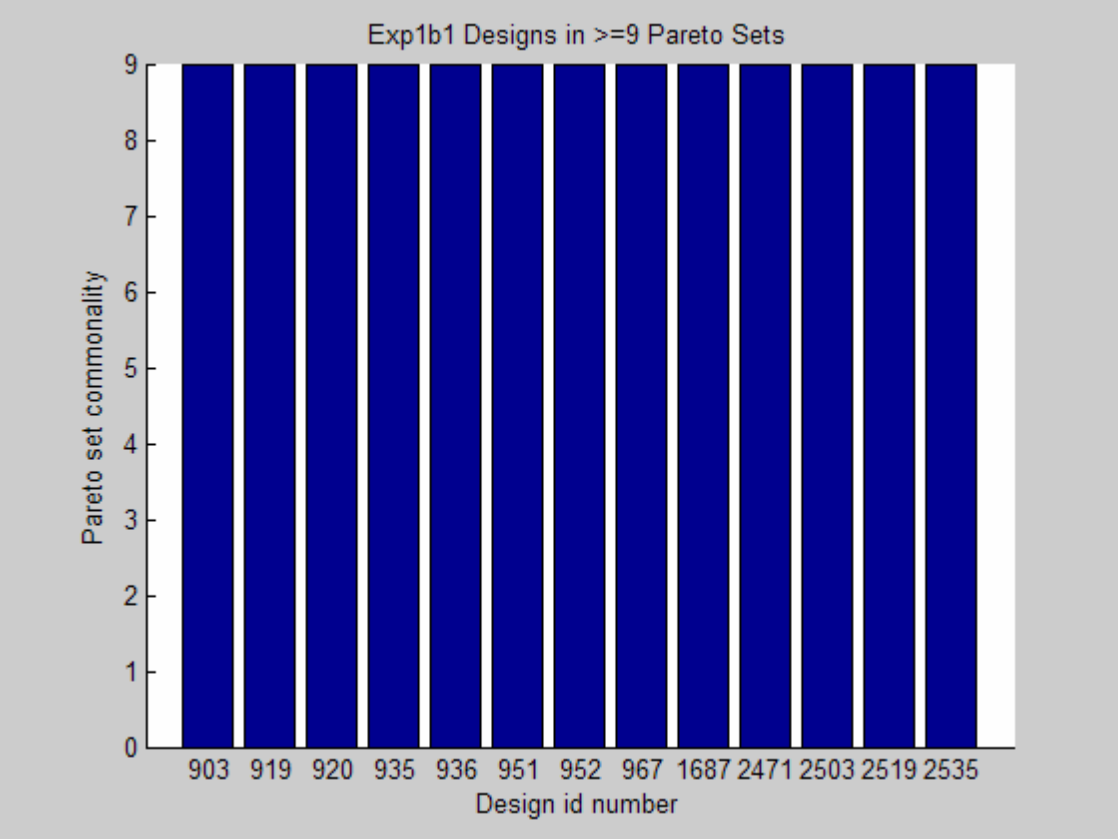


Figure 231 Exp1b1 Design ID number versus Pareto Trace number (Pareto Trace >=9)

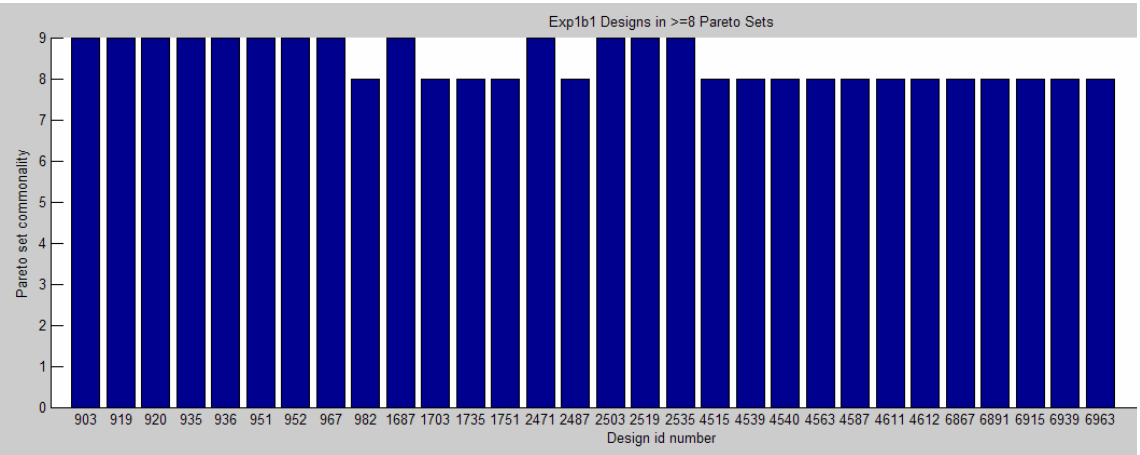


Figure 232 Exp1b1 Design ID number versus Pareto Trace number (Pareto Trace >=8)

Due to the shear number of cases inspected over the three sub-experiments (9+10+13=32), and the volume of charts that could be generated, all of the Experiment 1b data were compared to determine Pareto Traces across all 32 cases. Figure 233 below shows the distribution of number of designs appearing in different numbers of Pareto Sets for all Experiment 1b. 8 designs appear in all 32 Pareto Sets and are shown in Figure 234 below. Again, all four designs, 2471, 903, 1687, and 2535 appear in all 32 Pareto Sets, showing that these designs are in fact robust to preference variations in Experiment 1a and Experiment 1b.

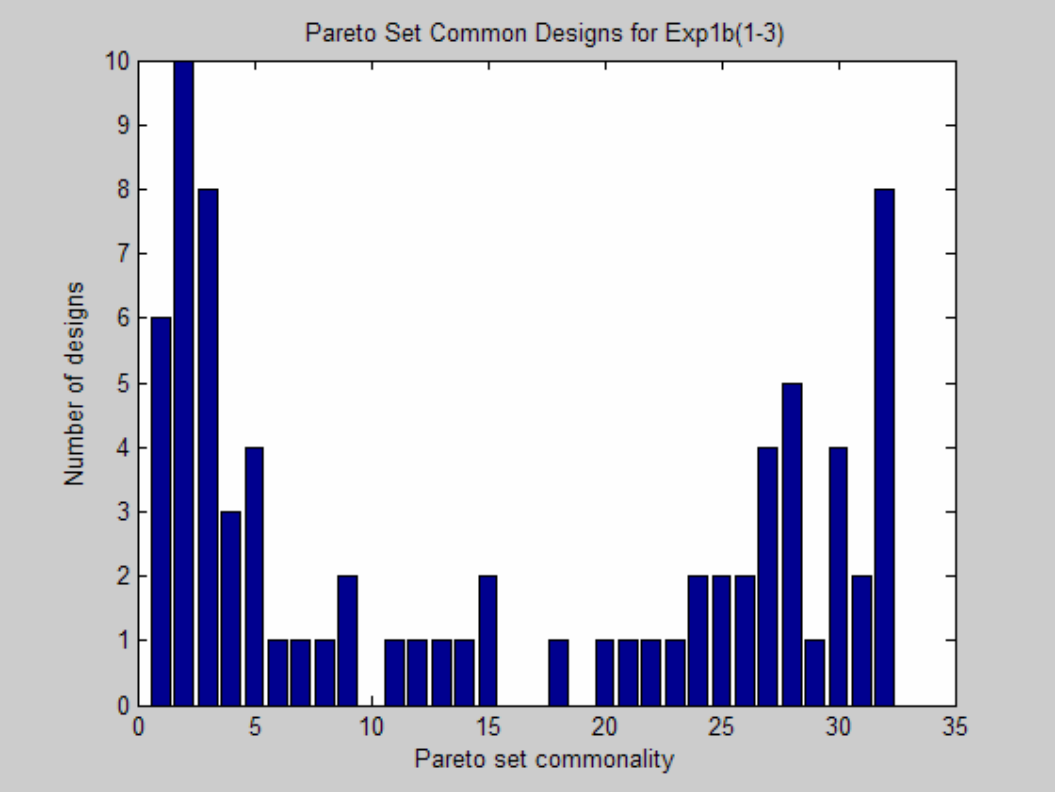


Figure 233 Pareto Trace number distribution across all Exp1b (1-3)

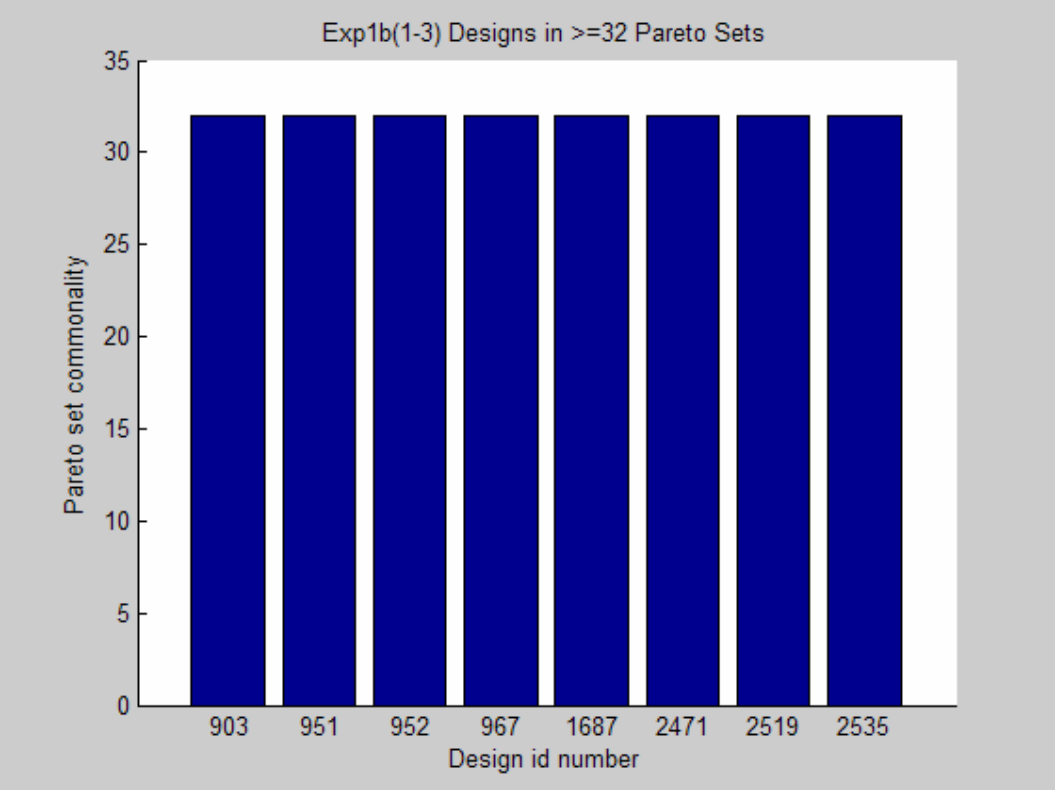


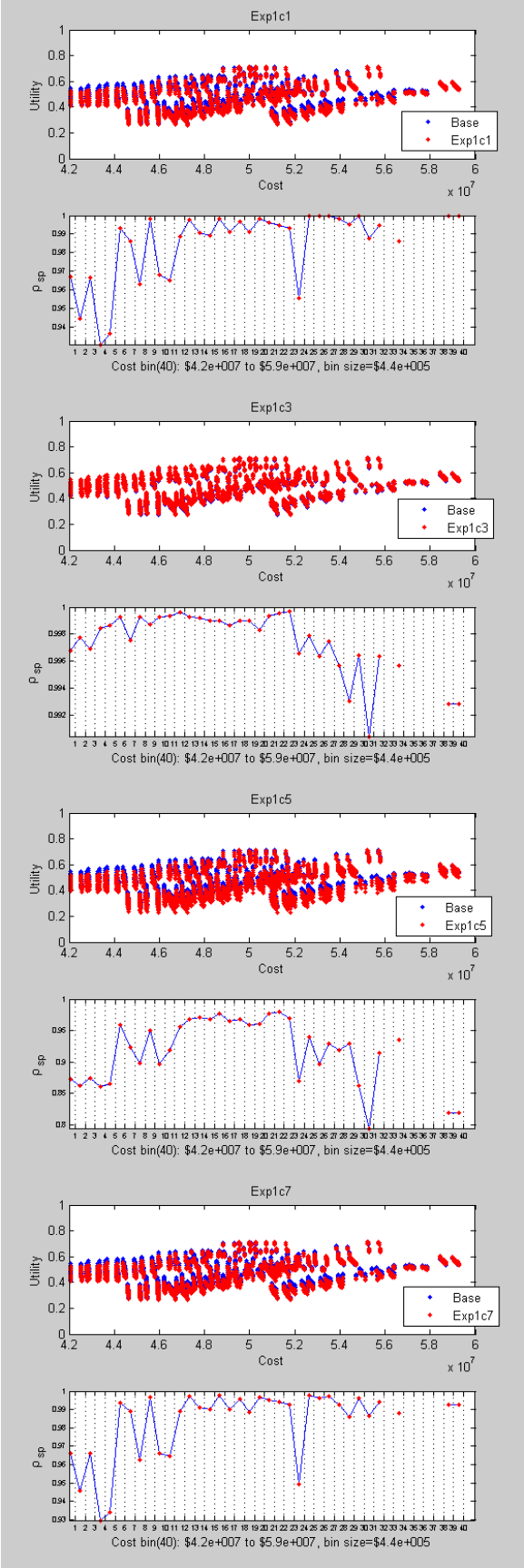
Figure 234 Design ID number versus Pareto Set number for Exp1b(1-3) (Pareto Trace >=32)

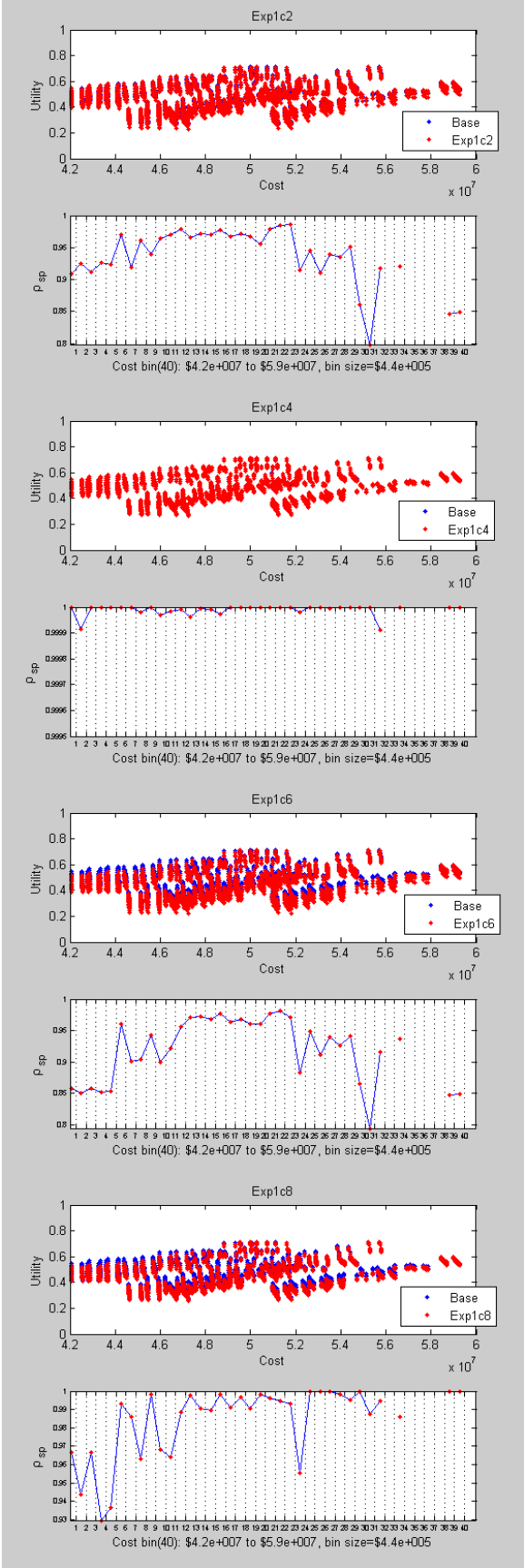
Experiment 1c: Subtle change case

The results of this experiment are more in lines with expectation. The experiment linearized select single attribute utility functions and the enumeration is shown in Figure 235.The range on the Spearman Rho statistic is smaller than that of Experiments 1a or 1b. Figure 236 on the following pages show the 15 cases considered (plus case 16, which is the original, unperturbed case). In hindsight, it is clear that the experiments with the smallest Spearman Rho variation from 1 are those whose attributes originally had a close to linear utility function. An analyst without knowledge of the "true" utility function "shape" will not know a priori that a linear approximation will result in low bias from the true rankings. Overall, the effect appears to be relatively small (worst case Spearman statistic on the order of 0.8).

Expc:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
DL	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
LD	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.175
L	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425
SM															

Figure 235 Exp1c run enumerations


Exp1c1
Utility
Cost
x 10^7
Base
Exp1c1
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005
Exp1c3
Utility
Cost
x 10^7
Base
Exp1c3
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005
Exp1c5
Utility
Cost
x 10^7
Base
Exp1c5
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005
Exp1c7
Utility
Cost
x 10^7
Base
Exp1c7
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005


Exp1c2
Utility
Cost
x 10^7
Base
Exp1c2
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005
Exp1c4
Utility
Cost
x 10^7
Base
Exp1c4
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005
Exp1c6
Utility
Cost
x 10^7
Base
Exp1c6
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005
Exp1c8
Utility
Cost
x 10^7
Base
Exp1c8
ρ sp
Cost bin(40): $4.2e+007 to $5.9e+007, bin size=$4.4e+005

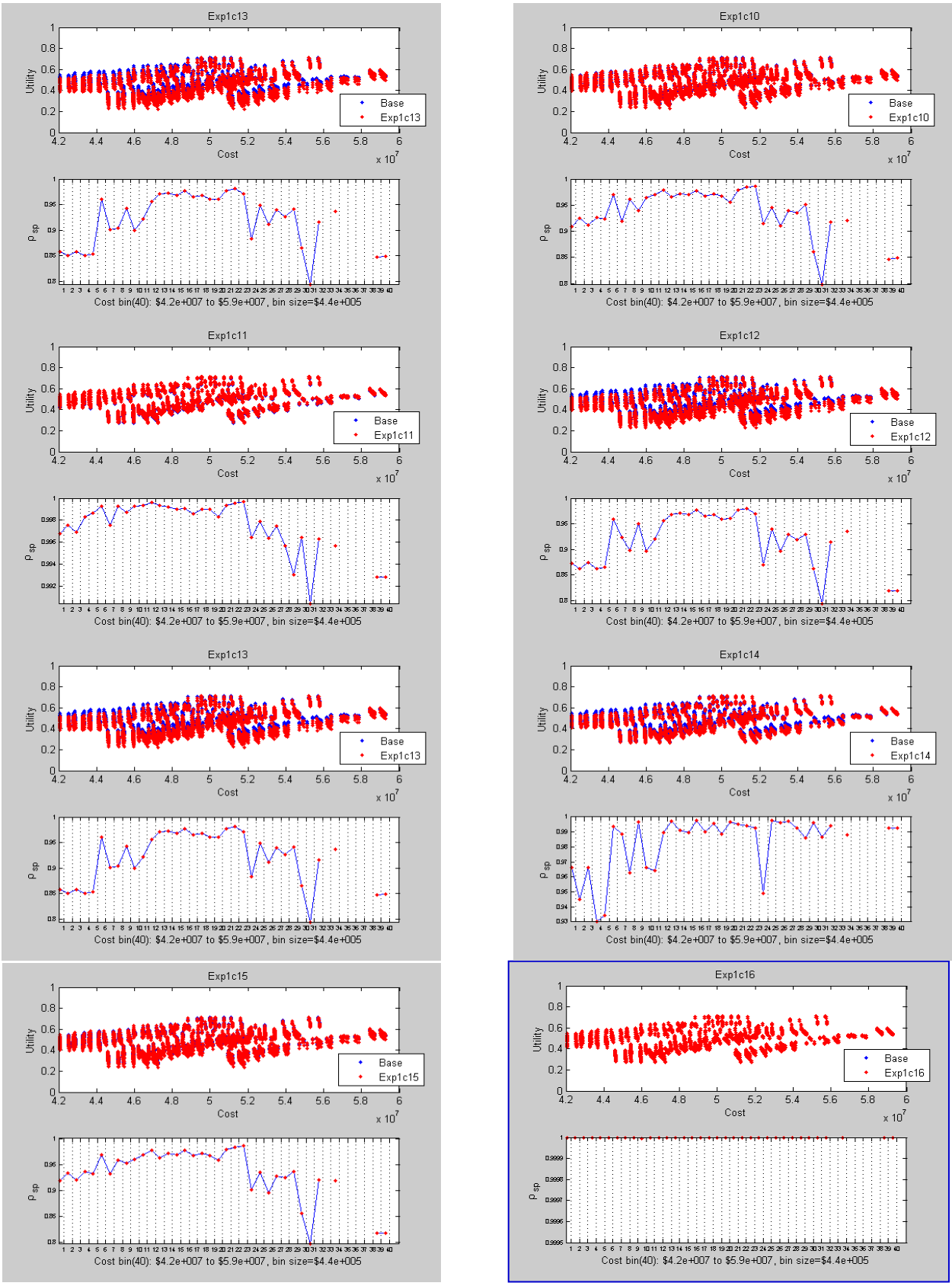


Figure 236 Exp1c results: Tradespace shifts and Spearman Rho statistics (runs 1-16)

Pareto Tracing reveals 15 designs in all 16 Pareto Sets. The tracing is shown in Figure 237 and Figure 238. Figure 239 below shows the distribution of number of designs appearing in different numbers of Pareto Sets for Experiment 1c. Once again, all four designs, 2471, 903, 1687, and 2535 appear in all 16 Pareto Sets (Figure 240 below), showing that these designs are in fact robust to preference variations in Experiment 1a, Experiment 1b, and Experiment 1c.

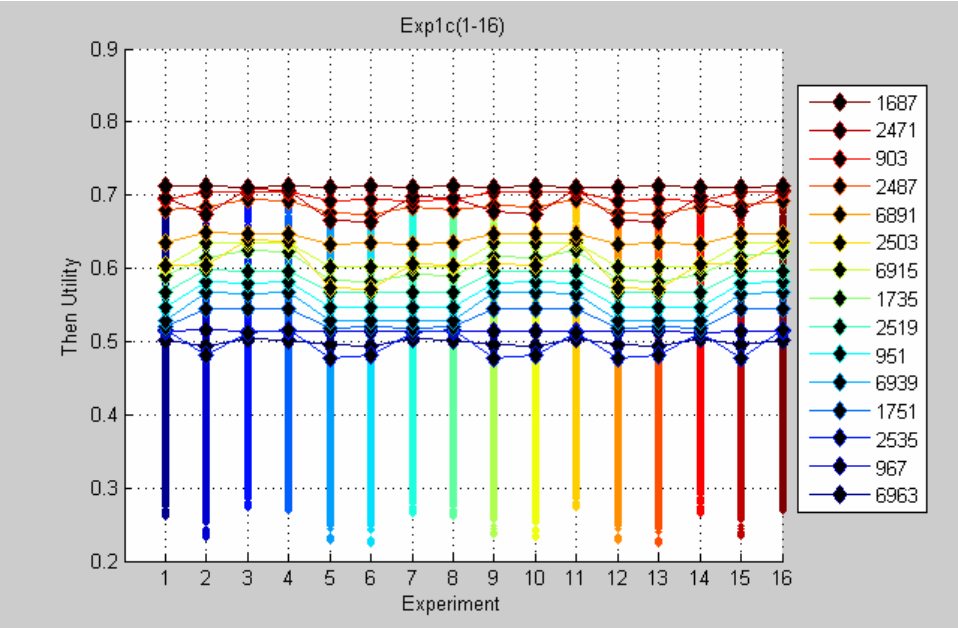


Figure 237 Two dimensional Pareto Tracing Exp1c(1-16) (Experiment-Utility)

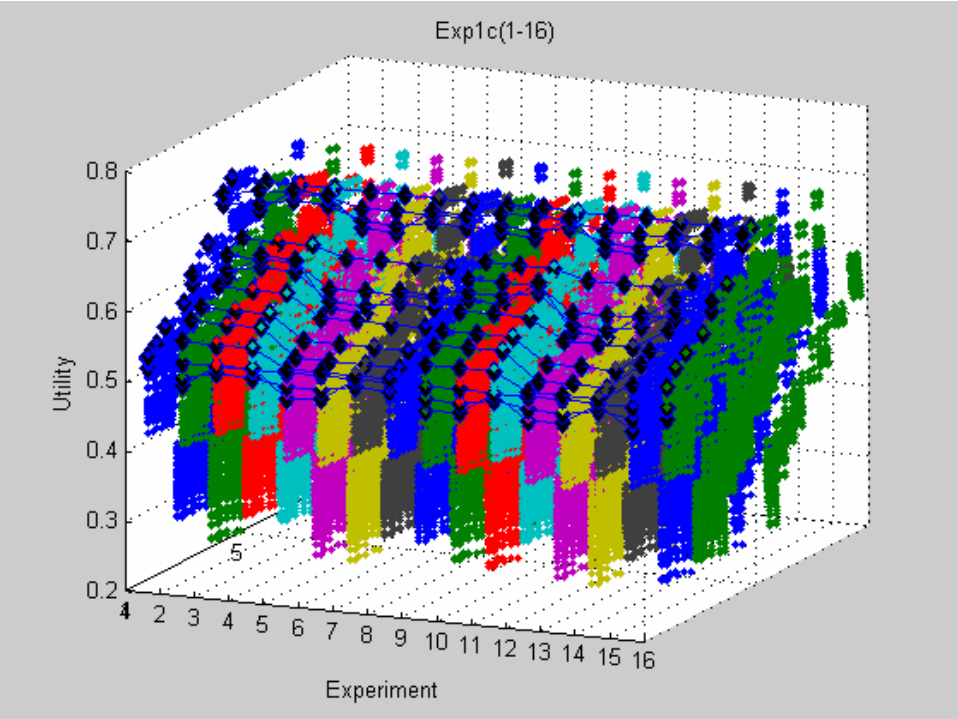


Figure 238 Three dimensional Pareto Tracing Exp1c(1-16) (Experiment-Cost-Utility)

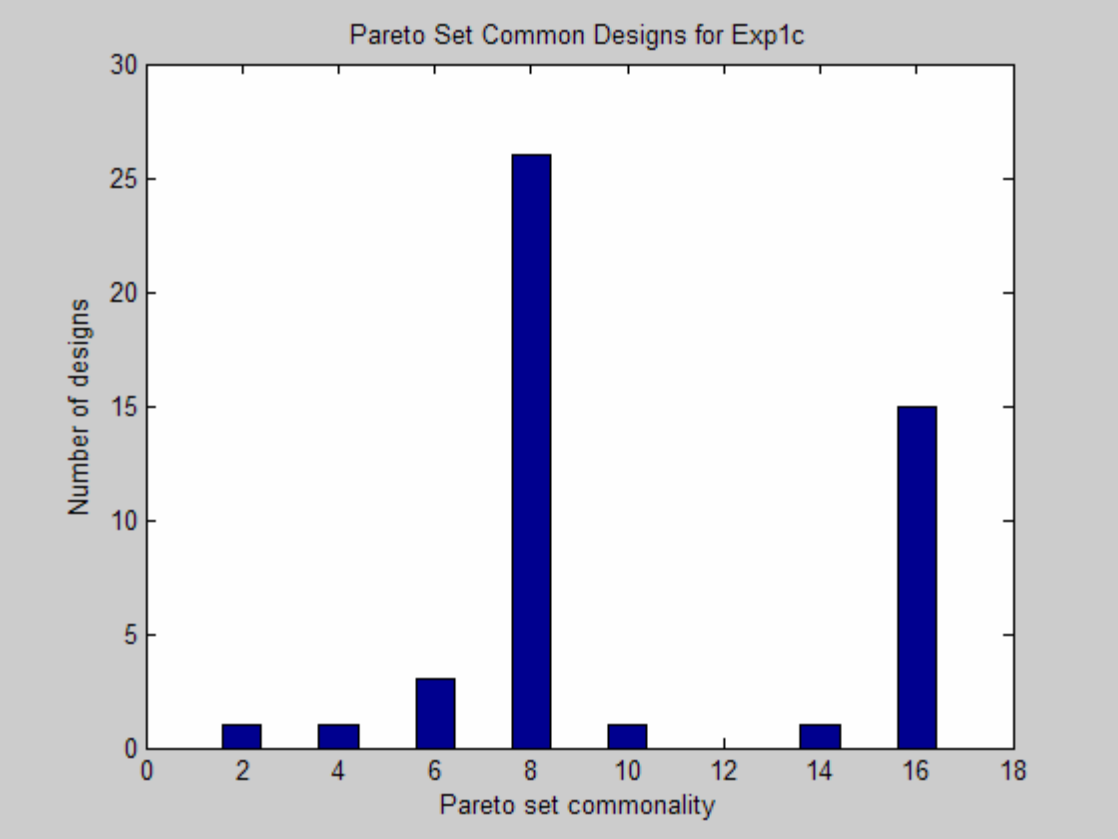


Figure 239 Pareto Trace distribution (Exp1c)

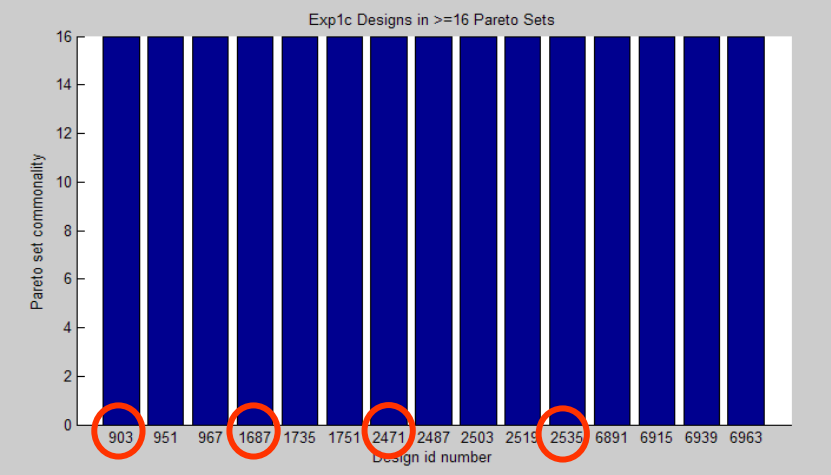


Figure 240 Design ID number versus Pareto Trace number (Pareto Trace >=16)

Experiment 1d: Evaluative change case

The results of this experiment are at first a little surprising, given the almost identical results for all but one experiment. The run enumerations are given in Figure 241.

Since these experiments altered the utility functional form, comparing utility values is not meaningful. Instead, the Spearman's Rho statistic was calculated on the iso-cost rankings of design options, and the Pareto Set was likewise captured.

The Pareto Sets for MAUF, M3, and M4 were identical. In hindsight, the result is predictable since for the X-TOS mission, $\sum k_i = 1.125 \approx 1$ and in the case that the sum of the k_i equals one, the MAUF collapses to a simple weighted sum (M3). In general, the equivalence of M3 and MAUF is not guaranteed.

Looking at the Spearman Rho statistic, usage of M1 results in a variation from 0.05 to 0.95 over the iso-cost bands. The next "worst" function is M2, with a variation from 0.9865 to 0.9995, which is essentially the same rank ordering. (Results are shown in Figure 242.)

The interpretation of these results is that over the range of these evaluation functions, the rank orderings of designs for selection is relatively insensitive. The analogy is that designers have some freedom over evaluation functions to determine best designs. The designs are in a sense "robust" to evaluative interpretation.

Figure 243 and Figure 244 below show the Pareto Tracing for this experiment. 26 designs are in all 5 Pareto Sets. (Recall the size of the original Pareto Set is 36 designs.) Figure 245 shows the distribution of designs appearing in different numbers of Pareto Sets for Experiment 1d. Figure 246 shows the designs that are in all 5 sets. Three of the four "robust" designs from previous experiments are included in the 26: 2471, 903, and 1687. Design 2535 is *not* in all 5 Pareto Sets.

Expd:	1	2	3	4	5
DL	0.3	0.3	0.3	0.3	0.3
LD	0.125	0.125	0.125	0.125	0.125
ET	0.175	0.175	0.175	0.175	0.175
L	0.1	0.1	0.1	0.1	0.1
SA	0.425	0.425	0.425	0.425	0.425
SM					
$U(U_i)$	MAUF	M1	M2	M3	1-M4

MAUF $$U = \frac{\left(\prod_{i=1}^{N}\left[Kk_iU_i + 1\right]\right) - 1}{K}$$

M1 $$U = \prod_{i=1}^{N} k_iU_i$$

M2 $$U = \prod_{i=1}^{N}\left[k_iU_i + 1\right]$$

M3 $$U = \sum_{i=1}^{N} k_iU_i$$

M4 $$U = \prod_{i=1}^{N}\left[Kk_iU_i + 1\right]$$

Figure 241 Exp1d run enumerations

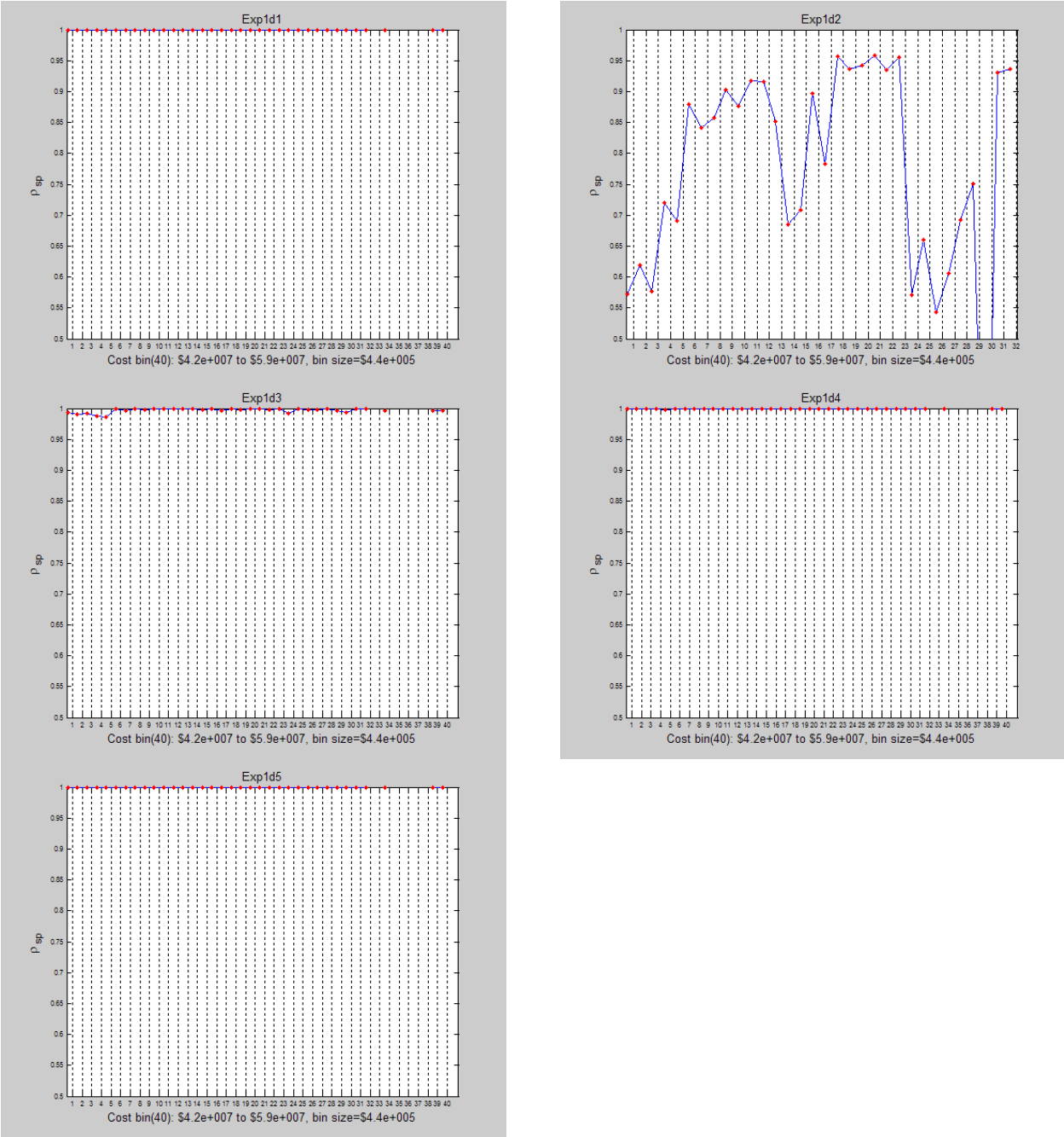


Figure 242 Exp1d results: Spearman Rho statistics (runs 1-5)

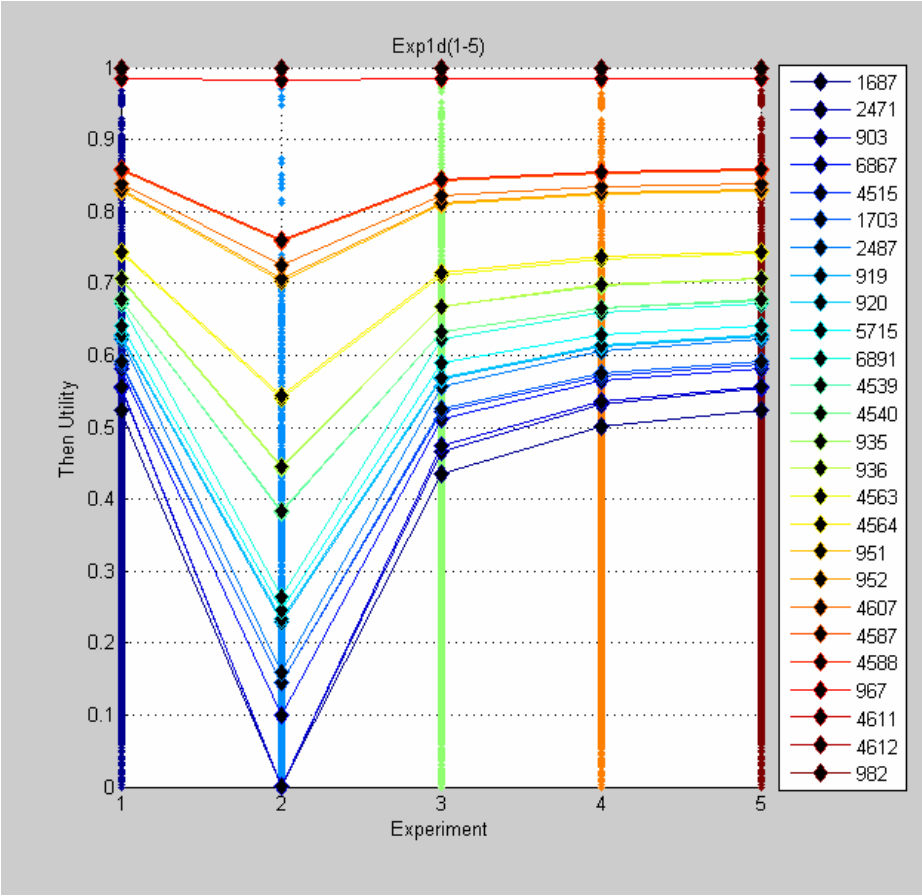


Figure 243 Two dimensional Pareto Trace Exp1d (Experiment-Utility)

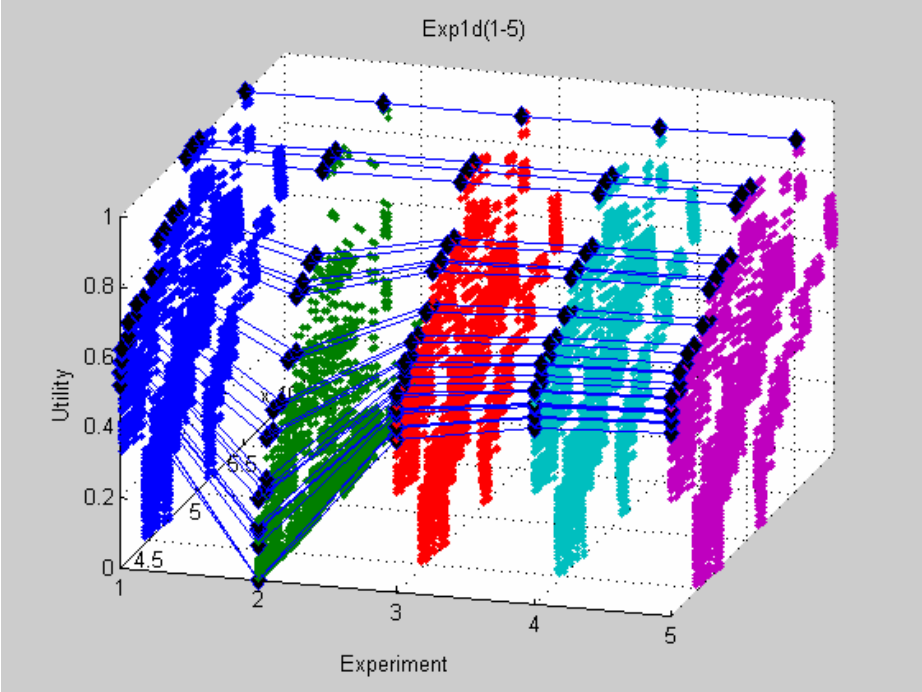


Figure 244 Three dimensional Pareto Trace Exp1d (Experiment-Cost-Utility)

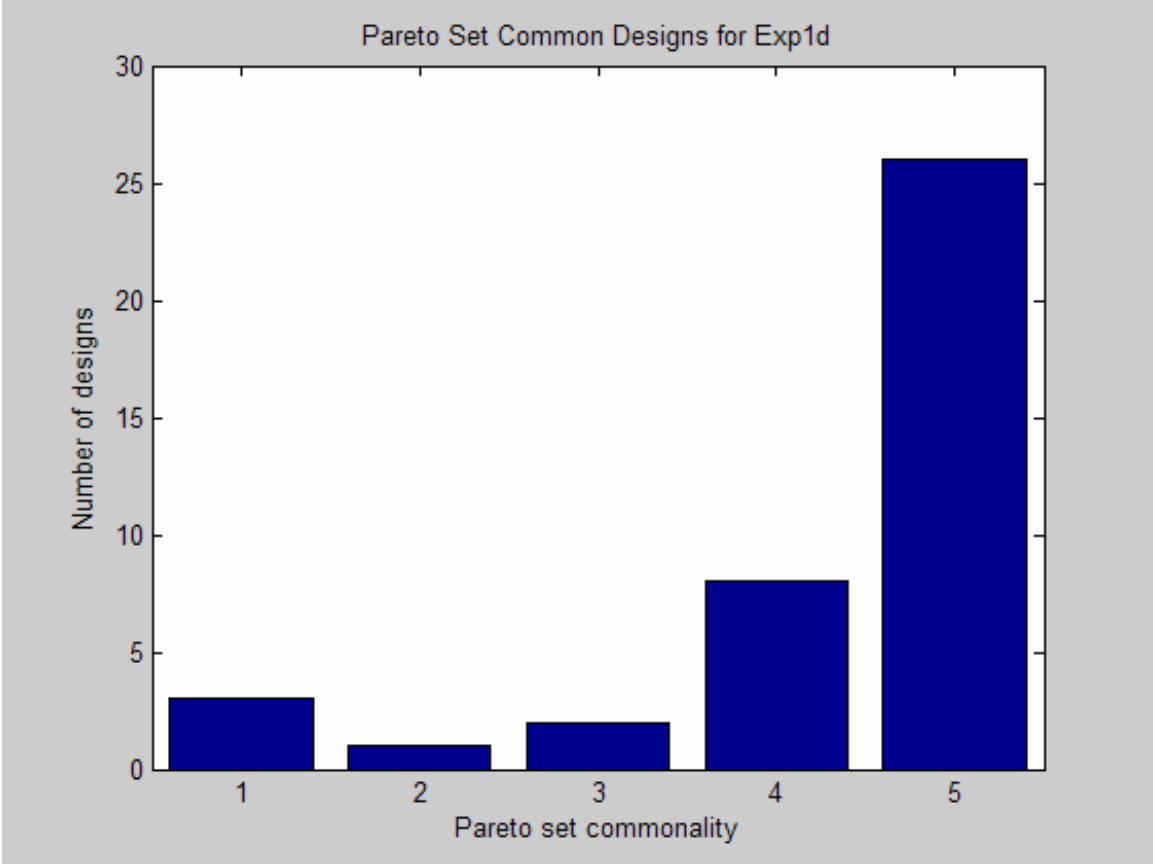


Figure 245 Pareto Trace number distribution (Exp1d)

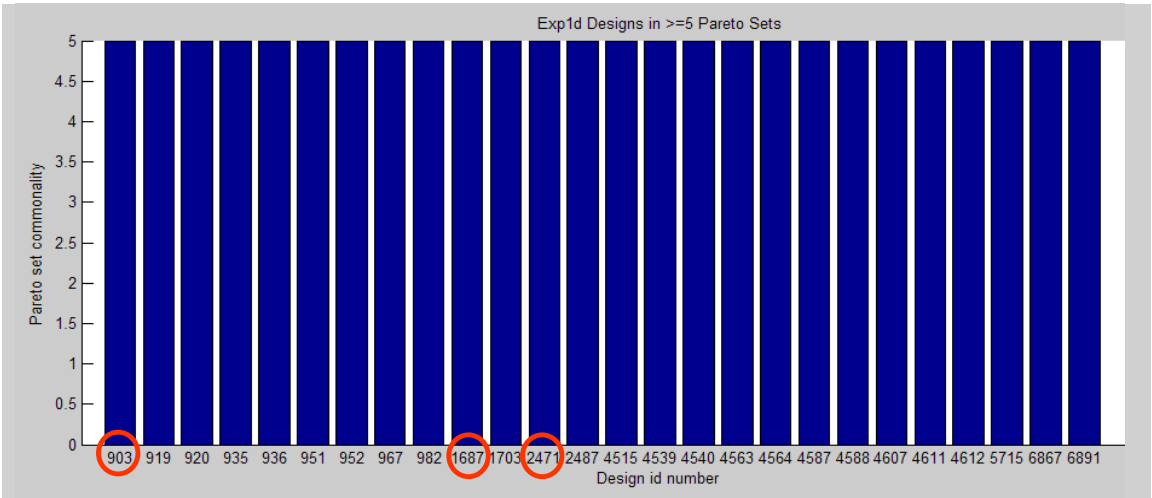


Figure 246 Design ID number versus Pareto Trace number (Pareto Trace >=5)

Synthesizing the results from all of the single decision maker preference experiments results in the distribution shown in Figure 247. Figure 248 reveals that one design appears in all of the Pareto Sets, and thus has the highest (best case) Pareto Trace number of 60: design 2471. Four

other designs have Pareto Trace numbers over 57: 903, 967, 1687, and 2535. The possible reason for the high Pareto Trace numbers is discussed in Section 7.2, “Discussion.”

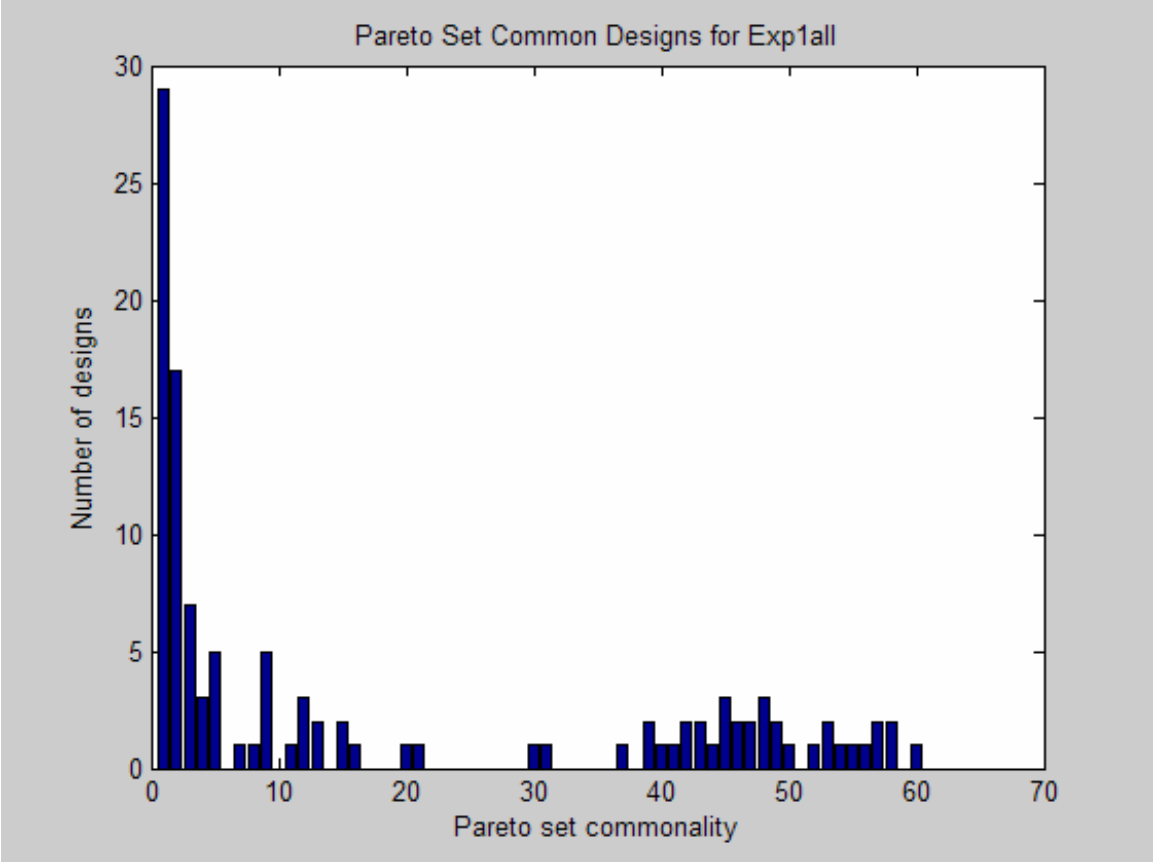


Figure 247 Pareto Trace distribution (all Exp1)

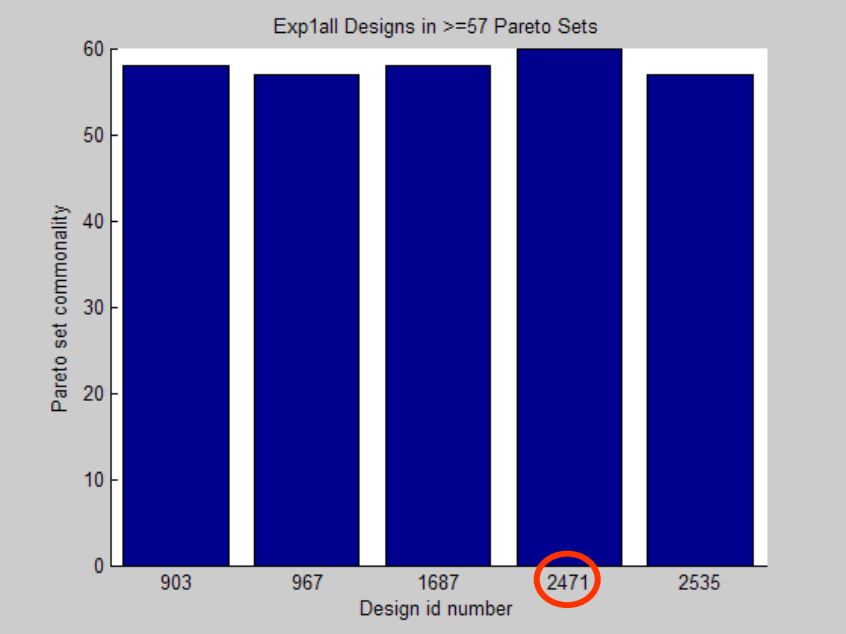


Figure 248 Design ID number versus Pareto Trace number (all Exp1a)

Appendix E: Outdegree Discussion

The outdegree calculated from a tradespace network analysis is completely dependent on the transition rule specification, and designs considered in the analysis. Bias in the enumeration of the design space will result in skewed outdegree values. In theory, an analysis of the "complete" tradespace will give an "absolute" outdegree measure of changeability for a design. The following is a discussion for estimating the de-biased absolute outdegree from the actual measured outdegree.[259]

Given a rule set, and design variable set, let us define the following quantities:

$$\mathcal{R} \equiv \text{span}\ (\{R^K\})$$
$$R \equiv \dim\ (\mathcal{R}) = K$$
$$\Gamma \equiv \text{span}\ (\{DV^N\})$$

In order to assess the absolute outdegree of a node, it is necessary to know how an actual MATE study relates to a theoretically complete MATE study. The goal is for the calculated outdegree of a design to not be dependent on the enumeration strategy of the MATE analyst. In order for that to be possible, it is necessary to remove the enumeration strategy artifact from the calculation.

The complete enumeration of a design variable can be calculated as[260]:

$$D^i = \left[\frac{DV^i_{\max} - DV^i_{\min}}{mms^i} \right] + 1, \text{ for } DV^i$$

Thus the complete enumeration of the design vector $\{DV^N\}$ is:

$$n = \prod_{D^i \in \Gamma} D^i$$

By comparison, the actual enumeration of a design variable during a MATE study is:

$$d^i$$

And the enumeration of the design vector is:

$$S = \prod_{d^i \in \mathrm{D}} d^i$$

[259] The discussion of completeness and tradespace outdegree convergence is relatively simplistic and would benefit from a rigorous application of real analysis techniques. Concepts such as countably and uncountably infinite sets are readily applicable, as well as convergence and DOE sampling techniques.

[260] The assumption here is a uniform minimum meaningful scale over the range of acceptable design variable values. In the event of non-uniform mms, a complete listing of DV values may be required.

Note that in the limit $d^i \rightarrow D^i \ \forall \ i$, $S \rightarrow n$, also the number S represents an upper bound. It is possible that constraints reduce the actual enumerated set below S. (For example, enumeration of design vectors that have apogee altitude less than perigee altitude would be considered "unphysical" and thrown out by some expert filter. In fact, in practice, it is a good idea to have an expert filter screen enumerated design vectors before passing them to the system model to ensure that nonsensical designs are not considered.)

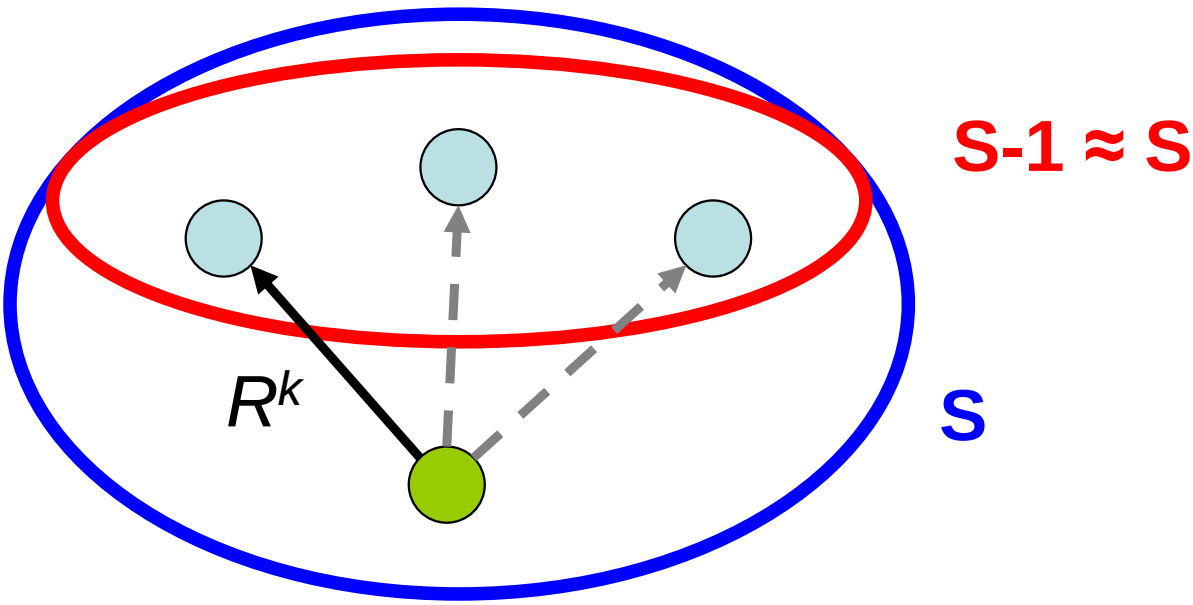


Figure 249 Design (node) connections determined by rule^k, leading to maximum connectivity to full space S

Figure 249 shows an illustration of the base node and other nodes that may be connected through rule R^k. The maximum number of nodes accessible to the base node is S, with the maximum number of paths being $S \times K$.

Assume that for a full tradespace, some fraction α^k of n is accessible from a given node through rule k (α^k may be different from node to node, but stabilizes to a constant as $S \rightarrow n$). The maximum outdegree from a given node using R^k is

$$OD^k = \alpha^k n = \alpha^k \prod_{D^i \in \Gamma} D^i$$

Then the maximum outdegree from a given node, over all rules, is

$$OD = \sum_{k=1}^{K} OD^k$$

Let the measured α and OD be $\overline{\alpha}$ and $\overline{OD}$ respectively. Then

$$\overline{OD}^k = \overline{\alpha}^k \prod_{d^i \in \Gamma} d^i$$

As the actual enumeration approaches full enumeration, $S \rightarrow n$ and $\overline{\alpha}^k \rightarrow \alpha^k$. Convergence, or stabilization in changes of α^k, may occur long before complete enumeration, thus saving the analysis from excessively burdensome computation. An analyst can test for convergence by successive enumerations of the tradespace and comparing the α^k values for given nodes. Clever enumeration strategies may result in faster convergence and less biased results with less required computational effort than a "dumb" enumeration strategy (such as complete enumeration or arbitrary sampling).

When converged,

$$\overline{\alpha}^k = \text{const} = \alpha^k = \left[\frac{\overline{OD}^k}{\prod_{d^i \in \Gamma} d^i} \right]$$

So when $\overline{\alpha}^k$ is stable, the total outdegree can be determined by actual measurements:

$$OD = \sum_{k=1}^{K} \left[\frac{\overline{OD}^k}{\prod_{d^i \in \Gamma} d^i} \right] \prod_{D^i \in \Gamma} D^i \text{ , with } D^i = \left[\frac{DV^i_{\max} - DV^i_{\min}}{mms^i} \right] + 1$$

As an example of this calculation process, consider the following example:
Suppose the design variable set contains 3 design variables and the rule set contains 2 rules.

$\{DV^N\} = \{DV^1, DV^2, DV^3\}$, N=3
$\{R^K\} = \{R^1, R^2\}$, K=2

Further suppose that each DV^i has a complete enumeration as [min:mms:max]

DV^1: [0:0.1:1]	D^1=11
DV^2: [10:10:1000]	D^2=100
DV^3: [1:1:3]	D^3=3

Complete tradespace enumeration: n = 11×100×3 = 3300

But the actual enumeration has

DV^1: [0:0.2:1]	d^1=6
DV^2: [100:100:1000]	d^2=10
DV^3: [1:1:3]	d^3=3

Actual tradespace enumeration: $\overline{n}$ = 6×10×3 = 180

The transition rules are as follows:

Γ: $\{DV^1, DV^2, DV^3\}$

R^1: $DV^1 > DV^2$, increase DV^2 decrease DV^1 at 2×increase amount of DV^2
$Cost^1 = 10\times|\Delta DV^2|$
$Time^1 = 5\times|\Delta DV^2|$

R^2: Two of three DV^i must be same, change one at a time by mms^i
$Cost^2 = 100\times|\Delta DV^1| + |\Delta DV^2| + 10\times|\Delta DV^3|$
$Time^2 = 15\times|\Delta DV^1| + 2\times|\Delta DV^2| + 5\times|\Delta DV^3|$

And then calculating the enumeration vector has:

$$D^i \in \{11,100,3\}$$
$$d^i \in \{6,10,3\}$$

The maximum possible outdegree from a node is when $\alpha^k=1$, so

$\max OD^k = n^k$, $\max OD = \sum \max OD^k$

$\max OD^1 = 11\times100\times3 = 3300$,
$\max OD^2 = 11\times100\times3 = 3300$,
$\max OD = 3300 + 3300 = 6600$

Notice that the total number of nodes in the complete tradespace is 3300. The fact that maxOD is greater than 3300 is because more than one path leads to all of the nodes.

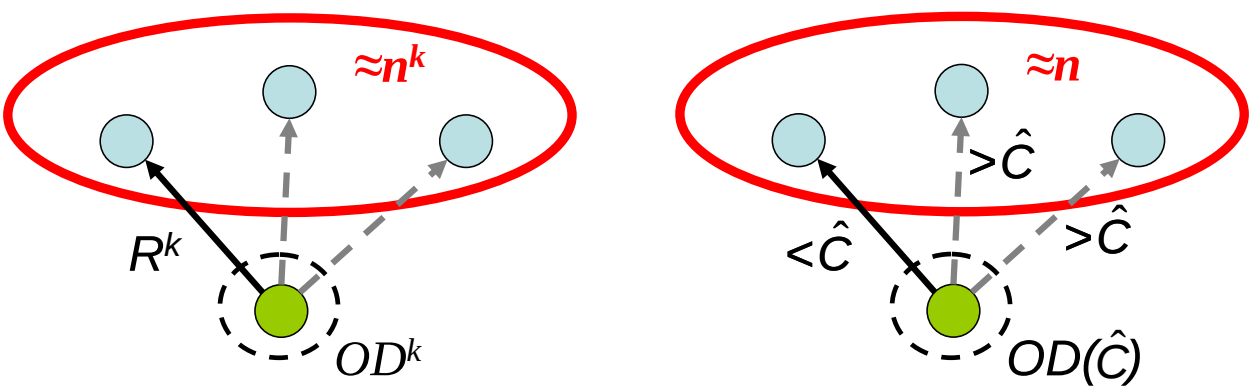


Figure 250 Outdegree^k from node due to rule^k and Outdegree($\hat{C}$) for arcs costing less than $\hat{C}$

Suppose the actual OD^k is measured and α^k is "converged."

$$\overline{OD} = \{14, 34\}$$

$$\bar{\alpha}^k = \left[\frac{\overline{OD}^k}{\prod_{d^i \in \Gamma} d^i} \right] = \alpha^k$$

$$\bar{\alpha}^k = \{14/(6\times10\times3),\ 34/(6\times10\times3)\}$$
$$= \{0.078,\ 0.189\}$$

$$OD^k = \alpha^k n = \alpha^k \prod_{D^i \in \Gamma} D^i$$

$$OD^1 = 0.078\times3300 = 257$$
$$OD^2 = 0.189\times3300 = 624$$
$$OD = 257 + 624 = 881$$

In summary:

Enumerated tradespace size:	180
Complete tradespace size:	3300
Complete transitioned tradespace size:	6600
Measured OD:	48
Theoretical OD:	881

For this example, the theoretical OD is an absolute measure of the changeability for the design. Changes in mms, min/max DV, or transition rules would alter that value, as would be expected. In this way a designer could intentionally increase the changeability of a design.[261]

[261] No discussion of the subjective aspect of changeability is included in this statement. Increasing the *perceived* changeability of a design could also be accomplished by raising the acceptability threshold to the $\hat{C}_\infty$ level.

Appendix F: Methods Used

- Semi-structured interviews
- Surveys
- System dynamics
- Network theory
- MATE
- Multi-objective optimization
- Parametric models
- Time-based simulation
- Decision analysis
- Multi-attribute utility analysis

12.22 Methods Mentioned

The following are methods referred to explicitly or implicitly during the course of the work. In particular, these methods are useful for gathering information for, representing, and analyzing engineering systems.[262]

12.22.1 Modeling Techniques

System dynamics
Network models
Agent-based models
Parametric models
Time-based simulation
Discrete event simulation

12.22.2 Analysis Techniques

Multi-objective optimization
Operations research (linear, discrete, dynamic, nonlinear, integer programming)
Discrete choice analysis
Network analysis
Statistics
Econometrics
Cost-benefit analysis
Real options analysis
Portfolio theory analysis

12.22.3 Information Gathering Techniques

Semi-structured interviews
Surveys
Expert panels

[262] Some techniques are listed more than once due to category overlap

12.22.4 Decision Theory

Utility Theory
Multi-Attribute Utility Theory
Analytic Hierarchy Process
Prospect Theory
Decision Tree Analysis

12.22.5 Forecasting

The following methods attempt to predict future conditions or events.[263]

Qualitative methods
The Delphi method
Market research
Panel consensus
Grass-roots forecasting
Historical analogy

Time series methods
Moving average
Exponential smoothing
Box Jenkins
Trend projections

Causal methods
Regression analysis
Econometric models
Input/output models
Life-cycle analysis
Simulation

12.23 Software Used

- Matlab, The MathWorks Inc.
- ModelCenter, Phoenix Integration
- Excel 2003, Microsoft
- Word 2003, Microsoft
- Powerpoint 2003, Microsoft

[263] These methods are discussed in Chapter 12 of Cook and Russel. Introduction to Management Science..

Appendix G: Software Supplements

- Inclusion of CD with Matlab code (m-files)
- Presentation(s)
- Paper(s)