UTILIZING MULTIPLE ATTRIBUTE TRADESPACE EXPLORATION WITH CONCURRENT DESIGN FOR CREATING AEROSPACE SYSTEMS REQUIREMENTS

by

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Submitted to the Department of Aeronautics and Astronautics Engineering
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ABSTRACT

Introduced herein is a process named Multiple Attribute Tradespace Exploration with Concurrent Design (MATE-CON), which seeks to capture and aggregate decision maker preferences for the conception and evaluation of a multitude of system designs and thereby create and propagate a common and continuous metric for communication throughout the design enterprise. The process was developed to systematically approach the following problems commonly found in front-end space system design:

1. Establishing design requirements a priori with limited consideration of other options
2. Inadequate means of systematically evaluating broad trades in the early stages of design
3. Lack of regard for the complete preferences of the decision maker
4. Inaccurate characterization of decision maker preferences
5. Pursuit of a detailed design without understanding the effects on the larger system
6. Limited incorporation of interdisciplinary expert opinion and diverse stakeholder interest

MATE-CON uses advances in tradespace modeling to develop potential system designs. It then uses Multi-Attribute Utility Theory to gather preferences and evaluate those designs. Finally it employs concurrent design for simultaneous (immediate), common (stakeholder inclusive), and continuous (intertemporal) propagation of the value metric. Tradespace modeling numerically enumerates the options to provide the design. Utility theory establishes the metric to evaluate the design. Concurrent engineering creates a forum to validate the design. This threefold emergence is investigated through the use of a series of university space system design studies intended to simultaneously provide the government sponsor technically valid products in addition to advances in product development processes. The process is then explicated through a series of fifty step-by-step activities. Finally it is qualitatively evaluated. In doing so the groundwork is established for new quantitative methods to understand technical, political, market, and budgetary uncertainty in addition to providing the basis for rigorously developing techniques of improved conceptual design for manufacturability, logistics, reliability, maintainability, human factors, disposability, and in particular life-cycle affordability. The following pages attempt to introduce the means by which MATE-CON could improve requirements creation processes to promote learning throughout the design enterprise for enhanced aerospace system value.

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DISCLAIMER

The conclusions and opinions expressed in this document are those of the author only. They do not reflect the official position of the U.S. Government, the National Reconnaissance Office, the Department of Defense, the United States Air Force, or the Air Force Institute of Technology. Furthermore, these conclusions and opinions are those of a U.S. Air Force 2nd Lieutenant that has significant interest but much less than significant experience in the practical application of issues addressed herein.

ACKNOWLEDGEMENTS

It goes without saying that I could never have done this project with out the support and great advice of many.

I must first thank the Air Force and the National Reconnaissance for providing the opportunity for this research and the funding for my graduate studies. I also want to thank the Space Systems Policy and Architecture Research Consortium (SSPARC) of MIT, Caltech, and Stanford for providing the primary motivation and the projects to enable this research. Many were associated with the consortium and provided helpful input throughout. Among these were Prof. Elisabeth Paté-Cornell (Stanford), Prof. Fred Culick (Caltech), Dr. Joel Sercel (Caltech), Dr. Amar Gupta (MIT), Dr. John Ballenthin (AFRL), Dr. Bill Borer (AFRL), Kevin Ray (AFRL), Mr. Pete Hendrickson (NRO), Dr. Steve Wall (NRO), Ms. Nicki Nelson (Aerospace Corp.), and Mentor Marine Mike Kramer (Aerospace Corp.).

I also want to thank the various members of the SSPARC project research teams who were busy trying to design technically legitimate space systems with semi-legitimate prototyped design processes. All were at MIT unless otherwise specified.
A-TOS: Dave Ferris, Andre Girerd, Bill Kaliardos, Adam Ross, Dan Thunnissen, Myles Walton, and Brandon Wood
B-TOS: Nathan Diller, Qi Dong, Carole Joppin, Sandra Jo Kassin-Deardorff, Scott Kimbrel, Dan Kirk, Michelle McVey, Brian Peck, Adam Ross, and Brandon Wood
C-TOS: *Caltech* - Nathan Brown, Sascha Calkins, John Geiszler, Minh Hodac, Todd Shuman, Mike Strumpf, Jon Erickson, Dan Thunnissen; *MIT*- Maddie Close, Jason Derleth, Nathan Diller, Cindy Perreira, Chris Roberts; *Stanford* – Jimmy Benjamin
X-TOS: Mirna Daouk, Jason Derleth, Kevin Duda, Bobak Ferdowsi, Deborah Howell, Geoff Huntington, George Leussis, Stephen Long, Christopher Roberts, Nirav Shah, Tim Spaulding, Dave Stagney, and Ludovic Talon

Particular members of SSPARC at MIT provided additional help. Satwik Seshasai must be commended for his work in developing the Multi-attribute Interview Software Tool (MIST) to support the MATE-CON research. Dr. Hugh McManus, the SSPARC executive director provided great technical expertise to ensure that the final products of the design exercises made technical sense, providing additional interesting tips on life along the way. I would also like to thank Professor Daniel Hastings the SSPARC PI. He provided not only experienced advice throughout the research but made great efforts to ensure that the students were walking away with the necessary tools for the real world. In particular he offered great insights to me on the Air Force, based on experience with those at the opposite end of the chain of command than I.

Besides SSPARC members other MIT faculty provided great insights through their interactions with the TOS exercises among them were Col. Keesee, Professor Sheila Widnal, Dr. Ray Sedwick, and Professor David Miller who also helped in writing an NSF grant for this work.

While we had only limited interactions, Captain Robb Wirthlin (USAF) provided a wealth of information with his research that explicated the current state of front-end process and a framework for measuring relative maturity of those processes.

Besides passing on his engineering knowledge, Captain Brandon Wood (USAF) provided great practical advice being the first to explain how I might get two degrees in two years from Harvard and MIT.

I would particularly like to thank Adam Ross who co-authored a significant amount of this research and will be providing a much more valuable thesis on this same subject in the coming months. His enthusiasm for space helped drive this project, and I deeply hope that I have an opportunity to work with him again in the future to help actualize many of his dreams about the space frontier (this will of course be after he completes his PhD).

Dr. Joyce Warmkessel not only acted as a great advisor throughout my research but she really made it all possible by first suggesting that I work with SSPARC over the summer of 2001. Her years of experience with space system engineering provided some of the greatest insights available, yet they bear in comparison to her ability to provide mentorship and kind words to the many students that she helps. May more come to understand her contributions and may we stay in touch in the future.

Though already mentioned, I want to specifically thank my officemates and friends Jason Derleth, Chris Roberts, Michelle McVey, Nirav Shah, Satwik Seshasai, Myles Walton, and Annalisa Weigel.

Besides everyone that I have come to know through my work at MIT I want to especially thank my perfect family who has provided unwavering encouragement and support throughout my life. I absolutely could not ask for a better brother and sister. My deepest appreciation goes to my parents who never once considered putting their own interests before those of their children. I will spend my entire life striving to give as much love as they have given and to become as good of a parent as they have been.

With a lifetime of such a loving and supporting family I could have never imagined how life could be better. Then I met Robin Marie. A relationship spanning 2000 miles, uniting 2 families, writing 2 theses for 2 degrees from 2 schools all in 2 years...such a challenge is not for the faint of heart, yet she gently and confidently confronted the trial with faith, hope, and love surpassing any I have ever seen, and this is just the beginning ...BRAVO DELTA!!! May the many stars shine brightly.

My deepest gratitude to all, I could not have done it without your prayers. The blessings infinitely abound with only finite time to return that which has been given. "Lord Jesus Christ, take all my freedom, my memory, my understanding, and my will. All that I have and cherish you have given me. I surrender it all to be guided by your will. Your grace and your love are wealth enough for me. Grant me these, Lord Jesus and I ask for nothing more. Amen." (St. Ignatius Loyola 1491-1556)

BIOGRAPHICAL NOTE

Nathan P. Diller was born in Texas and raised on a family farm in the country near Hereford, Texas where he did most of his learning. Building an experimental aircraft with his Father and earning a pilot license and instrument rating, he hoped to serve his Country through a career in military aviation. After graduating from Hereford High School in 1996 he entered basic training with the U.S. Air Force Academy Class of 2000. At the Academy, Nathan was a member and captain of the flying team while he pursued double majors in Physics and Humanities with Math and Philosophy minors. In May 2000, Nathan, was commissioned as a Second Lieutenant in the U.S. Air Force. He earned a Bachelor of Science Degree and graduate scholarships in physics, philosophy, engineering, and government, as he was interested in the intersection of the various disciplines. He spent the following summer at home on the farm where he became reacquainted with Robin Marie Bell, a fellow graduate of Hereford High School. In August of 2000 Nathan took his first assignment at the National Security Program at Harvard University where he was to complete a Masters of Public Policy in International Security and Political Economy at the Kennedy School of Government. Interested in researching National Missile Defense, Nathan's KSG advisor, Ashton Carter, encouraged him to develop his technical depth by cross enrolling in MIT engineering courses. One of these courses was 16.89, Space Systems Engineering, taught by Daniel Hastings and Joyce Warmkessel who persuaded Nathan to work on a National Reconnaissance Office university spacecraft design project as the MIT program manager. Nathan spent the summer working on the C-TOS project with the Space System Policy and Architecture Research Consortium (SSPARC) in addition to working with Adam Ross on developing Multiple Attribute Tradespace Exploration with Concurrent Design (MATE-CON). On September 11, 2001, Nathan was officially accepted into MIT's Department of Aeronautics and Astronautics.

After being married to Robin on December 29, 2001, Nathan spent his fourth and final semester in Cambridge, Massachusetts enjoying Robin's companionship and unwavering support as he completed his policy and engineering degrees. Upon graduation, Nathan will finally begin pursuing his military aviation career at Sheppard Air Force Base's Euro NATO Joint Jet Pilot Training (ENJJPT).

Nathan is an active member of his Catholic parish and he enjoys spending time on the farm with his family.

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1 INTRODUCTION

The purpose of this thesis is to provide an introduction to a new process for improving the early phases of aerospace system development. This research builds on the work of others who have evaluated processes to create requirements aerospace systems, and found a series of limitations to those processes that undermine performance, cause excessive cost, and require prolonged development times. Using those findings as the baseline the approach here is to introduce a potential means of systematically chipping away those limitations identified by previous study. In the various explications of current process deficiencies one finds common themes that suggest that the underlying problems in aerospace system development arise from[1]:

1. **Establishing design requirements a priori with limited consideration of other options**: This is the so-called problem of "point designing," where the designers fail to explore and evaluate a broad tradespace of solutions and thereby undermine innovation. From the outset requirements are specified limiting the degree to which the designer can search for a more optimal solution.
2. **Inadequate means of systematically evaluating broad trades in the early stages of design:** Building off of problem one, if drastically alternative designs are considered in the early stages it is rare that the alternative designs are measured using a standard systematic process for comparison. This lack of technical rigor in the early stages of

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[1] To reiterate, this thesis does not prove the existence of all of these problems. They were surmised through literature and through interactions with those who have spent time employing sub-optimal processes under the ever pressing constraints of cost and schedule where there was not time to reflect on how these processes might be improved. This research sponsored by a government organization provided the opportunity to contemplate current practices and potential means of improvement. The first segment of the references section provides a list of books for exploring some of these problems. For a three hundred page discussion of these problems in the military, especially the Air Force, see J.R. Wirthlin, *Best Practices in User Needs/Requirements Generation*, MIT 2000.

design fails to capture the physical drivers of the design. This is usually incarnated in the so-called "power point engineering" where the marvels of Microsoft© are used to persuade budget authorities.

3. **Lack of regard for the complete preferences of the decision maker:** This results from the failure of the designer to be able to quantitatively aggregate a diverse variety of preferences, by understanding what the decision-maker wants not what the designer wants to build for the decision-maker. Fundamentally it arises from the designer's hastiness and lack of desire to pursue and capture sufficient communication with the decision-maker.
4. **Inaccurate characterization of decision maker preferences:** In the problem arises from the inability of the decision makers to explicate their preferences and maintain those preferences throughout the design process. The decision makers need means to clarify their preferences so that they can act more rationally. Under current processes either they do not know what they want or if they do know they will change their mind. There is a need to create more static and dynamic consistency or at least clearer recognition of the inconsistencies and the underlying causes of those inconsistencies (i.e. recognizing changes in the environment). Failure to recognize these inconsistencies undermines the designers ability to create a valuable design.
5. **Pursuit of a detailed design without understanding the effects on the larger system:** Many times a design will be selected based on very course models of the potential system, and as the details of the system are worked out it is determined that this course model had a fundamentally flawed assumption making the design physically unfeasible. Conversely, as engineers work though higher fidelity design they find that it is necessary

to make a modification from the original plan and in doing so they fail to realize the effect that the seemingly minor modification might have on the overall mission effectiveness. A language of expense and utility needs to be exchanged for the current language of requirements.

6. **Limited incorporation of interdisciplinary expert opinion and diverse stakeholder interest:** Many times designs will proceed with infrequent and low bandwidth interaction among the design specialists. This allows for oversights creating effective interfaces frequently leading to costly re-engineering steps. Furthermore, in the initial design in efforts to maximize performance for minimum costs the designers fail to recognize the various stakeholders that will be interacting with the system that will in the end drive up lifecycle cost or reduce mission performance. These stakeholders might include the end user, the policy maker, the acquisition agent, the manufacturer, the logistician, the maintainer, or even the customer. Fundamentally there is a failure to recognize the holistic or interdisciplinary approach necessary for effective design.

These six macro problems are the basis for the development of MATE-CON, and they will be referenced throughout as the thesis attempts to prove the viability of MATE-CON as a solution or at least a partial solution to these six problems.

The thesis is organized into three parts. **Part I** addresses the emergence and rational for the MATE-CON process. Of this part, Chapter 2 discusses the problem of quantitatively modeling a design tradespace, beginning with MIT's Space Systems Laboratory (SSL) Generalized Information Network Analysis—GINA[2] (macro problems 1 and 2). Chapter 3 deals with the difficulty of evaluating a tradespace with a common and complete criterion, decision

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[2] Shaw, G. *The Generalized Information Network Analysis Methodology for Distributed Satellite Systems.* Ph.D. Dissertation, MIT, 1999.

maker preference—a criterion that can be generalized for any aerospace system design (macro problems 3 and 4).[3] Chapter 4 shows how it is possible to help ensure that the metric provides a vision to pursue throughout the design process with inclusion of necessary stakeholders that interact with the design to ensure it validity and avoid surprises by unforeseen preferences or external pressures (problem 5 and 6). **Part II** introduces a complete set of generalized activities of the MATE-CON process. This part is approached as a tutorial for someone that would want to use MATE-CON with step-by-step directions.[4] **Part III** finally attempts to give a qualitative and semi-quantitative description of how MATE-CON is usefully implemented as a means of creating requirements.

Multiple Attribute Tradespace Exploration with Concurrent Design (MATE-CON) seeks to capture and aggregate decision maker preferences for the conception and evaluation of a multitude of system designs and thereby creates and propagates a common and continuous metric of value for communication throughout the design enterprise. In the most simplistic terms MATE-CON is improving the capacity to: 1) examine a broad variety of possible options; 2) analyze those options; 3) implement the best option. Certainly, these three steps are not new to design, but it does provide a new synergistic approach to examination, analysis, and implementation. These are three facets of MATE-CON and to achieve that end a framework is established to: 1) use improved modeling techniques to develop a broad set of options (GINA); 2) use Multi-Attribute Utility Theory for the capture and aggregation of preferences to create a common metric to analyze those options; 3) employ advances in

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[3] It is important to note that while one should collect the preferences of the user (chapter 3) prior to conducting modeling and simulation (Chapter 2) the sequence of the thesis comes from the chronological development of the process.

[4] If one wants to just quickly apply MATE-CON it would be possible to refer only to Part II, but doing so would be like using an equation without knowing the derivation of the equation. The derivation is necessary to understand and make explicit the assumptions fundamental to knowing the equation's appropriateness for a given problem.

concurrent engineering for simultaneous (immediate), common (all stakeholders), and continuous (intertemporal) propagation of the metric to detailed design. Utility theory establishes the metric concurrent engineering employs the metric. While any approach to design will always require some degree of art, this thesis suggests that requirements creation processes can still significantly gain from a more quantitative analysis—analysis that is more inclusive of interdisciplinary stakeholders. That being said one must understand that the analysis done by MATE-CON does not suggest that everything can be reduced to a number and equation.

1.1 MOTIVATION, SCOPE, AND METHODOLOGY

Upon its establishment, the Space System Policy and Architecture Research Consortium (SSPARC) set out with a mission to "develop new tools and processes to produce better, less expensive space systems more rapidly within the technical and economic limits, while considering the impact of policy."[5] It was indeed the objective to develop a new process for systematic analysis of new aerospace design concepts. This research took the unique approach of developing for the sponsor a series of particular space system designs called the Terrestrial Observer Swarms (TOS). The NRO was quite interested in an innovative and technically valid system designs, which were developed by some fifty graduate and undergraduate students from MIT, Caltech, and Stanford. While the NRO expected a high level of technical rigor in these conceptual designs there was an additional expectation that these designs would provide experiments for academic researchers to develop improved tools and processes for the conceptual design phase.

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[5] Daniel E. Hastings *SSPARC Executive Overview Presentation.* This was the overall purpose of SSPARC that was briefed on several occasions to the sponsor and associated organizations.

This thesis then takes the approach of explaining the development of Multiple Attribute Tradespace Exploration with Concurrent Design (MATE-CON) a new process for space system design that sprung from this series of TOS exercises and associated study. Figure 1 shows the MATE-CON development timeline with the three main methodologies that were incorporated into the various design iterations to create the final MATE-CON process. These exercises do not meet the standard of MATE-CON case studies since its actual development was ex post facto. Since these exercises will be discussed throughout the paper it is important to have a brief overview of each of the missions, so that the time is spent focusing on the process instead of the products.[6]

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[6] It is worth reiterating the author's appreciation to all of those mentioned in the acknowledgements section who dedicated significant time to these various projects. Without their pursuit of these designs it would not have been possible to gain the insights necessary to advance the research for improving design processes.

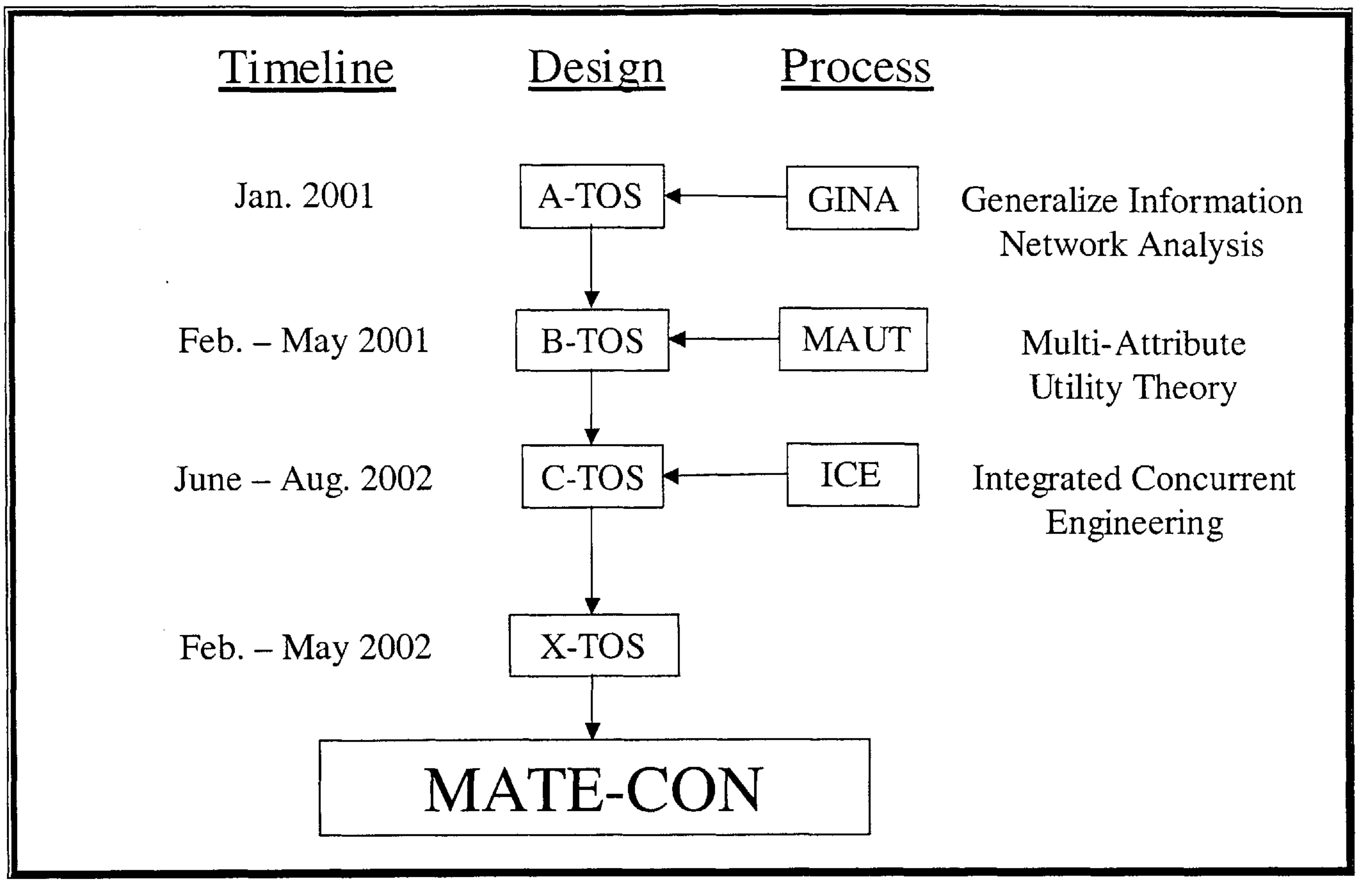

Figure 1 MATE-CON Development Timeline

1.1.1 A-TOS (MIT, Caltech, and Stanford: January 2001)

The first design of the series of Terrestrial Observer Swarm (TOS) exercises was A-TOS. Intended as a case study utilizing the GINA methodology, A-TOS had the mission to "develop a set of architectures for a swarm-based space system for ionosphere observations, and capture the process by which this product is designed, through a government-sponsored consortium that involves MIT, Cal Tech, and Stanford. The objective is to develop a preliminary family of architectures by January 31 2001 as a basis for future design cycles."[7] The design was to collect in-situ measurements of the ionosphere by flying the swarm through the region of interest. In order to accomplish this mission the A-TOS design team considered varying several different parameters shown in Table 1.

Table 1: A-TOS Design Vector

A-TOS DESIGN VARIABLES	**Range**
Bulk Orbit Variables	
Swarm inclination	63.4°
Swarm perigee altitude (km)	200 – 800
Swarm apogee altitude (km)	200 – 800
Swarm argument of perigee	0°
Number of orbit planes	1
Swarms per plane	1
Swarm Orbit Variables	
Subsats per swarm	1 – 26
Number of subplanes in each swarm	1 – 2
Number of suborbits in each subplane	1 – 4
Yaw angle of subplanes (a vector)	±60°
Maximum satellite separation	1 m – 200 km
Non-orbit Variables	
Mothership	(yes/no)
Total # of Explored Architectures = 1380	

This particular design session concluded with an architecture study. The study looked at the various cost and performance parameters of the 1380 architectures investigated.

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[7] This was the mission statement developed by the A-TOS design team consisting of SSPARC students from MIT, Caltech, and Stanford. Dr. Hugh McManus and Dr. Joyce Warmkessel, "Creating Advanced Architectures For Space Systems: Product And Process" *AIAA 2001-4738.*

1.1.2 B-TOS (MIT, 16.89 Space Systems Engineering Course: Spring Semester 2001)

For the B-TOS mission, the focus was again to develop an architecture for ionospheric measurement. The mission statement was to "Design a conceptual swarm-based space system to characterize the ionosphere. Building upon lessons learned from A-TOS, develop deliverables, by May 16, 2001, with the prospect for further application. Learn about engineering design process and space systems." The last part of the mission was quite important as the design study was conducted in an MIT course, 16.89 Space Systems Engineering. The high level concept of the mission was a top-side sounder that would characterize the earth's ionosphere. Like A-TOS, B-TOS approached the problem of designing the architecture and did so by varying the parameters in the shown in Table 2. The final product was a report on this architecture analysis with a first cut at a spacecraft design.

Table 2: B-TOS Design Variables

A-TOS DESIGN VARIABLES	Range
Large Scale Architecture	
Circular orbit altitude (km)	1100, 1300
Number of Planes	1, 2, 3, 4, 5
Swarm Architecture	
Number of Swarms/Plane	1, 2, 3, 4, 5
Number of Satellites/Swarm	4, 7, 10, 13
Radius of Swarm (km)	.18, 1.5, 8.75,50
Vehicle Architecture	
5 Configuration Studies	Trades payload,
	communication,
	and processing
Total # of Explored Architectures = 4,033	

1.1.3 C-TOS (MIT, Caltech, and Stanford: Summer 2001)

This study was conducted by some twenty students and faculty at MIT, Caltech, and Stanford, using geographically distributed teams linked with video and telecommunication technology. The purpose of the study was to design the spacecraft for the architecture selected in the B-TOS study using the Laboratory for Space Mission Design (LSMD) Integrated Concurrent Engineering (ICE) methodology. The teams divided up into various subsystem chairs and developed a parameter set that was passed between chairs using ICEMaker, software built as an Excel interface. The C-TOS team presented a final conceptual design of the Mothership and Daughtership spacecraft to the government sponsor in August after two months of work.

1.1.4 X-TOS (MIT, 16.89 Space Systems Engineering Course: Spring Semester 2002)

The X-TOS team, made up of 16.89 students, established the mission statement which says, "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." In this instance the Terrestrial Observer Swarm became the Terrestrial Observer Satellite, except in the case of multiple launches, which was one of the many parameters traded as shown in Table 3.

Table 3: X-TOS Design Variables

A-TOS DESIGN VARIABLES	Range
Mission Scenarios	
Single satellite, single launch	
Two satellites, sequential launch	
Two satellites, parallel	
Orbital Parameters	
Apogee altitude (km)	200-2000
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 Architectures = 50,488	

It should be clear that these projects and their outcomes were the result of the efforts of university and inter-university design teams. While the author participated in these design exercises as one of the design team members in B-TOS, then as the MIT program manager in C-TOS, and as a lecturer and process consultant for X-TOS, the development of the process would not have been possible without the hard work of all of the students and faculty involved in these design exercises.

While various pieces of the continually maturing process were applied to each of these TOS design exercises, insufficient prior development was done that might allow these different exercises to be considered true case studies. Such progression was not the result of poorly planned research design, but was rather the full intent of the research approach funded by the NRO. Space systems students would get experience working on real NRO problems through the design exercises and the graduate researcher could use these exercises to study the process of developing the end products with the intent of developing a new and improved holistic framework for approaching design.

The intent was that these projects provide a baseline to consider new methods in initial design, and it was from these projects that MATE-CON emerged. This thesis does not make an attempt to prove categorically that the MATE-CON is an optimal process tried and tested in a variety of applications. Rather current problems and their causes were explored as they arose from these exercises, followed by a discussion of a potential solution of these problems and incorporation of that solution into a macro framework for aerospace system design. The thesis will state in a step-by-step approach how MATE-CON is executed. The final section attempts to put MATE-CON into a context where it might be useful and applies a maturity matrix to qualitatively measure where it lies on the spectrum of best practices.

1.2 TAXONOMY

The title provides an initial scope of the thesis, and it contains some very critical terms that will be used throughout the thesis. As a reminder the title is, ***Utilizing Multiple Attribute Tradespace Exploration with Concurrent Design for Creating Aerospace Systems Requirements.*** Possibly the most complicated of all of the terms is the first. **Utilizing**

In some ways this first term might be the most problematic of the title. To utilize is "to make or render useful; to convert to use."[8] Certainly, this thesis will discuss how one might convert MATE-CON to use, but the readers must understand that the usefulness or the goodness of this process might not yet be completely established by the end. Thus far

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[8] "Utilize, v." def. 1, *The Oxford English Dictionary Online,* http://dictionary.oed.com/cgi/entry/00274056 Second Edition, 1989.

there has not been an experiment designed or conducted to categorically prove that this is a better approach to creating aerospace systems requirements. It will however have a complete section on reasons that MATE-CON is an improvement on many current processes, highlighting characteristics of an ideal process and showing at least to some degree how it provides those characteristics.

Multiple Attribute refers to the broad variety of metrics upon which an individual makes a decision, and in this case a design decision. More technically, the terms arise from the applications of multi-attribute utility analysis derived in Keeney and Raiffa's *Decisions with Multiple Objective* (1976)[9]. This utility analysis characterizes the various *good* output attributes of the design, but by defining MATE-CON with Multiple Attribute one arrives at a more inclusive definition that allows consideration of those attributes that create a dis-utility or an expense, this approach intends to generalize, considering also the complexity of design input or expense attributes. Multi-attribute utility analysis was developed in the fields of economics and decision sciences as a formal means of measuring the utility or the goodness of a system. While MATE-CON has thus far relied heavily on multi-attribute utility theory, it does not seem that it is necessary fundamental to the process. It is likely possible that other approaches would provide a similar benefit, again providing greater rationale for not specifying this process as intrinsically relying on multi-attribute utility theory, but certainly relying on the notion that decisions are based on multiple and very likely interdisciplinary objectives. Additionally, the existence of these multiple attributes implies that the designer is cognizant of their impact on the design. This

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[9] Keeney, R. L., Raiffa, H. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Cambridge University Press: Cambridge U.K. 1993.

cognizance is to the level of being able to wisely aggregate[10] this multiplicity of preferences into a common metric for design so that one can compare a wide variety of designs and correctly weigh their *goodness* against one another. The ability to aggregate these preferences is fundamental to exploring the tradespace, which will be discussed next.

Tradespace is the full range of possible concepts that could define the design. These are all of the different things that the designer can manipulate to develop a new design. The expansion of this tradespace is the essence of innovation—a *creative* recombination of current resources or systems to *create* a new system, which never before existed. The ability of MATE-CON to enumerate a set of design variables against each other is one of its greatest benefits. While certainly questions will remain on how to stimulate innovation, MATE-CON's mandate to construct a tradespace, as a minimum, prevents a designer from slipping into the false assumption that the first design put on the table is the optimal design. It requires one to question if there are other, possibly drastic, re-combinations of resources or systems that might create a better design.[11]

Exploration elucidates the fact that this approach is not an optimization technique in the strict mathematical sense of the word but is instead a means for investigating a multitude of options, thus deriving information that will become the basis of decision-making. This "action of examining; investigation, or scrutiny"[12] is where the designer begins to creatively consider the

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[10] This is one of the most important intellectual points of MATE-CON. There are some good and some very, very poor methods of aggregating these preferences. The wise aggregation requires significant mathematical training with recognition of the importance of psychometrics, statistics, and decision theory. Great skepticism of such a process arises from the poor application of such aggregation techniques. Include in the reference section is a series of citations that that discuss correct aggregation.

[11] Additionally, while MATE-CON can likely be generalized for application across a broad variety of disciplines, the fact that the name has the terms trade**space exploration**, ensures its original application is not forgotten, i.e. finding better ways to develop space systems for actually exploring space.

[12] "exploration" def. 1, *The Oxford English Dictionary Online,* http://dictionary.oed.com/cgi/entry/00080548 Second Edition, 1989.

various possibilities contained in the tradespace, and how that tradespace might be broadened. In order to do such exploration the designer must have collected the various attributes of the decision-maker, the one who will decide which design to pursue, and have aggregated those attributes. This aggregated metric will then be used to measure the different possible designs in the tradespace, and the importance of exploration is finding the design that most closely fulfills the multiple attributes of the decision-maker. Many times this requires human interaction that is simply not conducive to optimization techniques in the strict sense. The exploration of all design combinations with respect to a common metric is fundamental to MATE-CON.

Concurrent Design refers to techniques of design that utilize information technology for real-time interaction among specialists. One can find significant literature on this technique of design conceived in the early 1990s. Essentially, it entails putting all of the experts in the various fields affected by the design and provide information technology to facilitate these experts in designing the system for development, production, operation, maintenance, and retirement. The addition of concurrent design to this process is critical in that it requires that all of the experts be in the room, but more importantly it ensures that the various stakeholders and experts are being driven by the common goal, which is the aggregation of the decision-making attributes. Providing this common goal creates motivation and cohesion among the stakeholders that under current practices only arises under the most skilled managers.

Creating highlights a very important fact that the fundamental purpose of MATE-CON is "to bring into being or cause to exist"[13] a system that fulfills as completely as possible a specified need of an individual or organization. The thesis focuses here on creating requirements, but one should not expect a legal discussion of how to write requirements for

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[13] "create, v." def. 1 *trans*, *The Oxford English Dictionary Online*, http://dictionary.oed.com/cgi/entry/00080548 Second Edition, 1989.

aerospace system contracts. Rather the approach here is to suggest that the creation of a concept that is then executed with requirements must be approached differently to include an exploration of the tradespace using the multiple preference attributes of the individual or organization in need of the new system. It seems that to a large degree this notion of creating is frequently lost behind the political and budgetary maneuvering needed to navigate the requirements process. Fundamentally, behind specifying the requirements needed to produce the system is a creation process that brings in to being a new system, and if this initial creation is done poorly it does not matter how well the requirements are met, the system as a whole entity simply will not fulfill the specified need.

Aerospace is a term that has been rather controversial since Air Force Chief of Staff, General Thomas White coined the word.[14] The purpose here is not to explicate the philosophical, political, cultural, budgetary, economic, strategic, or tactical implications of using the terms air and space vs. aerospace. However, the *interdisciplinary* nature of the divisiveness surrounding the word might help one to more fully understand the importance of the requisite *interdisciplinary* nature of any effective system for *creating aerospace systems requirements.*

System is certainly a word with similar philosophical implications. Deming defines a system as "a network of interdependent components that work together to try to accomplish the

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[14] White wrote in 1958 that, "Air and Space are not two separate media to be divided by a line and to be readily separated into two distinct categories; they are in truth a single indivisible field of operations. Space is the natural and logical extension of air; space power is merely the cumulative result of the evolutionary growth of air power. It would be more accurate, rather than to speak of two separate and distinct eras, to adhere to a more descriptive frame of reference, one which would clearly show these phases of man's entry into the universe in their proper perspective. Precisely speaking, we are and have been operating in the 'Aerospace Age.'" Gen Thomas D. White, "The Inevitable Climb to Space," *Air University Quarterly Review* X, no. 4 (Winter 1958-1959): 3-4, cited from Major Steven Rothstein, *The Development of the Aerospace Concept 1944-1958,* School for Advanced Air Power Studies, Maxwell Air Force Base Alabama.

aim of the system."[15] A system is necessarily composed of a variety of constituent parts with the notion that the synergistic interaction of those parts is capable of creating more utility than the sum of the utilities created by the parts individually. Good creation of requirements then necessarily mandates the synergistic combination of those constituent parts. This thesis then will focus primarily on the utilization of MATE-CON in designing aerospace systems, but the precepts of this approach could certainly be applied to the design of other systems. In his discussion of systems Deming suggests that the every organization should be designed as a system and fundamental to that design is creating a common aim. Certainly one of the primary purposes of MATE-CON is to communicate a common aim or notion of creating utility throughout the design, here applied to aerospace system design, but potentially, MATE-CON could be more broadly utilized to organization structural design.

Requirements in this thesis will refer to the specific parameters to which a designer must build a new product. The creation and fulfillment of these requirements has been the subject of a multitude of literature and government documents, and there are many who feel that the current requirements process needs to be completely reconsidered. Among these advocates is Major General Cash, the Director of Joint Experimentation at NATO Headquarters. When discussing current military practices he said, "the procurement process that is requirements driven is old and wrong." While it seems unlikely that the word requirement will soon disappear from the procurement lexicon this thesis does propose an approach that views requirements and their generation under a different light. It seems that there must be a greater understanding that

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[15] W. Edwards Deming, *The New Economics for Industry, Government, Education*. Second Ed. MIT Center for Advanced Educational Services, 1994, 50. Deming suggests that the every organization should be designed as a system and fundamental to that design is creating a common aim. Certainly one of the primary purposes of MATE-CON is to communicate a common notion of utility throughout the design, here applied to aerospace system design, but potentially MATE-CON could be more broadly defined to organization structural design.

something is required only in so far as one intends to accomplish a specified function, but it may be that the final end could be better achieved through a different function. Therefore requirements should not be thought as something that must be done. While eventually a contract may arise to ensure that a particular service or good is being provided to specifications, individuals create those requirements based on a conceptual design of a solution to meet their particular need. The proper process for knowing what requirements to create will be the discussion of this thesis with the inherent hypothesis that MATE-CON one of the more optimal techniques for generating these requirements.

There certainly remain some philosophical questions of who really creates requirements? It seems that in the case of the military the enemy creates the requirements or maybe the president creates them, or maybe the citizens create them. What is really required? Publicly it is required to enhance the public good by protecting the citizenry (DOD/CIA) and advancing science and technology (NASA). Privately perhaps at the highest level the same motivators should be present, but they are translated through notions of efficient markets and shareholder profits. Regardless of who fundamentally creates requirements, these requirements are eventually documented and in this documentation decisions are made about the scope of the design. These decisions regarding the design almost rise to the level of going beyond just decision-making to the point of designing. In fact, it seems that at least to some degree, the one writing the requirements is necessarily engaging in some level of design. In this regard this thesis sees the requirements creation process as almost synonymous with initial design.

Besides the terms of the title it will be important to understand how the word utility is used. Fundamentally, it is simply a measure of *goodness* of a design. An ideal design is one, which creates the most utility. Typically the creation of this utility arises from the fulfillment of several different attributes. This thesis relies highly on the formalized multi-attribute utility theory, which mathematically aggregates those attributes into a single measure through a series of utility interviews. A later section of the thesis will describe this process in detail, but for now it is at least important to have a baseline understanding of utility in this context. Later there will be a discussion of expense which is simply considered as the opposite of utility, drawing to some degree a contrast of utility being the *good things* that come from the system (high performance) and expense being the *bad things* that go into the system (consumption of resources). Expense follows the same definition as utility but is simply the inverse. Expense is a measure of pain. Instead of being a formal aggregate of all "good" it is the aggregate of all "bad." This notion of utility is one of the most important intellectual points of MATE-CON. There are some good and some very, very poor methods of aggregating these preferences. The wise aggregation requires significant mathematical training with recognition of the importance of psychometrics, statistics, and decision theory. Great skepticism of such a process arises from the poor application of such aggregation techniques, and therefore on must be very clear about the validity of a particular approach.

1.3 DISCLAIMER FOR AN INTRODUCTION TO MATE-CON

Throughout lifetime of the system different stakeholders will be interacting with the system, and the success of the system will be dependent on the aggregate success this multitude of interactions. It is therefore quite useful to design a system from the outset with models that provide such aggregation of utilities and expenses, and use these aggregated utilities and expenses as a common metric for evaluating many different possible design combinations. It is then fundamental to allow experts in the organization to interact concurrently to begin to understand the impact that the details of the design then have on the overall aggregated utility and expense so that decisions are made based upon the effect on the whole system. Through improving front-end processes for better requirements creation MATE-CON ensures learning throughout the design enterprise enhancing aerospace system value.

In doing so the groundwork is established for new quantitative methods to understand technical, political, market, and budgetary uncertainty in addition to providing the basis for rigorously developing techniques of improved conceptual design for manufacturability, logistics, reliability, maintainability, human factors, disposability, and in particular life-cycle affordability. Do not be mistaken in thinking that this thesis develop all of these facets, rather it develops this macro framework to simultaneously aggregate preferences to create a common and continuous metric for a design that can be easily communicated throughout the design enterprise. It would then be atop this structure that those other analytical capabilities could be modularly developed and plugged into this macro framework for holistic consideration. These different modules have just begun to be researched, but such research is necessary to truly make MATE-CON complete.

The focus is on improving innovation in the early stages of design. The proposition here is that the best means of achieving that innovation is by looking at a broad array of desires from throughout the proposed system lifecycle and work to meet those desires.

MATE-CON is a new and holistic approach to design. It is certainly naïve to think that such a process could be exhaustively developed and justified in a single masters thesis. This is therefore only meant as an introduction to the process, with the full confidence that designers much more capable than this author will continue this development while this author goes to reap the benefits of their work and that of their predecessors through the opportunity to begin operating aerial weapons systems in the U.S. Air Force.

2 MODELING TRADESPACES

This Chapter seeks to address macro problems 1 and 2 introduced in Chapter 1by discussing the problems of quantitatively modeling a design tradespace, beginning with MIT's Space Systems Laboratory (SSL) Generalized Information Network Analysis—GINA.[16] It then discusses the application of GINA to A-TOS the first of the SSPARC design exercises showing how advances were made to MATE-CON's ability to address the problems of:

1. **Establishing design requirements a priori with limited consideration of other options**: This is the so-called problem of "point designing," where the designers fail to explore and evaluate a broad tradespace of solutions and thereby undermine innovation. From the outset requirements are specified limiting the degree to which the designer can search for a more optimal solution.
2. **Inadequate means of systematically evaluating broad trades in the early stages of design:** Building off of problem one, if drastically alternative designs are considered in the early stages it is rare that the alternative designs are measured using a standard systematic process for comparison. This lack of technical rigor in the early stages of design fails to capture the physical drivers of the design. This is usually incarnated in the so-called "power point engineering" where the marvels of Microsoft© are used to persuade budget authorities.

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[16] Shaw, G. *The Generalized Information Network Analysis Methodology for Distributed Satellite Systems.* Ph.D. Dissertation, MIT, 1999.

Multiple Attribute Tradespace Exploration with Concurrent Design (MATE-CON) seeks to capture and aggregate decision maker preferences for the conception and evaluation of a multitude of system designs and thereby create and propagate a common and continuous metric of value for communication throughout the design enterprise.

2.1 INTRODUCTION

While one might think that the inventive nature of engineers would encourage the initiation of new designs with a clean sheet to provide full opportunity for innovation, this fundamental desire is overshadowed by budget and schedule constraints and even more by the high risks associated with a new untested idea. These constraints tend to leave open tradespace design as a virtually unacceptable option. "The need for a well-integrated approach to system design and development can be better appreciated when it is realized that approximately eighty to ninety percent of the development cost of a large system is predetermined by the time only five to ten percent of the development effort has been completed."[17] Quite simply development programs do not have the resources or time in the early stages of a product to exhaustively consider optimal designs. Such limitations could not come at a worse time in the process since it is during this time that the majority of resource allocations are fixed.

This results in the common practice of picking up an old design that performed a similar function and doing a minor perturbation. Needless to say such approaches to systems design profoundly undermine innovation. Certainly, there is no need to reinvent the wheel each time, but design environments should not be built that encourage a predisposition to modify an old design without the means or incentive to deeply consider other, potentially more optimal

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[17] San Francisco Bay Area Chapter International Council on Systems Engineering. *Systems Engineering Handbook.* Technical report, INCOSE, January 1998.

possibilities. Besides this problem there is a related issue that deals with inadequate technical feasibility studies. In the initial phases of design, available resources are less than sparse, limiting the amount of time that can be committed to technically legitimate design studies.

As the figure shows, in the first 25% of the time spent on the project some 70% of the resources are committed though only 10% of the funding has been expended.[18] This leads advocates of the program to rely on so called "power point engineering," where the marvels of Microsoft© are used to convince decision-makers that the new project has been fleshed out in adequate detail. If these decision makers are convinced to expend more funds the designers must justify a design that was decided upon using only the heuristics of the decision maker without the insights of rigorous modeling. As mentioned in the introduction the excruciating details of current process are not going to be proven again, rather the jump will be made to say that current practices of jumping to a point design without sufficient thought to technical feasibility motivated work to develop a systematic process for creating a broad tradespace and modeling it for quantitative evaluation. Since it is unlikely that these budgetary profiles will change the remaining option is to find a faster and less expensive means of understanding the infinitely large tradespace of solutions. Computer modeling can provide that means, and while computer modeling is certainly nothing new, it is important to understand the value that it provides in this context.

2.2 GINA: GENERALIZED MODELING ANALYSIS

In an effort to systematically develop and explore tradespaces, the Space System Laboratory at MIT developed the Generalized Information Network Analysis method (GINA).

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[18] Casani, Kane, *Reengineering the JPL Project Design Process*, August 1st, 1994.

The GINA method is based on information flow network optimization theory, and began on the basis that, "there are many commercially available software tools that could in theory perform...requirements and functional analysis, trade studies, and system synthesis...there is no well-publicized generalization of the procedural logic that should be followed in order to obtain objective, relevant, and quantitative results."[19] Certainly, the objective of creating a systems engineering tool that will provide such analysis is commensurate with solving problems 1 and 2 discussed in the introduction. The analysis tool would facilitate an investigation of a multitude of designs with a common evaluation encouraging the designer to avoid beginning with a point design (problem 1). Furthermore, it will increase the level of technical rigor in the early stages of design (problem 2).

To provide such a tool GINA set out with the concept to enumerate a large number of design variables to create a broad tradespace. The fundamental question then was how to quantify the relative values of these different designs. GINA's answer is to convert every space system into an information network, using information network attributes as the metrics for relative evaluation. The premise was that,

> Almost all envisioned satellite systems are information disseminators that can be represented as information transfer networks. These systems are characterized by a set of standardized and measurable parameters for the quality of service they provide. Using these parameters to define quantifiable cost-effectiveness and sensitivity metrics, a generalized system analysis methodology for satellite systems can be formulated. This is

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[19] Graeme B. Shaw. *The Generalized Information Network Analysis Methodology for Distributed Satellite Systems.* MIT Aeronautics and Astronatics. 1999. p. 35.

> useful for Systems Engineering of satellite systems as well as competitive analysis and investment decision-making.[20]

The space system is transformed into an information flow diagram in order to apply the optimization rules developed for information systems to space systems. This approach allows the design team to compare different architectures based on performance and cost to determine the best architectures.

The GINA method includes mapping the system as an information network, defining the Quality of Service metrics [signal isolation, information rate, information integrity, availability], defining the performance parameters, simulating and modeling the system, and evaluating a large number of architectures, each defined by a design vector, to study the trades in performance—cost space. Fundamentally, GINA developed a means of providing comparative analysis between different systems with large architectural differences. This was done with the creation of the cost per function (CPF) metric. The work of the Space System Laboratory provided some of the first motivations for plotting an enumerated architecture set in a performance—cost space which would illuminate a pareto optimal front of architectures of best value.[21]

2.3 A-TOS: THE DIFFICULTY OF METRICS

The first of the problems that arose in addressing the macro-objectives with GINA was the difficulty in applying the appropriate metrics to architecture evaluation. This problem first arose in A-TOS, the first in a series of space system design exercises called the Terrestrial Observer

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[20] Graeme B. Shaw. *The Generalized Information Network Analysis Methodology for Distributed Satellite Systems.* MIT Aeronautics and Astronatics. 1999. p. 27. Some would certainly take issue with this limited role of space that is implied in this statement, and it will become apparent later that restriction one's view of space systems as glorified info-nets becomes quite complicated and maybe unnecessarily so.

[21] Jilla, C.D., Miller, D.W., and Sedwick, R.J., "Application of Multi-disciplinary Design Optimization Techniques to Distributed Satellite Systems," Journal of Spacecraft and Rockets, Vol. 37, No. 4, 2000, pp. 481-490.

Swarm (TOS). To reiterate these exercises do not meet the standard of MATE-CON case studies since its development was ex post facto, particularly in this case since A-TOS which was intended to be a case study utilizing the GINA methodology. In the end the method actually used did not closely match that prescribed by GINA, but did result in important insights for improving design processes.

To understand the role of A-TOS in advancing MATE-CON one must have a baseline understanding of the mission, which was as stated by the design team to: "Develop a set of architectures for a swarm-based space system for ionosphere observations, and capture the process by which this product is designed, through a government-sponsored consortium that involves MIT, Cal Tech, and Stanford. The objective is to develop a preliminary family of architectures by January 31 2001 as a basis for future design cycles."[22] This inter-university design team was going to use GINA to explore several different architectures of multiple formation-flying spacecraft (swarms) for characterizing the ionosphere.

The team identified that one of the first vital steps was to assemble the needs of the various customers for the proposed system. Members of this design team had experience in adapting notions of decision-maker value to design through collaborative work that they had conducted with MIT's Lean Aerospace Initiative (LAI). This research group had done significant work on the dimensions of value, and the assessment of total lifecycle value. This background coupled with the peculiarities of this swarm's effect on the collection of the information made led the A-TOS design team to believe that the GINA metrics [signal isolation, information rate, information integrity, availability] were not necessarily the desired basis of analysis between

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[22] This was the mission statement developed by the A-TOS design team consisting of SSPARC students from MIT, Caltech, and Stanford. Dr. Hugh McManus and Dr. Joyce Warmkessel, "Creating Advanced Architectures For Space Systems: Product And Process" *AIAA 2001-4738*.

different architectures. In contrast, the team developed value functions for two primary mission functions of Equatorial Snapshot Utility and High Latitude Survey Utility. [23] Figure 2 shows the plot of these combined utilities plotted with cost. While one can certainly gain some insights from the graph, it will be shown soon that the data plot might not be the true utility, and while it would be quite difficult to claim that one could perfectly model utility the next section will bring out some of the major disadvantages of this approach.

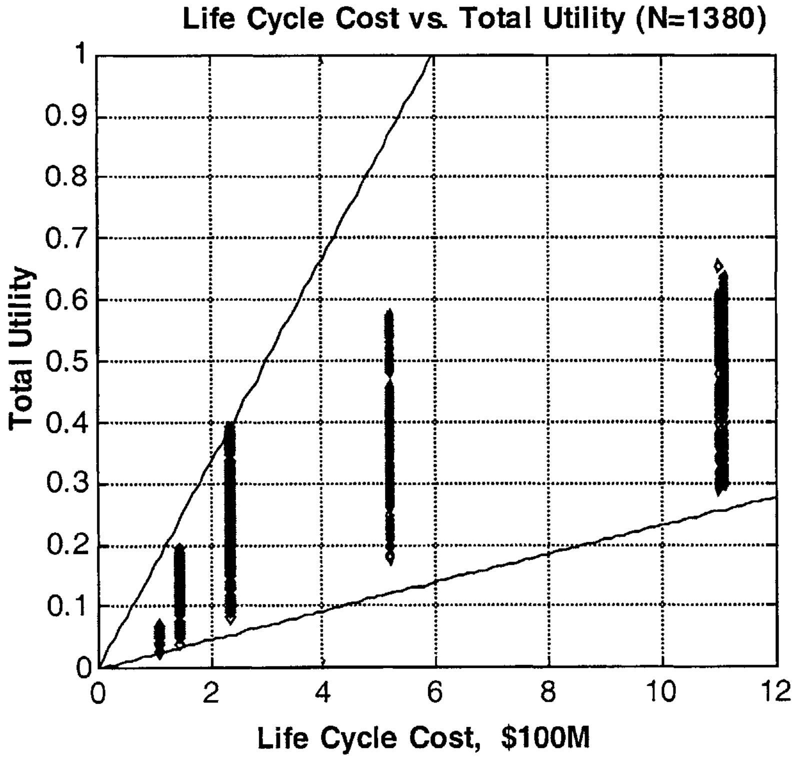

Figure 2 A-TOS Life Cycle Cost vs. Utility

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[23] One should note that in this A-TOS section the term utility is used very loosely, and not quite in conformity with the definition established in the introduction. The reason for this was to be consistent with the language used during this time of the process development. The notion of user value was referred to as utility even though that utility was not measured using formal psychometric techniques. Throughout the rest of the paper utility terminology will be consistent with the introduction definitions. As will be shown below there are very important mathematical distinctions, and properly understanding these distinctions is fundamental to the integrity of any process that claims to aggregate preferences. Proper aggregation is one of the most controversial facets of the MATE-CON process...can all preferences legitimately be combined into a single metric? Multi-attribute utility theory, discussed in the next section, proposes such aggregation, but the assumptions and details of this process must be clearly understood.

Figure 3 shows some of these difficulties right away. The plot shows the disaggregate utilities plotted on the vertical and horizontal axes with the color shaded according to cost. Here it is possible to see that the value is highly dependent on the weights imposed on each mission, and it does not account for the fact that the simultaneity of the two missions could detract or improve the overall utility.

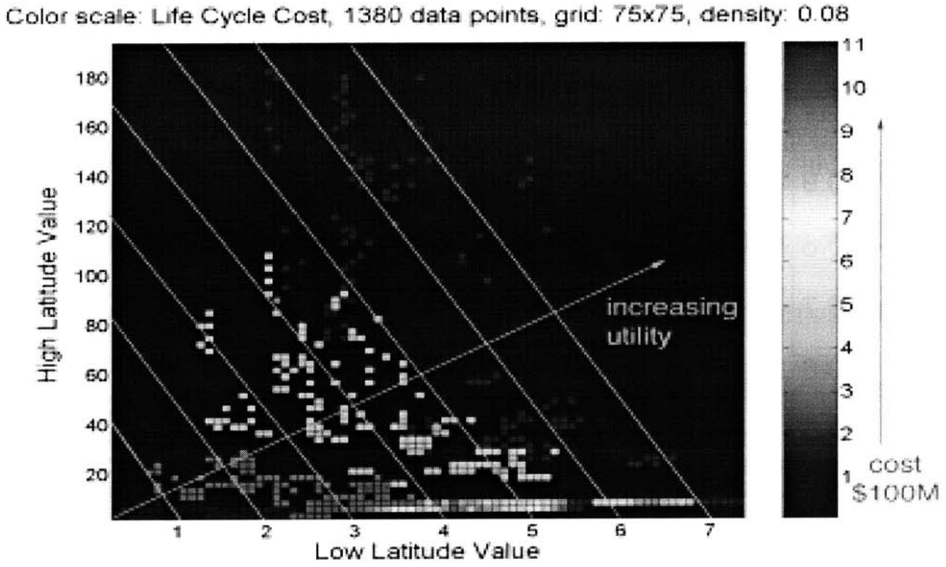

Figure 3 A-TOS Cost/Value Plot

The fundamental problem was the need to determine the "value" of an architecture to the customer. The "value" and cost of each architecture were to be the primary outputs of the A-TOS tool. The notional information flow that was modified from GINA is shown in Figure 4. In A-TOS this was captured through the "value" function that assigned accumulated points each time the architecture performed "valuable" tasks in the course of a simulation. These points were termed utility during the time of development. Each architecture would get a score for each mission. The score for the low latitude mission ranged from 1-8. The score for the high latitude mission ranged from 1-200, though there was no hard upper bound. In theory they could have infinite utility or be infinitely good just based on these two metrics. Results of the simulations were plotted in three dimensions: high latitude value, low latitude value, and cost. This was the means by which decision-maker preferences were aggregated to inform decision process in architecture selection.

Several problems plagued the A-TOS value capture method. First, it became clear that the two major preferences of the decision-maker were in direct conflict, but it was not possible to easily weigh the combined benefit versus cost. There was no pareto frontier of architectures.[24] Additionally, the scales of worst and best values for the value were arbitrary. The values could be normalized, however due to the lack of a hard upper bound on the high latitude utility, the normalization would not be strictly correct. Additionally, there was at first no ability to compare the two separate values. Does a 0.8 high latitude value correspond to a 0.8 low latitude value? Further interviewing with the decision-maker revealed that he valued the low latitude mission "about twice" that of the high latitude mission. This information led to an iso-value curve on a high latitude value versus low latitude value plot of 2 to 1.

$$V(X) = g(X_1, X_2, \ldots, X_n) \qquad \text{high latitude value}$$

$$V(Y) = h(Y_1, Y_2, \ldots, Y_m) \qquad \text{low latitude value}$$

Additionally, a total architecture value variable was defined as a weighted sum of the two separate mission values.

$$V(X,Y) = a_X V(X) + a_Y V(Y)$$

Total value = high latitude value + 2*low latitude value

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[24] Pareto, Vilfredo, *Manuale di Politica*, Societa Editrice Libraria, Milano, Italy, 1906. Translated into English by A.S. Schwier as *Manual of Political Economy*, Macmillan, New York, NY, 1971. Cited in Jilla 2002.

The problem with linear weighting is that it does not account for tradeoffs in value to the customer. *Complementary goods* will both result in higher value if both are present together. *Independent goods* will not result in additional value based on the presence of another good. *Substitute goods* will result in lower value if both are present, with it preferred to having one or the other present. These effects would be present in a multi-linear value function.

$$V(X,Y) = a_X V(X) + a_Y V(Y) + a_{XY} V(X) V(Y)$$

In this case, if $a_{XY} > 0$, X and Y are complements; if $a_{XY} < 0$, X and Y are substitutes; if $a_{XY} = 0$, there is no interaction of preference between X and Y. However, this form was not used in A-TOS. It was assumed that there was no interaction of preference. The lack of a rigorous value-capture and representation process in A-TOS resulted in an unsettling weakness of the results, (at least in an academic sense). It became clear that a more formal and generalized approach was needed for aggregating decision-maker preference if the models of these tradespaces were going to ever provide a useful decision tool for architecture selection.

2.4 NOTIONAL FLOW FOR MODELING A TRADESPACE

While questions remained about the robustness of the metrics for evaluating the tradespace after the A-TOS exercise there were significant strides made in formalizing the method of modeling a tradespace of architectures[25] by building on the GINA framework. Fundamentally, the development of these models has the purposed of meeting the macro objectives of nurturing innovation through looking at a broad possibility of solutions (MO1). Requirements should not specify a point design until the designer provides the decision-maker with other potential

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[25] The term architecture, like many terms throughout systems engineering, is riddled with stigmas. Some consider the differences between what is referred to here as an architecture as nothing more than a variation of parameters. Certainly, more work should be done on standardizing the system engineering lexicon, but for now this thesis will assume the definitions found in the glossary.

solution points. The other advantage is the increased level of technical rigor in the early stages (MO2). The long-term advantage is that key drivers can be recognized as early as possible providing direction for the entire design enterprise. This section will outline the generalized modeling approach that was used in A-TOS, B-TOS, and X-TOS. The development of these models will leave a placeholder for the final evaluation algorithm. The evaluation scheme has already been discussed for A-TOS, but the improvements to evaluation will be developed in much greater detail in the next Chapter.

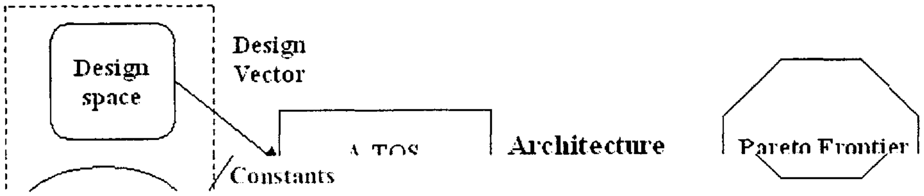

Figure 4 A-TOS Tradespace Modeling Information Flow

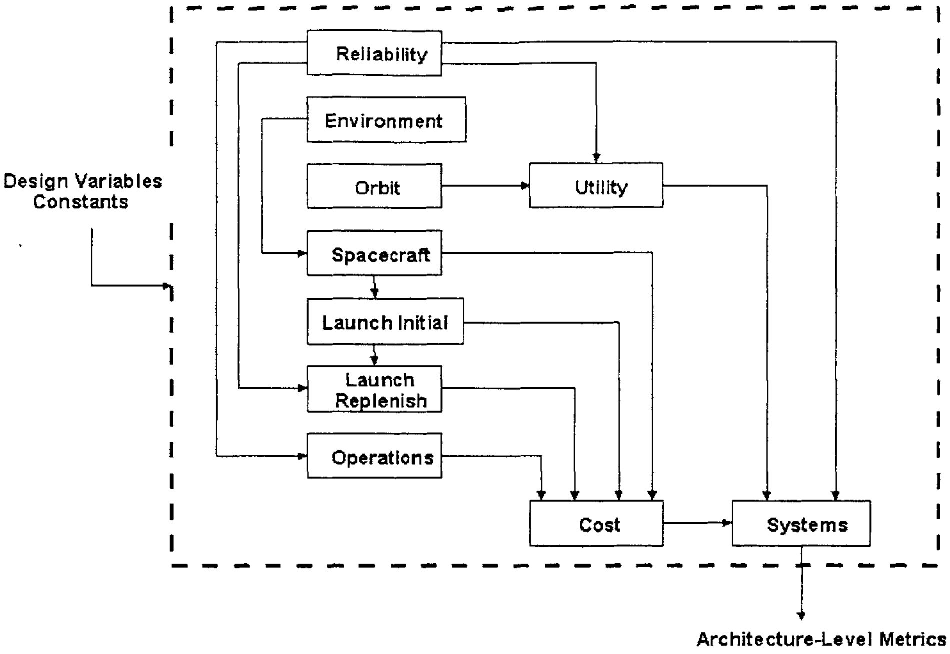

Figure 5 A-TOS Model Decomposition

To model the system it is fundamental to understand the necessary outputs of the model. Obviously, knowing the inputs and outputs are the first step. In this case the outputs are measures of the performance of the various system architectures, measures that allow the architectures to be evaluated against one another. Again, this will be taken up more rigorously in the next section, but for now these parameters to determine value will simply be referred to as model outputs. Once the model outputs have been determined the modeler can better understand the architecture trade study variables that will act as the input. It is important in developing these design variables that the designer verifies that the variables will have an impact on the model output. A typical tool used for this evaluation is Quality Functional Deployment (QFD). If they do not impact the model output there is no reason to include them in the design vector.

Figure 4 shows the notional flow of information in the model. The flow is initiated by a constants space and a design space. In developing any systems there are particular resources and constraints that drive the design. These things define the environment in which the designer works, and correctly ordering them is the difference between a good and a poor design. Several different classes of parameters are needed for the model:

1. Design variables – the changes to the design that are possible, what things can the designer manipulate in the design? They must meet two criteria:
    a. They are things that the designer has the capacity to change.
    b. They are things that can alter the output.
2. Constants – are those things that the designer is not interested in or cannot change. The following are not criteria but rather classes:
    a. Scientific Constants – physical constants that are typically well known.
    b. Decision-maker Defined Constants – include parameters that are fixed because of a constraint imposed by the decision-maker.
    c. External Constants – fixed parameters as a result of an external factor
    d. Assumed Constants – assumptions made to limit design complexity

All of these parameters are either in the design space or the constants space.[26] Evaluating different design vectors is the purpose of this entire process for each populated vector defines one architecture. By wisely choosing those variables that will define the architecture, a multitude of designs can be considered and comparatively evaluated. It is the purpose of the designer to wisely determine which parameters can be manipulated and which among those will

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[26] The list of design variable criteria and constant categorization were adapted from, Joyce M. Warmkessel and Nathan P. Diller, *Applying Multi-Attribute Utility Analysis to Architecture Research for the Terrestrial Observer Swarm*. Digital Avionics Conference, Daytona Beach, Florida. October 2001.

affect the performance of the system. Designing is populating the design vector with parameters that provide good alternatives for the decision-maker, thereby educating the decision-maker so that the ultimate decisions are as informed as possible. The inputs to the model then typically flow through a series of modules. In the cases discussed here these are Matlab modules. While some of these are general to the development of any model it is worth considering a few main issues as they relate to modeling architecture tradespaces in this context:

1. It is possible to either create innovation through opening the tradespace or restricting innovation through complexity of model development
2. Developing sufficient fidelity in the model with known uncertainty or outputting nonsense that is little better than power point engineering.
3. One must trade between a generalized model or a computationally efficient model.
4. It is critical to ensure sufficient software development experience among the modelers.
5. Improvements should be made by incorporating tradespace searchers as means of more complete tradespace modeling.[27]

The actual construction of the tradespace comes from selecting which parameters of the architecture will be varied. This activity determines the design variables that will compose the design vector and determining these variables dictates the concept selection. The population of the tradespace then comes from selecting how many values of each design variable will be included in the enumeration. This is a very important point because as one would suspect the growth of the tradespace is exponential with the increased number of design variables and increased number of values over which to enumerate. Obviously when the design vector

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[27] Jilla, C.D., Miller, D.W., and Sedwick, R.J., "Application of Multidis-ciplinary Design Optimization Techniques to Distributed Satellite Systems," *Journal of Spacecraft and Rockets*, Vol. 37, No. 4, 2000, pp. 481-490.

includes some continuous variables it is impossible to fully enumerate the tradespace, for the tradespace is in reality infinite, and the complexities of even simple models can quickly congest current top of the line PCs. As a result the selection of design variables and their enumeration is still to a large degree an art.

2.4.1 Design Vector

Essentially, one must go through the design vector and consider what values are reasonable for each of the variables in the vector. Again, this is critical because limiting the enumeration too excessively could result in a failure to analyze the best option for the decision-maker, but enumerating too much of the tradespace might drive computation times so high that the decision will be made before the computation is complete.

Knowing the general preferences of the user it was necessary to consider the possible means that a Terrestrial Observer Swarm (TOS) could meet those needs. Selecting the conceptual approach for the architecture comes in developing the list of design variables. These design variables define the tradespace and are considered to be the critical aspects of the architecture that can be varied to affect the user utility. Below lists both the design variable at the chosen values over which the tradespace was enumerated. The first three variables deal with the orbit-level, the next two are swarm-level, and the final one is a trade of different spacecraft functionality.

Table 4: A-TOS Design Vector

A-TOS DESIGN VARIABLES	
•Bulk Orbit Variables	
–Swarm inclination	63.4°
–Swarm perigee altitude (km)	200 – 800
–Swarm apogee altitude (km)	200 – 800
–Swarm argument of perigee	0°
–Number of orbit planes	1
–Swarms per plane	1
•Swarm Orbit Variables	
–Subsats per swarm	1 – 26
–Number of subplanes in each swarm	1 – 2
–Number of suborbits in each subplane	1 – 4
–Yaw angle of subplanes (a vector)	±60°
–Maximum satellite separation	1 m – 200 km
•Non-orbit Variables	
–Mothership	(yes/no)
Total # of Explored Architectures = 1380	

After collecting the attributes and selecting the design variables it was possible to determine the main inputs and outputs for the model. For B-TOS the model consisted of several Matlab modules. The primary purpose of the model is to input a design vector that defines an individual architecture and measure the performance of that architecture with respect to the decision-maker's preferences. In order to do this well it is important to first have the design scoped and the initial selection of the performance metrics selected-attributes with complete definitions. Quite simply the vectors are the inputs and the attributes are the outputs and it is obviously impossible to develop a model if the desired inputs and outputs are unknown. Once these inputs and outputs are selected it is then the purpose of the model to measure the performance of the physical system.

Keep in mind, the information for the design trades are only as accurate as the model. If the model is not capable of correctly determining the performance or attributes of different architectures, it is not possible to make decisions based on utility. The utility function requires valid attribute values if it is to be accurate. If the model cannot output those attributes the utility values are not legitimate for architecture trades.

3 EXPLORATION BASED ON MULTIPLE ATTRIBUTES

This Chapter seeks to address macro problems 3 and 4 introduced in Chapter 1by dealing with the difficulty of evaluating a tradespace with a common and complete criterion—decision maker preference—a criterion that can be generalized for any aerospace system design.[28] In the most simplistic terms MATE-CON is analyzing the various options using Multi-Attribute Utility Theory for the capture and aggregation of preferences to create a common metric to analyze those options

3. **Lack of regard for the complete preferences of the decision maker:** This results from the failure of the designer to be able to quantitatively aggregate a diverse variety of preferences, by understanding what the decision-maker wants not what the designer wants to build for the decision-maker. Fundamentally it arises from the designer's hastiness and lack of desire to pursue and capture sufficient communication with the decision-maker.
4. **Inaccurate characterization of decision maker preferences:** In the problem arises from the inability of the decision makers to explicate their preferences and maintain those preferences throughout the design process. The decision makers need means to clarify their preferences so that they can act more rationally. Under current processes either they do not know what they want or if they do know they will change their mind. There is a need to create more static and dynamic consistency or at least clearer recognition of the

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[28] It is important to note that while one should collect the preferences of the user (chapter 3) prior to conducting modeling and simulation (Chapter 2) the sequence of the thesis comes from the chronological development of the process.

inconsistencies and the underlying causes of those inconsistencies (i.e. recognizing changes in the environment). Failure to recognize these inconsistencies undermines the designer's ability to create a valuable design.

Multiple Attribute Tradespace Exploration with Concurrent Design (MATE-CON) seeks to capture and aggregate decision maker preferences for the conception and evaluation of a multitude of system designs and thereby create and propagate a common and continuous metric of value for communication throughout the design enterprise.

3.1 INTRODUCTION

Why create? This question is one the most fundamental of designers, yet many times it is pushed behind several layers of other concerns. The goal is that this question be ubiquitous throughout the design enterprise. MATE-CON attempts to make that question. The most rudimentary answer to that question is to satisfy the decision-maker's preferences. This chapter presents the emergence of an additional process that was eventually incorporated into the broader MATE-CON process. The purpose of this segment of the process is to ensure that the fundamental motivator, decision-maker preference, is established for propagation throughout the design enterprise, and it seeks to develop a systematic means of addressing the previously stated macro problems three and four:

3. Insufficient regard for the complete preference set of all decision makers. This problem is largely from designers presuming that they know what the decision-maker wants when really they just know what they want to build for the decision-maker.
4. Disconnects between communicated and actual decision maker preferences.

While number three is a result of the designer's hastiness and lack of desire to pursue communications with the decision-maker, problem four is attributed to the inability of decision-makers to know and communicate their preferences.

These two major problems could be summed up by saying that the decision-makers do not clearly know what they want and the designers do not appropriately extract the decision-makers' preferences. The objective of this chapter is explain how multi-attribute utility theory can provide a formal means by which the decision-maker can communicate true preferences to the designer. By providing this systematic framework it is proposed that the designer will obtain a better understanding of the decision-maker's preferences.

Furthermore this process should extract from the decision-maker a quantitative means by which preferences can be communicated and verified. The desire is to be able to take a multitude of the decision-maker's preferences and wisely combine them into a single metric by which all architectures can be measured. Multi-attribute utility theory (MAUT) makes such a claim, and when reflecting on the disadvantages of the value function used in A-TOS it seemed that MAUT was the optimal remedy.[29]

Again, this chapter is going to follow the development of MATE-CON via the TOS projects. In this case B-TOS will be the primary exercise of interest in that the application of MAUT to space system design, in the context of MATE-CON, was first applied in this exercise.[30] This theory seemed to provide a good replacement for the "value" function used in A-TOS. It provides for a systematic technique for assessing decision-maker "value", in the form of preferences for attributes. Additionally, it captures risk preferences for the customer. It also

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[29] Adam Ross, an MIT graduate student (2000 – Ph.D) has been the primary contributor to applying utility theory into space system design in the MATE-CON context.

[30] The B-TOS design study was conducted by a group of MIT Aeronautics and Astronautics Graduate students enrolled in 16.89 Space Systems Engineering taught by Daniel Hastings, Joyce Warmkessel, and Hugh McManus.

has a mathematical representation that better captures the complex trade-offs and interactions among the various attributes. In particular, the strength of multi-attribute utility analysis lies in its ability to capture a decision-maker's preferences for simultaneous multiple objectives.

3.2 B-TOS: INTRODUCING THE PROBLEM

Concerned by the ad hoc nature of the A-TOS "utility" function, the second iteration of the Terrestrial Observer Swarm, B-TOS, sought to incorporate a more formal utility theory.[31] One advantage that MAUT has over GINA is that it offers more flexibility and can be more easily adapted to the specific mission studied, since not all space systems are used strictly as communication networks. Instead of using the same performance parameters for all missions based on information network theory, attributes that characterize decision-maker desires are defined for the specific mission. MAUT maps decision-maker customer-perceived metrics (attributes) to the decision-maker value space (utility). This theory has been used in manufacturing materials selection and to help in airport design, but it seems that this was the first application of the theory to the design of complex space systems, which was the very intent of B-TOS.

One main advantage of MAUT is that it offers a rigorous mathematical basis for complex tradeoffs. As in the GINA process, cost is kept as an independent variable and used after the tradespace study to choose the best tradeoff between performance and cost. An extension of this notion will be briefly explored in this chapter even though it has not yet been completely employed into a design exercise. The extension is instead of keeping a monetary value of cost as

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[31] Adam M. Ross, an MIT Aeronautics and Astronautics and Technology and Policy graduate student, was introduced to this theory in Richard de Neufville's Dynamic System Planning at MIT and innovatively foresaw the potential of its application to space system design.

the independent variable, the independent variable will be expense. This expense, like utility will be composed of multiple attributes. These multiple attributes can be considered the multiple resources that the decision-maker is willing to provide as input to the system throughout its lifetime, while utility attributes are the multiple outputs the decision-maker expects to derive from the system throughout its lifetime. The combination of MAUT with GINA forms the basis of Multi-Attribute Tradespace Exploration (MATE)[32].

The primary factor for being able to do comparisons is creating a common metric. Fundamentally, the purpose of the aerospace system should be to provide value. This section will discuss the theory behind one such way of providing that common metric. It relies on economic and psychometric theory as a means of developing interviews for decision-makers and establishing a metric that aggregates these varied preferences. This is multi-attribute utility theory, and while there may be different and/or better means of creating an aggregated value metric, this research has primarily used this approach. It is therefore important to have a baseline understanding of the approach.

3.3 THEORY

While the matter has been taken up briefly in the previous section it is difficult to over-emphasize the need for reaching the highest possible degrees of mathematical rigor in developing a method that claims to aggregate a decision-maker's preferences into a single number. This is certainly a key intellectual point of MATE-CON. There are some good and some very poor methods of aggregating these preferences. The wise aggregation requires

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[32] Nathan Diller and Adam Ross conceived this name while at a NASA, New Design Paradigms conference in Pasadena CA. After Diller presented the B-TOS project findings and process and the two felt that the process needed a name and with over one hundred iterations of acronyms the two arrived at MATE. The CON was added shortly thereafter, once the need for concurrent engineering was realized.

significant mathematical understanding with recognition of the importance of psychometrics, statistics, and decision theory.

Significant skepticism of such a process arises from the frequent poor application of such aggregation techniques. Having seen improper applications of these methods some question the legitimacy of being able to combine all decision-maker preferences into a single metric? As will be shown below there are very important mathematical distinctions between value functions and formal multi-attribute utility functions. Properly understanding these distinctions is fundamental to the integrity of any process that claims to aggregate preferences. Multi-attribute utility theory proposes such an aggregation technique, but the assumptions and details of this process must be clearly understood. With these associated complexities anyone wishing to employ MATE-CON should have a clear understanding of this section.

A key difference between a "value" and a "utility" is that the former is an ordinal scale and the latter a cardinal one. In particular, the utility scale is an *ordered metric scale*. As such, the utility scale does not have an "absolute" zero, only a relative one. One consequence of this property is that no information is lost up to a positive linear transformation (defined below). It also means that the ratio of two numbers on this scale has no meaning, just as a temperature of 100°C is not four times as hot as a temperature of 25°C. The Celsius scale is an example of an ordered metric scale.[33]

Another difference is that "utility" is defined in terms of uncertainty and thus ties in a person's preferences under uncertainty, revealing risk preference for an attribute. It is this property along with other axioms that result in a useful tool: a person will seek to maximize

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[33] Richard de Neufville, *Applied Systems Analysis: Engineering Planning and Technology Management*, McGraw-Hill Publishing Co., New York, NY (1990). (See chapter 18 for a discussion regarding value and utility functions.)

expected utility. This is not true for value, which does not take into account uncertainty.[34] This definition gives utility values meaning relative to one another since they consider both weighting due to the attribute and to continuous uncertainty. In summary, the value function captures ranking preference, whereas the utility function captures relative preference.

3.3.1 Background

Before continuing, the term "attribute" must be defined. An attribute is a decision-maker preference. The power of MAUT is that this attribute can be a concrete or fuzzy concept. It can have natural or artificial units. All that matters is that the decision-maker being assessed has a preference for different levels of that attribute in a well-defined context. This powerfully extends the limitations of a value function in that it translates customer-perceived metrics into value under uncertainty, or utility. MATE-CON uses utility as a transformation from preference metric-space into decision-maker value-space.

The process for using utility analysis includes the following steps:

1. Defining the attributes and their ranges
2. Constructing utility questionnaire
3. Conducting initial utility interview
4. Conducting validation interview
5. Constructing utility function

These steps are discussed in more detail in the following sections. The remainder of this section will address the theoretical and mathematical underpinnings of MAUT.

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[34] Ralph L. Keeney and Howard Raiffa, *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*, John Wiley & Sons, New York, NY (1976). (See chapter 4 for a discussion of single attribute utility theory.)

As mentioned previously, a utility function, $U(X)$, is defined over a range of an attribute X and has an output ranging from 0 to 1. Or more formally,

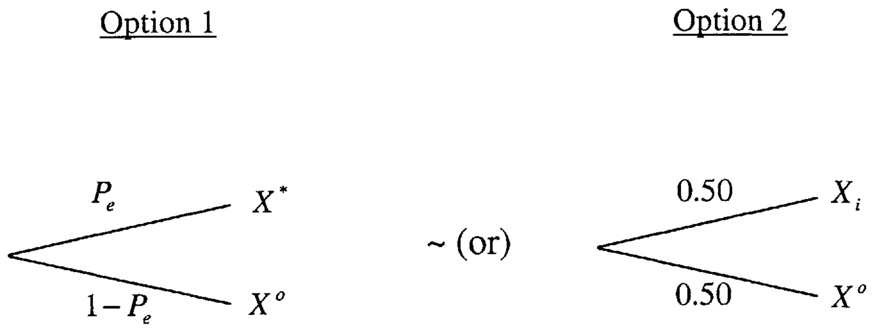
$$0 \le U(X) \le 1, \qquad X^o \le X \le X^* \text{ or } X^* \le X \le X^o$$

$$U(X^o) \equiv 0 \qquad U(X^*) \equiv 1$$

X^o is the worst-case value of the attribute X.

X^* is the best-case value of the attribute X.

Single attribute utility theory describes the method for assessing $U(X)$ for a single attribute.[35] In *Applied Systems Analysis,* de Neufville justifies adjustments to this method in the light of biased experimental results from previous studies. The recommendation is to use the lottery equivalent probability approach (LEP). It involves asking questions seeking indifference in the decision maker's preferences between two sets of alternatives under uncertainty. For example, a lottery is presented where the decision maker can choose between a 50:50 chance for getting the worst value X^o or a particular value X_i, or a P_e chance for getting the best value X^* or $1-P_e$ chance for getting the worst value. A diagram often helps to visualize this problem.



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[35] The theory was brought into modern thought by von Neumann-Morgenstern in 1947. See Ralph L. Keeney and Howard Raiffa, Decisions with Multiple Objectives: Preferences and Value Tradeoffs, John Wiley & Sons, New York, NY (1976). Chapter 4 provides a discussion of single attribute utility theory and von Neumann-Morgenstern single attribute utility functions.

The probability P_e is varied until the decision-maker is unable to choose between the two options. At this value, the utility for X_i can be determined easily by

$$U(X_i) = 2P_e$$

This directly follows from utility theory, which states that people make decisions in order to maximize their expected utility, or

$$\max\{E[U(X)]_i\} = \max\left\{\left(\sum_j P(X_j)U(X_j)\right)_i\right\}$$

Once the single attribute utilities have been assessed, MAUT theory allows for an elegant and simple extension of the process to calculate the overall utility of multiple attributes and their utility functions.

There are two key assumptions for the use of MAUT.

1. *Preferential independence*

That the preference of $(X_1', X_2') \phi (X_1'', X_2'')$ is independent of the level of $X_3, X_4, \ldots, X_n$.

2. *Utility independence*

For utility independence the "shape" of the utility function of a single attribute is the same, independent of the level of the other attributes. "Shape" means that the utility function has the same meaning up to a positive linear transformation, $U'(X_i) = aU(X_i) \pm b$. This condition is more stringent than preferential independence. It allows us to decompose the multi-attribute problem into a function of single attribute utilities. (See derivation below for mathematical implications.)

If the above assumptions are satisfied, then the multiplicative utility function can be used to combine the single attribute utility functions into a combined function according to

$$KU(\underline{X})+1=\prod_{i=1}^{n}\left[Kk_iU_i(X_i)+1\right]$$

- K is the solution to $K+1=\prod_{i=1}^{n=6}\left[Kk_i+1\right]$, and $-1<K<1$, $K\neq 0$. This variable is calculated in the *calculate_K* function.
- $U(\underline{X})$, $U(X_i)$ are the multi-attribute and single attribute utility functions, respectively.
- n is the number of attributes (in this case six).
- k_i is the multi-attribute scaling factor from the utility interview.

The scalar k_i is the multi-attribute utility value for that attribute, X_i, at its best value with all other attributes at their worst value. The relative values of these k_i give a good indication of the relative importance between the attributes—a kind of weighted ranking. The scalar K is a normalization constant that ensures the multi-attribute utility function has a zero to one scale. It can also be interpreted as a multi-dimensional extension of the substitute versus complement constant discussed above. The single attribute utility functions $U(X_i)$ are assessed in the interview.

If the assumptions are not satisfied by one or several attributes, the attributes can be redefined to satisfy the assumptions. (Many, if not most, attributes satisfy these conditions, so reformulation should not be too difficult.) Sometimes utility independence is not satisfied for several attributes. Several mathematical techniques exist to go around this problem. For example, define aggregate variables as made up of the dependent attributes. The aggregate variable is then independent. Nested multi-attribute utility functions can then be used in this case, with each function made up of only independent attributes.

3.3.2 Derivation of multi-attribute utility function[36]

If attributes are mutually utility independent,

$$x = \{x_1, x_2, \ldots, x_n\}$$

$$U(x) = U(x_i) + c_i(x_i)U(\bar{x}_i) \qquad i = 1,2,\ldots,n-1 \tag{1}$$

$\bar{x}_i$ is complement of x_i.

setting all $x_i = x_i^o$ except x_1 and x_j $j = 2,3,\ldots,n-1$

$$U(x_1, x_j) = U(x_1) + c_1(x_1)U(x_j) = U(x_j) + c_j(x_j)U(x_1)$$

$$\frac{c_1(x_1) - 1}{U(x_1)} = \frac{c_j(x_j) - 1}{U(x_j)} \equiv K \qquad j = 2,3,\ldots,n-1 \tag{2}$$

$$U(x_1), U(x_j) \neq 0$$

if $U(x_j) = 0$ → $U(x_1) = c_j(x_j)U(x_1)$ → $c_j(x_j) = 1$

from (2) above,

$$c_i(x_i) = KU(x_i) + 1 \quad \text{for all } i = 1,2,\ldots,n-1 \tag{3}$$

Multiplying (1) out yields:

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[36] Ralph L. Keeney and Howard Raiffa p. 289-291.

$$\begin{aligned} U(x) &= U(x_1) + c_1(x_1)U(x_2, x_3, \ldots, x_n) \\ &= U(x_1) + c_1(x_1)\left[U(x_2) + c_2(x_2)U(x_3, x_4, \ldots, x_n)\right] \\ &\quad \vdots \\ &= U(x_1) + c_1(x_1)U(x_2) + c_1(x_1)c_2(x_2)U(x_3) \\ &\quad + \cdots + c_1(x_1)\cdots c_{n-1}(x_{n-1})U(x_n) \end{aligned} \tag{4}$$

Substituting (3) into (4)

$$\begin{aligned} U(x) = U(x_1) &+ \left[KU(x_1) + 1\right]U(x_2) \\ &+ \left[KU(x_1) + 1\right]\left[KU(x_2) + 1\right]U(x_3) \\ &\quad \vdots \\ &+ \left[KU(x_1) + 1\right]\cdots\left[KU(x_{n-1}) + 1\right]U(x_n) \end{aligned} \tag{5a}$$

or

$$U(x) = U(x_1) + \sum_{j=2}^{n} \prod_{i=1}^{j-1} \left[KU(x_i) + 1\right]U(x_j) \tag{5b}$$

There are two special cases for equation (5b): where *K*=0, *K*≠0.

K=0:

$$U(x) = \sum_{i=1}^{n} U(x_i) \tag{6a}$$

K≠0:

Multiply both sides of (5b) by *K* and add 1 to each.

$$KU(x) + 1 = \prod_{i=1}^{n} \left[KU(x_i) + 1\right] \tag{6b}$$

since $U(x_i)$ means $U(x_1^o, \ldots, x_{i-1}^o, x_i, x_{i+1}^o, \ldots, x_n^o)$, it can also be defined as

$$U(x_i) \equiv k_i U_i(x_i),$$

with k_i defined such that $U_i(x_i)$ ranges from 0 to 1. This function, $U_i(x_i)$, is the single attribute utility function.

Plugging this result into (6b) results in the multiplicative multi-attribute function used in B-TOS.

$$KU(x)+1=\prod_{i=1}^{n}\left[Kk_iU_i(x_i)+1\right] \tag{7}$$

Since it was unlikely to be the case that the attributes did not have cross terms for utility, the utility team assumed that $K \neq 0$, and this equation is valid. Notice that it captures the tradeoffs between the attributes, unlike an additive utility function, such as (6a).

3.4 PROCESS

Fundamentally, this process is aimed at quantifying decision-maker preferences. The attribute definitions are a mechanism for decision-maker interaction and allow iteration of the definitions and expectations. This iteration should encourage clearer understanding of the underlying drivers for future requirements. Once the design team has gained a deep understanding of the mission and the requirements on the performance of the system, the architectures are evaluated on the basis of their utility and expense. The choice of the architecture is therefore motivated by a real trade study over a large tradespace.

The first step consisted of defining the attributes. Attributes are the quantifiable parameters that characterize how well the architecture satisfies the decision-maker needs (customer-perceived metrics). The attributes must be chosen carefully to accurately reflect the customer's wants for the system. Additionally, to truly characterize the system, the attributes should completely represent the system. The attributes themselves are not unique, but instead should represent a non-overlapping subspace of characterization since they are the basis for making trades. After defining the attributes, a utility questionnaire is developed. The questionnaire is then used in an interview with the decision-maker to find the shape of his preferences. A follow-up validation interview corroborates the results and adds confidence. The multi-attribute utility function is derived from the interview results and represents the utility that the decision-maker perceives from a given set of attribute values.

3.4.1 Preliminary definition of attributes

Early in the process, an initial list of possible attributes is defined for the specific mission under study. The attributes have to be defined in collaboration with the decision-maker and this is one of the crucial steps in the development of this method. Therefore, the preliminary definitions of the attributes should be submitted to the decision-maker to discuss any modifications. **It is fundamental to have attribute definitions that can easily be written in the form of a solvable equation.**

3.4.2 Determination of the ranges

The decision-maker is then asked to provide a range for each attribute corresponding to the best case and the worst case. The best case is the best value for the attribute from which the user can benefit; a better level will not give him more value. The worst case corresponds to the attribute value for which any further decrease in performance will make the attribute useless. These ranges define the domain where the single attribute preferences are defined. The attributes have to describe decision-maker needs accurately in order to meaningfully assist the trade study. Therefore, an iterative process is necessary to refine the list of attributes.

3.4.3 Interview

The aim of the interview was to determine the preferences of the customer. Two different kinds of information are required to calculate the utility for every combination of values of the attributes:

1. The single attribute preferences, which define the shape of the preference for each attribute within the worst/best range defined by the customer, independent of the other attributes.
2. The corner points, which allow a correlation between the single attributes and combinations of other attributes.

The probabilistic nature of the questions takes the issue of risk into account. It is important to consider the utility of different attributes based on uncertainty.

3.4.4 Validation Interview

The final step in the process was to check the consistency and the validity of the results of the first interview to ensure that the customer's preferences were captured. This was done during a second interview. This interview was also used to check the assumptions of the utility theory: preferential and utility independence. The utility independence is established using lottery equivalent probability method, for a specific level of each individual attribute. Two sets of questions should be asked using this format. One set is constructed with all of the other attributes at their best-case values and the other with the other attributes at their worst-case values. Ideally, these two levels of utility should match, as the levels of the other attributes should not change the customer's utility for the attribute in question. The preferential independence must also be established. These are asked for the customer's preference between two combinations of two attributes, given that each of the other attribute levels remains constant. After asking a set of questions of this format, the same questions should be asked again (in random order) with the other attributes at a different level. These questions established preferential independence of all of the attributes.

In addition to the utility and preferential independence questions, a set of questions should be asked to determine the customer's perceived utility for random mixes of varying levels of the attributes. These questions should be done in a probability format similar to that used in the other parts of the interview. The primary difference was that the decision-maker was asked to evaluate random mixes of the six attributes vs. the cases where all of the attributes are at their best and worst case values. The random mix values do not correlate closely with the values calculated with the original multi-attribute utility function. These results most likely reflect the extreme difficulty, if not the impossibility, for a person to comprehend more than a 6-dimensional problem. The MAUT approach for capturing utility therefore plays a very useful role, allowing a person to look at a smaller dimension problem, which they can comprehend.

3.5 B-TOS: IMPLEMENTING A SOLUTION

The Air Force Research Laboratory (AFRL) at Hanscom AFB was interested in developing a formation flying space system for characterizing the ionosphere. As electromagnetic waves pass through the earth's ionosphere, variations in electron density result in scintillation causing anomalies in navigation, communication, or data collection between the surface and space-based platforms. Currently, there are very limited methods of characterizing the ionosphere, consequently it is not possible to predict or correct for these anomalies.

Again, the GINA approach is to convert a space system into an information flow diagram in order to apply the optimization rules developed for information systems to space systems. This tool allows the design team to compare different architectures on the basis of performance and cost so as to be able to determine the best architecture. To reiterate the process follows the following path:

1. Define the mission objective by writing the mission statement
2. Transform the system into an information network.
3. Define the four Quality of Service metrics for the specific mission considered (signal isolation, information rate, information integrity, availability) so as to quantify how well the system satisfies the customer.
4. Define the quantifiable performance parameters: performance, cost and adaptability.
5. Define a design vector that groups all the parameters that have a significant impact on the performance or cost of the architecture. It represents the architecture tested.
6. Develop a simulation code to calculate the details of the architecture necessary to evaluate the performance parameters and cost.
7. Study the trades and define a few candidates for the optimum architecture.

For this second TOS iteration the methodology was similar since it aims at the same broad objective: **Apply a standard metric to evaluate a full tradespace of architectures rather than around a point design.**

The fundamental difference is the metric, and in this respect MAUT offers more flexibility and can be more easily adapted to the specific mission studied. Instead of using the same performance parameters for all missions based on the information network theory, attributes that characterize the decision-maker preference are defined for the specific mission studied. Importantly, MAUT maps decision-maker perceived metrics (attributes) to the decision-maker value space (utility). This allows for a better fit with the expectations of the customer.

MAUT also offers a rigorous mathematical basis for complex tradeoffs. As in the GINA process, cost (and with more development expense) is kept as an independent variable and used in presenting the data of the trade space study to choose the best tradeoff between performance and cost or more generally utility and expense.

3.5.1 Detailed process

First, it was critical to determine the objective, which in this case was to design a conceptual swarm-based space system to characterize the ionosphere. The decision-maker must then develop a list of key preferences for the system. This is distinct from constraints, which the decision-maker imposes on the system. Again, B-TOS will provide an example for how multiple attributes can be aggregated to form a single architecture evaluation metric versus cost. In this case the decision-maker chose six primary attributes that would become the basis of the utility function and developed the corresponding definitions:

1. Spatial Resolution: Arc length of Earth between complete measurement sets.
2. Revisit Time: Time between subsequent measurements of the same point above the Earth.
3. Latency: Time delay from measurement to data reception by the end user.
4. Accuracy: Measurement error in angle of arrival data from ground beacons.
5. Instantaneous Global Coverage: percent of Earth's surface in view between subsequent measurements
6. Mission Completeness: Combination of missions performed (AOA, EDP, turbulence).

The first five attributes had natural units (square degrees, minutes, minutes, degrees, and % of globe between +/- inclination). The last attribute had artificial units (0-3) defined in concrete, customer-perceived terms.

For clarification, the electron density profile (EDP) is one of the primary means for understanding the structure of the ionosphere. Further information can be derived from angle of arrival (AOA) of ground-emitted wavefronts incident on the plane of the swarm. In this case, all of the spacecraft are in the same swarm. With these attributes defined it was then possible to conduct the multi-attribute utility interview. By nature these interviews were quite difficult and demonstrated a clear need for developing new methods of data collection for attribute preference. This process has been chosen as a tool to decide the best architectures to perform the three decision-maker defined missions (EDP, AOA and Turbulence missions). The objectives were to study the MAUT process and apply it for the first time to a space system design in order to choose the best family of architectures for a space-based ionospheric mapping system. The next sections will show how MAUT was applied to this mission.

The attributes must be chosen carefully to accurately reflect the decision-makers preferences for the system. The attributes have to be defined in collaboration with the decision-maker and this is one of the crucial steps in the development of this method. Therefore, the preliminary definitions of the attributes were submitted to the decision-maker to discuss any modifications. The decision-maker was asked to provide a range for each attribute corresponding to the best case and the worst case. The best case is the best value for the attribute from which the user can benefit; a better level will not give him more value. The worst case corresponds to the attribute value for which any further decrease in performance will make the attribute useless. These ranges define the domain where the single attribute preferences are defined. Additionally, to truly characterize the system, the attributes should completely represent the system. The attributes themselves are not unique, but instead should represent a non-overlapping subspace of characterization since they are the basis for making trades. After defining the attributes, a utility questionnaire is developed. The questionnaire is then used in an interview with the decision-maker to find the shape of the preferences. A follow-up validation interview corroborates the results and adds confidence. The multi-attribute utility function is derived from the interview results and represents the utility that the decision-maker perceives from a given set of attribute values.

3.5.1.1 The Importance and Difficulty of Attribute Selection

The attributes have to describe decision-maker needs accurately in order to meaningfully assist the trade study. Therefore, an iterative process is necessary to refine the list of attributes. This step was a major issue in the B-TOS process and it ended up being similarly important with the X-TOS experience. For illustrative purposes of this complexity a quick example of the B-TOS difficulties will be discussed.

First iteration:

Lifecycle cost was taken out of the attributes and kept as an independent variable that would drive the choice of the architecture at the end of the process. The first iteration was a discussion with the decision-maker to come to an agreement on the definition of the attributes. The number of attributes drives the complexity and the length of the process and therefore, one goal was to minimize the number of attributes while still capturing all the important drivers for the customer. Mission completeness was suppressed because the instrument primarily drove how well the EDP mission was performed, which was not part of the trade.

Second iteration:

The first understanding was that two missions were to be considered: EDP and Turbulence measurements. It appears that an additional mission was to be performed: Angle of Arrival measurements. The attributes were defined only for EDP measurements and so major modifications were required. The writing of the code had already been started and the aim was to minimize the modifications to the attributes. Only one attribute was modified: mission completeness. Mission completeness was reinstalled as a step function giving the number of missions performed. The decision-maker gave us a ranking of the missions to help us define this function. If EDP was not performed the mission was useless. The second most important mission was AOA, and last turbulence. So mission completeness was defined as: 0 for EDP, 1 for EDP/Turbulence, 2 for EDP/AOA and 3 for all three missions.

Third iteration:

Many issues emerged during the interview with the customer. Accuracy was left as EDP accuracy but it appeared to cause a problem. Accuracy was defined for EDP measurements but it became apparent that AOA accuracy was driving the accuracy of the whole system. EDP accuracy depends on the instrument, which is not traded, and on the error due to the fact that the satellite is still moving while taking measurements. The AOA mission requires a very accurate measurement on the order of 0.005 radians. This issue appeared during the interview. The first idea was to consider only the AOA accuracy since it was driving the system's accuracy but the AOA mission was not always performed. The second solution would have been to define a coupled single attribute preference curve but that was not possible because the two accuracies have very different scales. Finally it was decided that accuracy would have two different preference curves, one for EDP measurements and one for AOA measurements. If the AOA or turbulence missions were performed, AOA accuracy would apply, if only the EDP mission is performed, EDP accuracy would apply.

Moreover, the definition of the time resolution was refined. It was originally defined as the time interval between two consecutive measurements, however the decision-maker had no real interest in this information. Instead, the decision-maker wanted the time between two consecutive measurements at the same point in space. To capture this modification, the attribute was changed to Revisit Time. In essence, the design team was thinking in terms of a moving (satellite-centric) coordinate frame, while the decision-maker was thinking in terms of a fixed (earth-centric) coordinate frame.

It is difficult to sufficiently emphasize the importance of this step of the process. Poor attribute definition completely undermines the ability of the MATE-CON process to adequately account for decision-maker preference, subsequently undermining the ability to evaluate a full tradespace of architectures accurately. Furthermore, poor attribute definitions lead to outrageous difficulties in modeling the system for in order to model the system one must calculate all of the attribute values. The framing of the definitions can certainly complicate this process. To check if these definitions are being done optimally one can sometimes just look at the units of the attributes.

Stepping forward to the X-TOS example again, one attribute was **Sample Altitude**, defined as "height above standard sea-level reference of a particular data sample, measured in kilometers. (Data sample = a single measurement of all 3 instruments)." This seems like a reasonable definition until one begins modeling. Unfortunately, it was not completely clear how frequently there would be a single measurement of all 3 instruments. This required a selection of an arbitrary frequency of sample in the orbit, so that in one orbit it was required to calculate a vector of utilities. Each utility was taken and divided by the total sample periods per orbit. The complication then came in the requirement to pass this vector of utility altitudes through the whole model until the end when all of the utilities could finally be summed. To avoid this problem the attribute could have likely been defined as an average altitude per orbit without losing information of the decision-makers preference. This would have been particularly appropriate since the decision-maker in this case had not preference for sampling a diversity of altitudes and would have significantly reduced the complexity of the modeling problem to leave more time to add fidelity.

3.5.1.2 Interview

The aim of the interview was to determine the preferences of the customer. Two different kinds of information are required to calculate the utility for every combination of values of the attributes:

1. The single attribute preferences, which define the shape of the preference for each attribute within the worst/best range defined by the customer, independent of the other attributes. Figure 6 is an example of one single attribute preferences obtained from the interview in B-TOS, for determining the users preference for accuracy. Certainly, more accuracy is better, but the question is asked in such a way that it is possible to determine how much utility the user will get out of the system which provides an accuracy between 0 and 0.5 degrees of error.

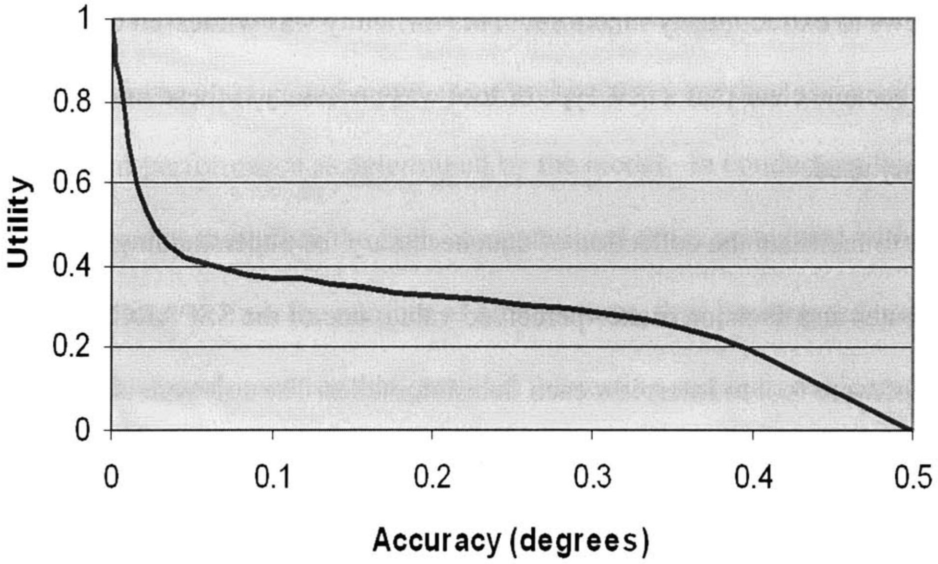

Figure 6 Example B-TOS Single Attribute Utility

2. The corner points, which allow a correlation between the single attributes and combinations of other attributes.

The probabilistic nature of the questions takes the issue of risk into account.

The final step in the process was to check the consistency and the validity of the results of the first interview to ensure that the customer's preferences were captured. This was done during a second interview. In the B-TOS case, this interview was also used to check the assumptions of the utility theory: preferential and utility independence. Assumption checking is usually done during the first interview, but time limitations pushed it to the second interview.

3.5.1.3 Multi-attribute Interview Software Tool

One thing that was found in conducting the utility interviews was that a complete interview takes more time than the decision-maker is really willing to offer. This coupled with the fact that the questions become a bit mundane highly complicates the implementation of commonly used utility interviews to extract utility functions. This difficulty was witnessed during the B-TOS project and it became clear that a new type of tool was necessary if these interviews were going to be commonly used.

In order to facilitate the collection of data necessary for understanding the relationship between attributes and decision maker-perceived value, one of the SSPARC research students developed a software tool to interview each decision maker. The software is based on the paper-centric face-to-face utility interview standards and formats used in the B-TOS project. The Multi-attribute Interview Software Tool (MIST)[37] is an Excel-based graphical user interface (GUI) that, after being prepared by the engineer with knowledge of the attributes for each decision maker, is fully deployable to the decision maker. This deployment allows the interviewee to take the interview at his convenience, removes biases that are present in human to human interviews, and makes the interview into a kind of game, reducing pressure and making it fun. The interviewer can easily speak to the interviewee by phone to clear up any misunderstandings and email provides for rapid turnaround for analysis and verification of data. MIST integrates nicely with the process in that it simplifies the utility interview, reducing time from over six hours to less than three in the case of the B-TOS and X-TOS projects. In the future, MIST may become web-based, streamlining further the communication between the decision makers and MATE engineers.

3.5.2 Interpreting Utility

Again, the purpose of this chapter is to demonstrate how utility theory can provide a common metric for evaluating multiple architectures it is important to consider a few examples

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[37] Satwiksai Seshasai, *A Knowledge Based Approach to Facilitate Engineering Design.* MIT M.Eng. June 2002.

to illustrate how that evaluation is possible. Recall that each architecture is found by varying the design variables over some enumerated range, these architectures are then assigned a particular utility based upon their performance as determined by the model. In conducting this analysis one it is important to remember that given the high computational times associated with each architecture, it was critical to limit the number of architectures, thus limiting the tradespace enumeration to only those architectures that provided interesting and reasonable trades. Limit here is a relative measure. For the B-TOS case over four thousand architectures were analyzed, and in C-TOS there were some sixty thousand.

After the enumeration and code run it was possible to compare different architectures with the first comparisons based on the cost vs. utility plots. While having output all of these series allows one to look at correlations between several of the parameters, the primary relationships of interests are the cost versus utility. Figure 7 is the entire enumeration plot. It is important to note that the x-axis is the lifecycle cost. This is the cost for the spacecraft, launch, and operations for five years. Later in the chapter an approach will be developed whereby the independent variable will also be a negative utility, or an expense.

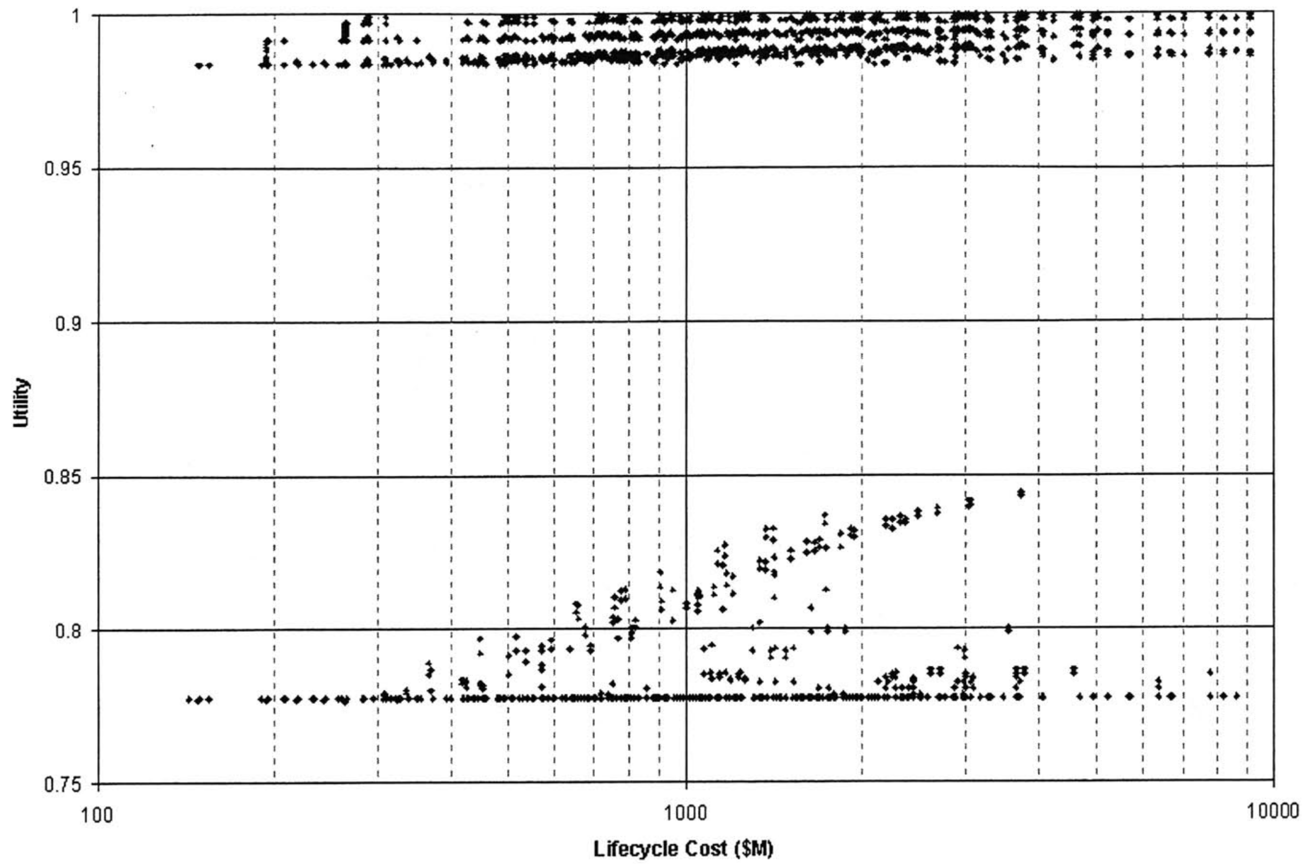


Figure 7 B-TOS Full Enumeration Lifecycle vs. Utility

By examining these plots one begins to see the advantage of this approach, for it highlights a multitude of drivers of the architecture that might not otherwise be understood. The lower values are those architectures that were unable to conduct the beacon angle of arrival mission. The ability to conduct this mission was one of the design variables. Following plots will focus on the higher utilities.

Figure 8 focuses on those higher utilities, and displays an interesting point regarding the swarm radii. In Figure 8, notice the bands for each of the different swarm radii, increasing utility with increasing swarm radius. Note that this is only a subset of the whole enumeration. This is primarily a result of the higher accuracies that come from the increased baseline length. Each band is correlated with the four different swarm radii selected for enumeration. One can recognize the difference in cost between the different radii looking for example the number of points less than one billion dollars for the 0.18 km band compared to the 50 km band at the top of the plot. In order to prevent ambiguity, more satellites are needed to fill as the swarm radius increases. This increase in number of satellites manifests itself in the increased cost.

The final cost vs. utility plot for analysis is shown below. This plot only considers those architectures with utilities greater than 0.98 and lifecycle costs less than one billion dollars. This plot highlights a few architectures of greatest interest.

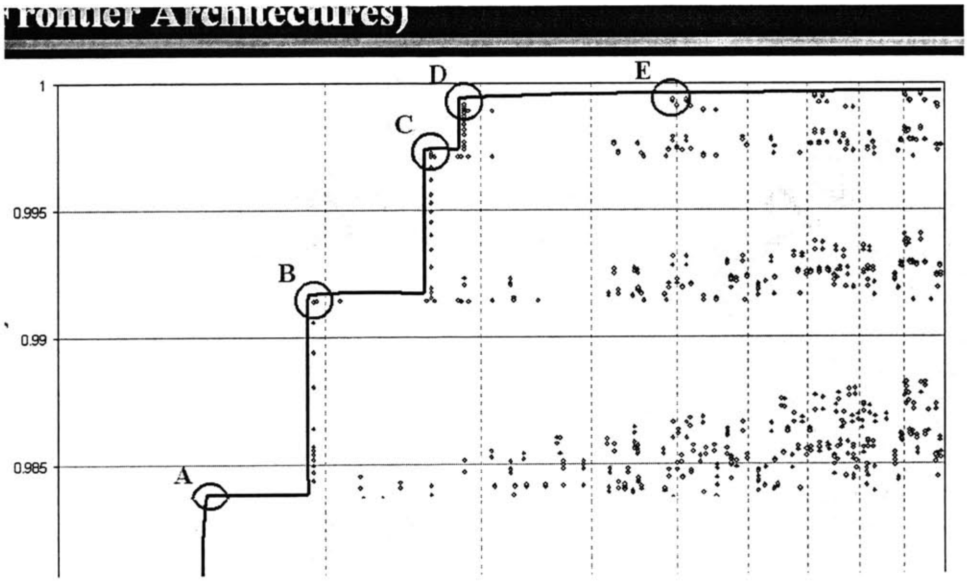


Figure 8 B-TOS Key Architecture Cost vs. Utility Plot

The vertical lines highlight additional enumeration with the only change being swarm radius. Points A-E are considered the knee points that will be used for further analysis and indicate the relative lowest cost with highest utility. After the initial run of the code, another short enumeration was performed varying only swarm radius. These architectures are seen near the dark stepped line. This showed that the highest utility swarm was one that had the largest radius. Again, recognize that this model does not indicate the best architecture, but instead gives the decision-maker a few key architectures on which to focus attention.

As was mentioned earlier experience shows that many have a difficult time in understanding plot of utility that is a non-dimensional value from zero to one. It is therefore important for anyone that attempts to implement MATE-CON to understand how to articulate these plots. In the previous figure architectures A, B, C, D, and E are identified. Returning to the data files, it is possible to reconsider the particular characteristics and the true attribute performance of each of these satellites. The following tables will elucidate some of the key differences between these different selected architectures.

Table 5 Frontier Architectures

Design Variable	A	B	C	D	E
Altitude(km)	1100	1100	1100	1100	1100
Number of Planes	1	1	1	1	1
Swarms/Plane	1	1	1	1	2
Satellites/Swarm	4	7	10	13	13
Swarm Radius (km)	0.18	1.5	8.75	50	50
Functionality Study	5	5	5	5	5

Table 6 Spacecraft Functionality Study 5

Spacecraft Type	Mothership	Daughtership
Number/Swarm	1	> 3
Payload (TX)	Yes	No
Payload (RX)	Yes	Yes
Processing	Yes	No
TDRSS Link	Yes	No
Intra-Swarm Link	Yes	Yes

Table 5 shows the orbit and swarm level variables for architectures A-E. All five points turned out to be configuration study five, which is shown in Table 6. The figure summarizes the design variables for the five different architectures. Notice that the main difference between the architectures is the different radii. Point E is an option with one more swarm per plane. Later, this will be indicated by an increase in re-visit time and increasing utility; however, the nominal increase in utility as indicated by the plot, comes at a significantly increased cost.

Table 7 B-TOS Key Architectures Attributes, Utility, and Cost

Point	**A**	**B**	**C**	**D**	**E**
Spatial Resolution (deg)	4.36	5.25	7.34	9.44	9.44
Revisit Time (min)	805	708	508	352	195
Latency (min)	3.40	3.69	4.36	5.04	5.04
Accuracy (deg)	0.15	0.018	0.0031	0.00054	0.00054
Inst.Global Coverage	0.29	0.29	1.15	2.28	4.55

Utility	0.9835	0.9914	0.9973	0.9992	0.9994
IOC Cost ($M)	90	119	174	191	347
Lifecycle Cost ($M)	148	194	263	287	494

Returning to the output data allows a more detailed examination of the different architectures, specifically their performance seen in both the values for attributes and the total utility value. It is critical that the customer understand the ability to transform from the univariate utility value to the multivariate attribute values. Table 7 shows the utility values transferred back to attributes space with corresponding costs for the five key architectures. Additionally, the different costs are shown for both total lifecycle and IOC. The plot can be presented to the decision-maker for the decision-maker to have a look at the most likely architectures from which to select. If there have been changes in decision-maker preference since the utility interview the decision-maker has the flexibility to choose the architecture based on adjusted preferences among the attributes, whose values are shown corresponding to each architecture.

For each of the specified points, the values for the five attributes are shown along with the associated utility value and IOC / Lifecycle costs in millions of dollars. Further detail may be considered for each of the architectures as well. For instance, the decision-maker may want to get an idea of the spacecraft characteristics. Again, these data are part of the model output and can be relatively easily assembled for initial spacecraft design considerations. In this case, all architectures had spacecraft characteristics based on configuration study five and gave the below values. Additionally, cost can be analyzed for each different design point.

In the B-TOS case, after running the model five key architectures were identified. All of them very closely met the needs of the decision-maker with slight differences in attributes that the decision-maker could examine and decide upon an architecture with the most preferred attributes. To develop a more accurate trade model there are several areas requiring further research. Overall, for the first round of a conceptual architecture this model is quite useful.

X-TOS provides another example of how one should interpret utility. It deals with a space mission designed to improve upper atmosphere drag measurements. The user again was AFRL, and this particular mission had been launched once. Unfortunately, a launch failure prevented the orbital insertion, and so AFRL is looking for another mission on which to launch its instrument suite. In doing this they were interested in considering how the space system architecture might be improved. Following the same order the first issue was to determine the customer's preferences. In this case the attributes had a particular range of best case and worst case:

1. Data Life Span: Elapsed time between the first and last data points. [0 –11 years]
2. Sample Altitude: Height of data sample. [150-1000 km]
3. Diversity of Latitudes: The spread of latitudes in the data [0-180 degrees]
4. Time Spent at the Equator: Time per day spent near the equator. [0-24 hours/day]
5. Latency: Time from collection to transmission. [1-120 hours]

Next it was necessary to consider the different design variables that would affect these attributes. The table below lists the six main design variables followed y

Table 8 X-TOS Design Variable Impact

Variable:	**First Order Effect:**
Orbital Parameters:	
•Apogee altitude	Lifetime, Altitude
•Perigee altitude	Lifetime, Altitude
•Orbit inclination	Lifetime, Altitude
	Lattitude Range
	Time at Equator
Physical Spacecraft Parameters:	
•Antenna gain (low/high)	Latency
•Comm Architechture (TDRSS/AFSCN)	Latency
•Propulsion type (Chemical / Hall)	Lifetime

Now that the design vector and the attributes are defined it was possible to begin the modeling. The modeling in this case did an enumeration of the different spacecraft types and after building a database of different spacecraft the spacecraft were enumerated through three different launch scenarios: 1) single satellite; 2) two satellites launched in parallel; 3) two satellites launched in series. The outputs of those different studies are shown below.

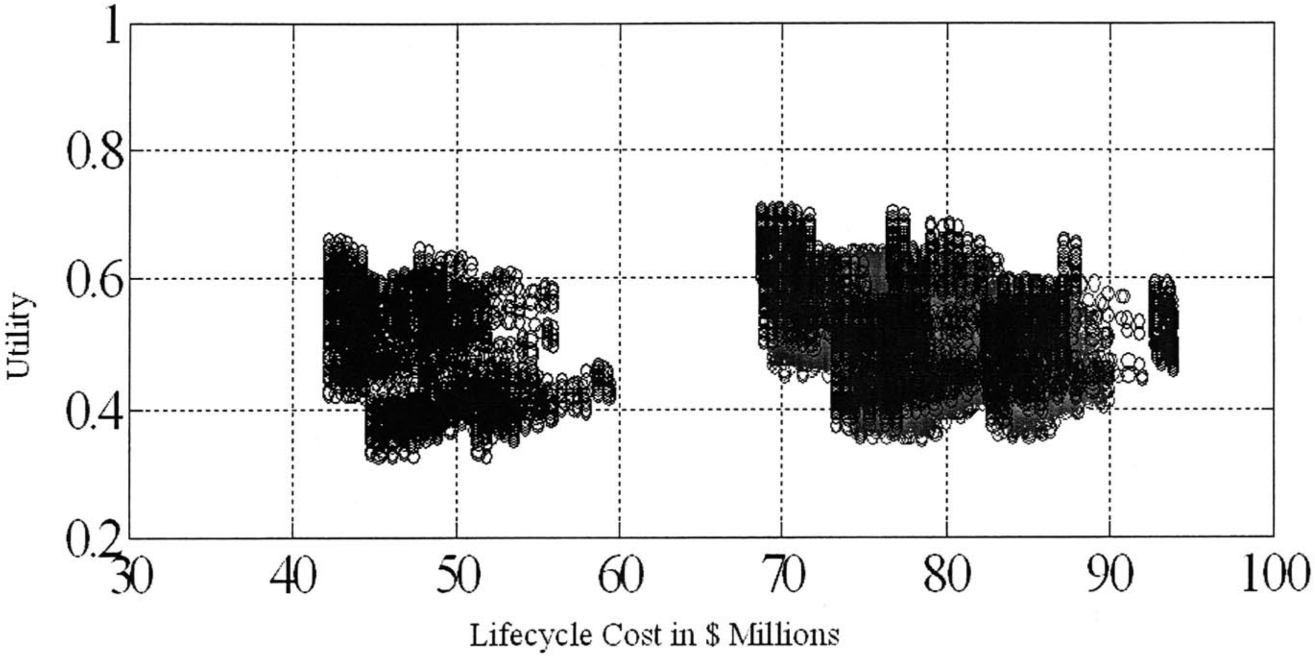


Figure 9 X-TOS Full Enumeration Cost vs. Utility

As one would expect the two-satellite case cost almost twice as much. The single satellite architectures are between forty and sixty million dollars. It is also clear that the higher utility in the two-satellite case it is better to launch two satellites in parallel, which broadens the coverage even though the series case could extend the data lifetime. In the single satellite case one sees that the highest utility actually comes at the point of lowest cost. This was a result of restrictions on launch vehicles.

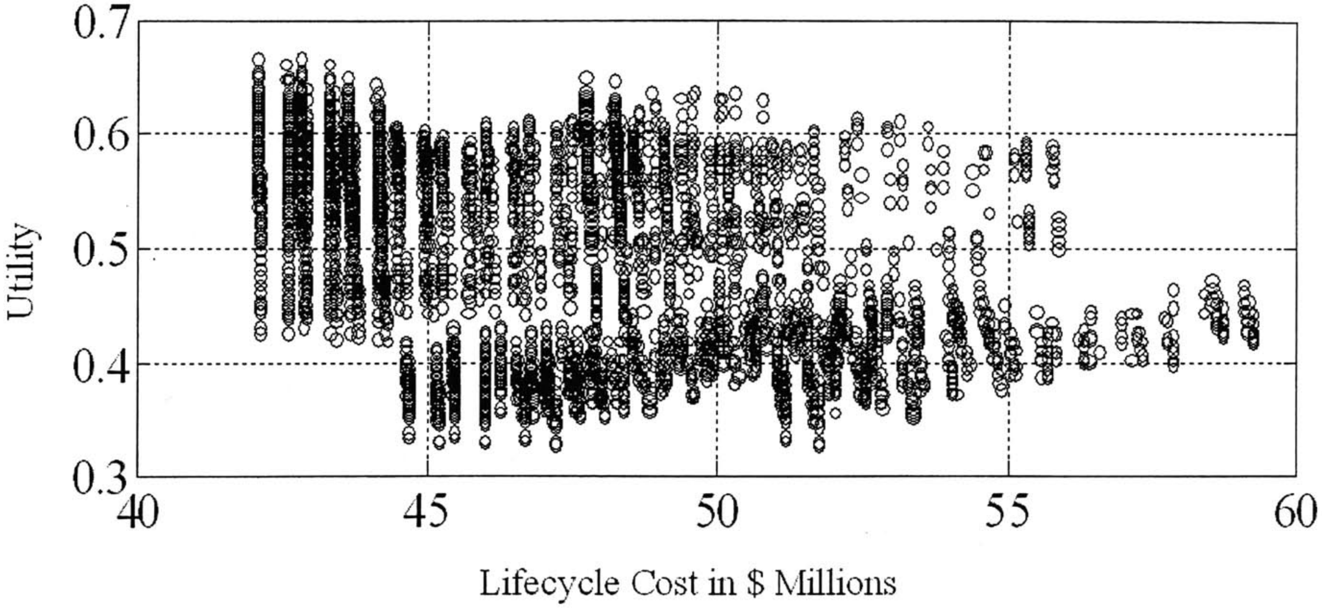


Figure 10 X-TOS Single Satellite Case

Overall, this case study showed that MATE-CON highlighted drivers at the architecture level that might otherwise not have been possible. This time the utility data will become another input into the concurrent design environment so that the utility can be constantly monitored and can provide a metric for trades at the conceptual spacecraft design level.

3.6 EXPENSE FUNCTIONS

As has been alluded to throughout this chapter, after recognizing the value of transforming a series of attributes values into a single value of utility, the question arose of whether it would be possible to take use a similar approach for cost. Specifically, can expense functions be developed to elucidate customer preferences for both monetary and non-monetary expenses? It seems that while there are multiple attributes of expected benefits of the space system, there are also multiple attributes of the cost of the space system. Ambiguities exist in understanding preferences for inputs and outputs to the space system, but notions of expense functions give greater tradespace exploration flexibility.

The intent is that this approach would highlight drivers of the design to better understand design trades just as is done in the utility approach. In an attempt to implement such an approach the B-TOS data files were used again under the light of two possible expense attributes of development time and initial operation cost. Based on an understanding the decision-maker has a preference for these two inputs to the space system design that are not necessarily linear expense functions for these two attributes were developed and plotted versus normalized expense for single attribute expense functions as is done in the utility case. These single attribute utility functions were developed for hypothetical expense functions base on expense preferences for development time and initial operation cost. For this case assumed that the decision-maker incurred significant expense if development time was greater than 3 years, and also assumed significant expense if IOC was greater than $250 million. The single attribute plots are show below.

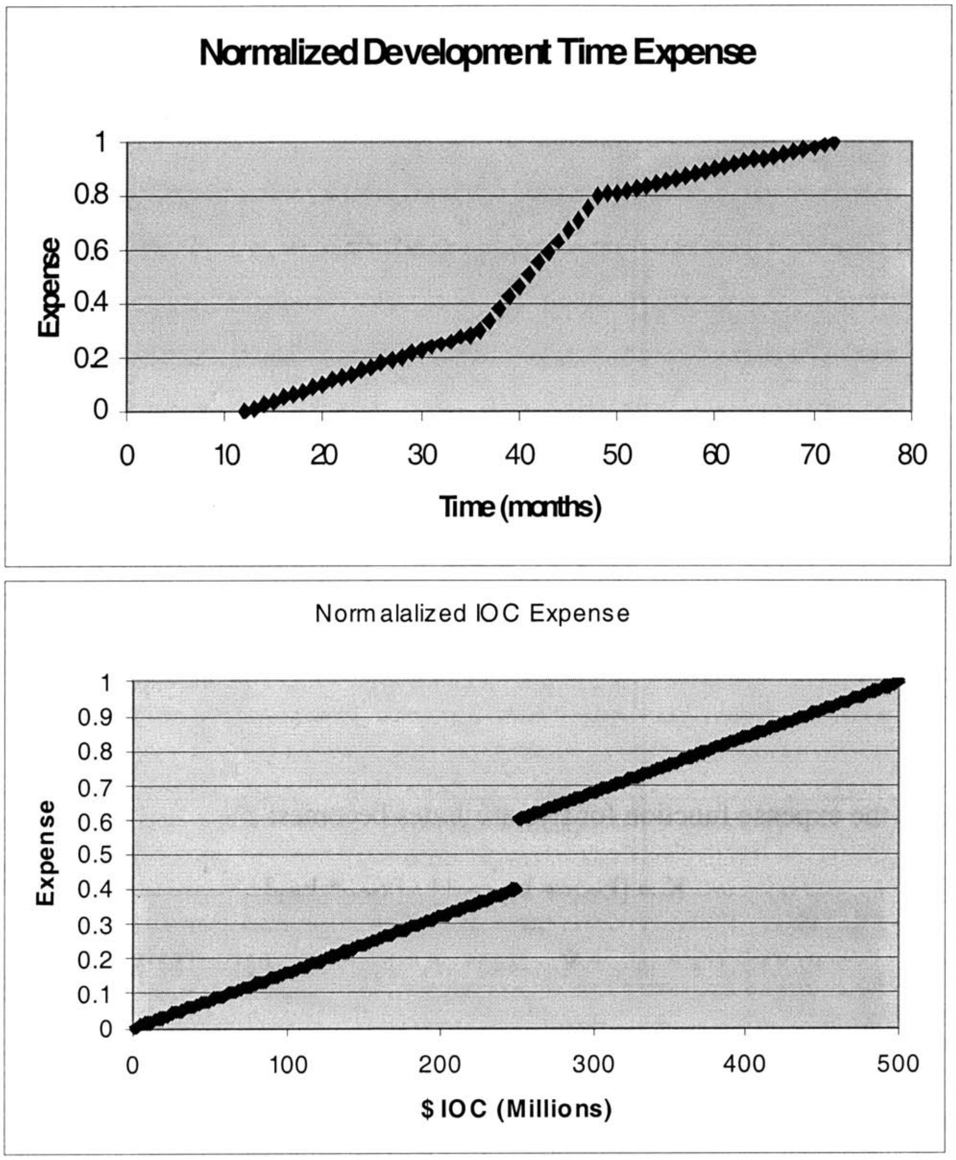
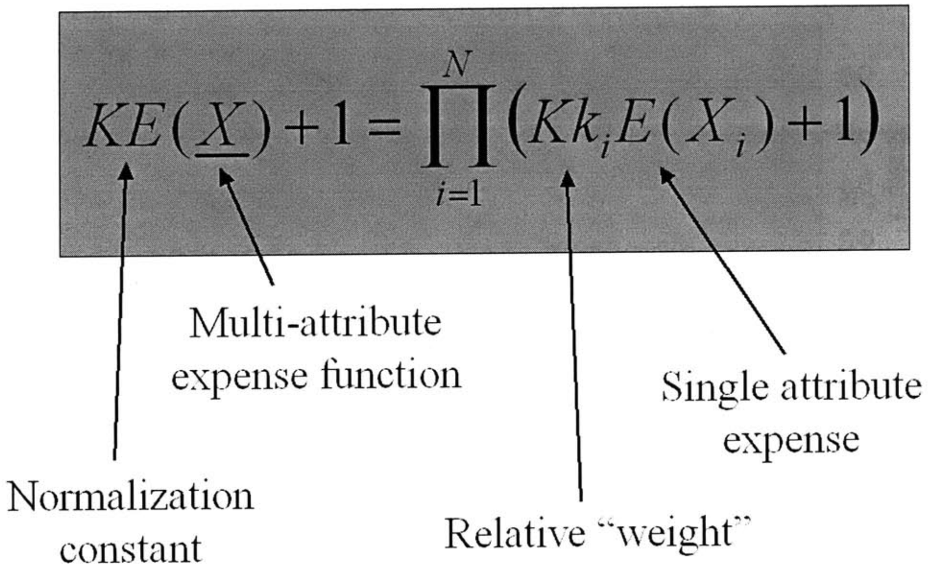


Figure 11 Single Attribute Expense Functions

Again following the utility example these expense attributes were combined to make a multiple attribute expense function using. Using SMAD a function was built for spacecraft development time. Based on this the normalized expense vs. utility was plotted for 4,033 different B-TOS architectures. It was then possible to consider how different preferences of development time and initial operation cost affected frontier architectures.

Multi-Attribute Expense Function*



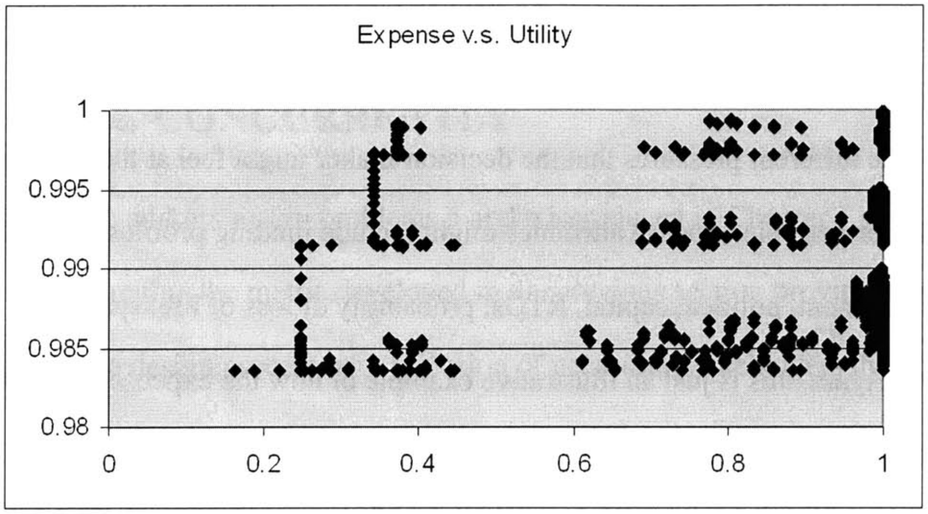
$$KE(\underline{X})+1=\prod_{i=1}^{N}\left(Kk_iE(X_i)+1\right)$$

After doing this the expense function for two attributes becomes:

$$K = [k_{IOC} + k_{DT} - 1] / [k_{IOC} * k_{DT}]$$

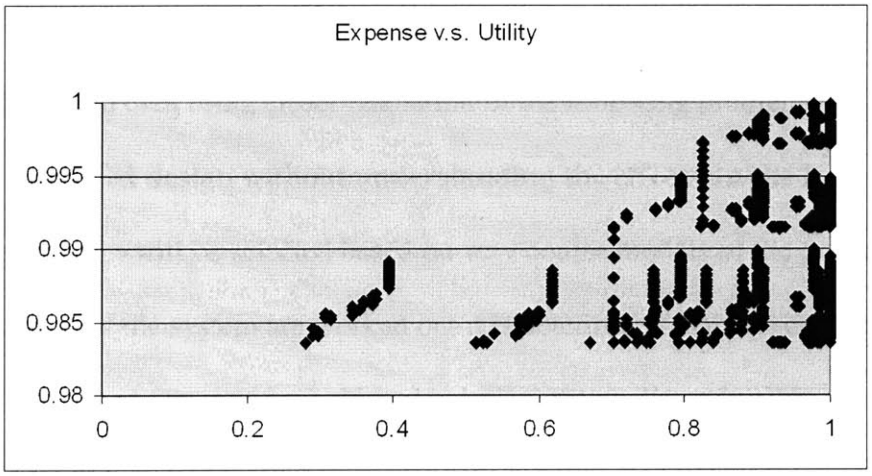
$$E(X) = [(K * k_{IOC} * X_{IOC}+1) * (K * k_{DT} * X_{DT}+1) - 1] / K$$

Different plots were then constructed by varying k_{IOC} and k_{DT} for changing preferences of the decision-maker. That is, when k_{IOC} was high, IOC is most important expense attribute. On the other hand when k_{DT} is high then there is a greater desire for quick development time.



IOC is the Driver: k(IOC) = 0.95 k(DT) = 0.1

Figure 12 Expense vs. Utility for IOC Focused Decision Maker



Schedule is the driver: k(IOC) = 0.15 k(DT) = 0.9

Figure 13 Expense vs. Utility for Schedule Focused Decision Maker

The two figures above are adjustments from Figure 8 of the B-TOS enumeration plot for the key architectures. In this case one can see how the pareto optimal frontier might change depending on the different pressures that the decision-maker might feel at the program progresses. Other possible expense attributes might include funding profiles, TDRSS time, technology investment, political capital, RTGs, probability of loss of life, space debris, diversity of vender, etc. Again, this is just an illustrative example of how the expense versus utility plots can provide important information to the decision-maker about where to invest further development funding. There is a significant amount of work done on characterizing political factors and uncertainty in initial

4 DESIGNING CONCURRENTLY

This Chapter seeks to address macro problems 5 and 6 introduced in Chapter 1 showing how it is possible to help ensure that the metric developed in the previous section provides a vision to pursue throughout the design process with inclusion of necessary stakeholders that interact with the design to ensure it validity and avoid surprises by unforeseen preferences or external pressures. In the most simplistic terms MATE-CON is improving the capacity to: 1) examine a broad variety of possible options; 2) analyze those options; 3) implement the best option. This Chapter takes on #3 by employing advances in concurrent engineering for simultaneous (immediate), common (all stakeholders), and continuous (intertemporal) propagation of the metric to detailed design. Utility theory establishes the metric concurrent engineering employs the metric. This should then bring closer resolution of the following problems:

5. **Pursuit of a detailed design without understanding the effects on the larger system:** Many times a design will be selected based on very course models of the potential system, and as the details of the system are worked out it is determined that this course model had a fundamentally flawed assumption making the design physically unfeasible. Conversely, as engineers work though higher fidelity design they find that it is necessary to make a modification from the original plan and in doing so they fail to realize the effect that the seemingly minor modification might have on the overall mission effectiveness. A language of expense and utility needs to be exchanged for the current language of requirements.
6. **Limited incorporation of interdisciplinary expert opinion and diverse stakeholder interest:** Many times designs will proceed with infrequent and low bandwidth interaction among the design specialists. This allows for oversights creating effective interfaces

frequently leading to costly re-engineering steps. Furthermore, in the initial design in efforts to maximize performance for minimum costs the designers fail to recognize the various stakeholders that will be interacting with the system that will in the end drive up lifecycle cost or reduce mission performance. These stakeholders might include the end user, the policy maker, the acquisition agent, the manufacturer, the logistician, the maintainer, or even the customer. Fundamentally there is a failure to recognize the holistic or interdisciplinary approach necessary for effective design.

Multiple Attribute Tradespace Exploration with Concurrent Design (MATE-CON) seeks to capture and aggregate decision maker preferences for the conception and evaluation of a multitude of system designs and thereby create and propagate a common and continuous metric of value for communication throughout the design enterprise.

4.1 INTRODUCTION

Imagine three engineers, each designing the thermal-control subsystem for a new satellite requested by a prospective commercial customer. Both are experienced and highly skilled; both have good tools at their disposal. They're trying to accomplish the same objective, but they're required to work in different environments, under vastly different circumstances. Consider for a moment the striking contrast in how they complete their tasks.

Scenario #1: The first engineer puts the finishing touches on his design. A week later, he attends a program team meeting with representatives from all involved subsystem disciplines and learns that while his design is impressive, it's too heavy. He goes back to the drawing board. In a couple of weeks, he's got a new design that's lighter. His colleagues give it a thumbs-up. But after a few days, the team learns that the customer has changed her mind about the payload performance requirements, so the entire mass budget has changed. It's back to the drawing board again.

Scenario #2: The other engineer puts the finishing touches on her design. She keys some values—power and thermal requirements, mass, and so on—into an electronic spreadsheet. She immediately receives feedback from the design lead, who tells her she's a bit over the mass budget. After 15 minutes of reviewing, recalculating, and consulting

> with the customer, the engineer makes a small change to the design. It's now within the mass budget. And the customer is pleased, to boot.[38]
>
> *Scenario #3*: A third engineer puts the finishing touches on the design. Immediately, after completing the adjustments she flips the MATE-CON visualization in her electronic spreadsheet and *she realizes* that *her decision* simultaneously reduced the customer utility and increased the customer expense. After 2 minutes of fine-tuning the subsystem with quick pre-coded pull-down menus she returns to her MATE-CON sheet and realizes that even though mass increased, she increased the customer utility and decreased expense. She immediately receives feedback from the design team lead, who asks her why she switched to the heavier component and she quickly reminds him that he is no longer working in the antiquated Aerospace Corp. Concept Design Center (CDC) but is working in a MATE-CON organization, where they no longer "point-design" to mass but they explore the tradespace to design to customer value.

The first three paragraphs were excerpts from a recent article in the Aerospace Corporation's *Crosslink* magazine where they noted that Scenario #2 "isn't just a fantasy; it's the way conceptual design studies are now being conducted at an innovative facility operating successfully at The Aerospace Corporation: the Concept Design Center (CDC)."[39] While the CDC has made great progress in advancing the state of the art in conceptual design they are one step behind the Space System Policy and Architecture Research Center where Scenario #3 was not just fantasy but it was the way that MIT's Space System Design course conducted their X-TOS design exercise in April of 2002.

The first two chapters of part one discussed how this research brought forth improved means of developing a tradespace of designs with technical models and the means of evaluating that tradespace based on the decision-makers true preferences. This final chapter of part one will introduce the mechanism by which this learning can be moved forward throughout the design enterprise to ensure that resources are not expended on designs without understanding the effects

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[38] Patrick L. Smith, Andrew B. Dawdy, Thomas W. Trafton, Rhoda G. Novak, and Stephen P. Presley , "Concurrent Design at Aerospace" *Crosslink* The Aerospace Corporation, Winter 2000/2001.

[39] *Crosslink.*

on the larger system and ensure that the design takes a truly interdisciplinary nature to avoid costly surprises late in the design.

4.2 TERMINOLOGY AND SCOPE

Before proceeding much further it is important to understand more specifically what is meant by concurrent design or its near synonym, concurrent engineering, since this phrase has taken on a variety of meanings. Many see concurrent design as nothing more than another modeling technique, but it seems that such a view fails to appreciate the full range of benefits of concurrent design. There are in fact, several strata of concurrent design or concurrent engineering as it is probably more frequently called. In the sense of The Aerospace Corporation Concept Design Center it is a room full of engineers from every spacecraft subsystem, connected with information technology and directed by a systems engineer. For the case of X-TOS concurrent design conformed to this instantiation. It does however take on a much broader definition to include "a disciplined, collaborative environment in partnership with industry, government, and academia."[40] When discussing the Army's new concurrent engineering program the author of a *Program Manager* articles says that collaboration makes the difference between standard modeling and simulation practices. The Army recognized that an, "integrated environment was needed where all the functions—from requirements analysis and concept generation through development, testing, and procurement to training and support—could collaborate through the use of models and simulations. In the past, these stakeholders had

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[40] Army Staff, "A Vision for SMART," cited in Bruce J. Donlin, Michael R. Truelove, "Simulation and Modeling for Acquisition, Requirements, and Training—SMART: Enabling the Transformation." *Program Manager*, January-February 2002, p. 63.

developed and used their own modeling and simulation in a stove-piped fashion, in many cases duplicating efforts that produced costly redundancies."[41]

In continuing to try to understand this word it is useful to consider concurrent engineering's "first definition" as noted by the Society for Concurrent Engineering, which recently changed its name to the Society for Concurrent Product Development (SCPD). In their literature they use the 1998 Institute for Defense Analysis definition, which defines concurrent engineering as, "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. This approach is intended to cause developers, from the outset, to consider all elements of the product lifecycle from concept through disposal, including quality control, cost scheduling, and user requirements."[42]

In trying to understand the full breadth of the notion SCPD provides further explanations that in the larger sense it involves, "the correct interplay of functional departments including customers and suppliers; and supporting infrastructure technologies. While in the more micro sense it includes, "the correct interplay of individuals whose intelligence and skill are necessary to successfully bring new products to market; and the sporting infrastructure technologies."[43] MATE-CON takes concurrent design to span this full spectrum as well. However, being that the MATE-CON design exercises thus far have been limited to the university environment, this chapter will discuss MATE-CON's application at the more micro sense for the SSPARC C-TOS and X-TOS designs and it will then extrapolate on these experiences to a discussion of the larger sense of concurrent design.

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[41] *Ibid.*

[42] *1998 Institute for Defense Analysis*, cited on the webpage of the Society for Concurrent Product Development (SCPD) http://www.soce.org/ce/ce4.html.

[43] The Society for Concurrent Product Development (SCPD) http://www.soce.org/ce/ce4.html.

4.3 ADVANTAGES OF CONTEMPORARY CONCURRENT DESIGN

While the virtues of the information might have been endlessly expounded upon, its benefits to design have only recently been realized. Concurrent engineering seeks to capture those benefits and incorporate them into a more holistic approach to design. *Business Week* reported that the benefits of CE include "30% to 70% less development time, 65% to 90% fewer engineering changes, 20% to 90% less time to market, 20% to 600% higher quality, and 20% to 110% higher white collar productivity."[44] Fundamental to the success is the ability to swarm experts on a design problem, optimizing potential synergies through tightly coupled groups. "Real-time interaction between specialists enables an accurate dialogue that resolves issues right away. With concurrent designing, a study can be completed in hours instead of months. And getting everyone—including the customer—together in the same place not only speeds up the process but also affords participants the ability to clear up misunderstandings with face-to-face communication."[45]

Its benefits are being seen across the product development community and even into defense acquisition reforms. The Army, in its attempt to design the Objective Force is employing a system called Simulation and Modeling for Acquisition, Requirements, and Training (SMART). "The concept of collaborative environments allows all stakeholders to contribute during the 'Concept and Technology Development Phase' and in the 'Systems Development Phase,' when inputs have the greatest impact. Bringing the end user into the

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[44] National Institute of Standards & Technology, Thomas Group Inc., and Institute for Defense Analysis, *Business Week*, April 30, 1990.

[45] Patrick L. Smith, Andrew B. Dawdy, Thomas W. Trafton, Rhoda G. Novak, and Stephen P. Presley , "Concurrent Design at Aerospace" Crosslink The Aerospace Corporation, Winter 2000/2001.

collaborative environment helps to ensure that the design meets the needs of the soldier."[46] With all of these great advantages one is sure to question how MATE-CON can improve these already highly effective processes.

4.4 MATE-CON AS AN ADVANCEMENT TO THE STATE OF THE ART

It is important to briefly return to the macro discussion of MATE-CON. In the most simplistic terms it is improving the capacity to: 1) examine all possible options; 2) analyze those options; 3) implement the best option. These are the three facets of MATE-CON and to achieve that end a framework is established to: 1) use improved contemporary modeling techniques to develop a broad set of possible designs (GINA); 2) use multi-attribute utility theory for the aggregation of preferences to create a common metric to analyze those options; 3) employ advances in concurrent engineering for simultaneous (immediate), common (inclusive of all stakeholders), and continuous (inter-temporal) propagation of the metric to detailed design. Utility theory establishes the metric concurrent engineering employs the metric. While any approach to design will always require some degree of art, this thesis suggest that requirements creation processes can still significantly gain from a more quantitative analysis. That being said one must understand that the analysis done by MATE-CON does not suggest that everything can be reduced to a number and equation. This final statement is one of the most important reasons that front-end design must include the notions of concurrent design. **There must be humans in the loop.**

It might also be fruitful to briefly return to the last two of the six macro questions that MATE-CON attempts to address:

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[46] Bruce J. Donlin, Michael R. Truelove, "Simulation and Modeling for Acquisition, Requirements, and Training—SMART: Enabling the Transformation." *Program Manager*, January-February 2002, p. 63.

5. Pursuit of a detailed design without understanding the effects on the larger system.
6. Limited incorporation of interdisciplinary expert opinion and diverse stakeholder interests.

While significant advances have been made in concurrent design, MATE-CON improves upon those processes by explicitly motivating the work that is done in the concurrent environment. To reiterate, MATE-CON's purpose is to simultaneously aggregate preferences to create a common and continuous metric for a design that can be easily communicated throughout the design enterprise. Concurrent design creates the capacity for the simultaneity in the process by getting all of the key stakeholders in a single room for design. Besides the work that is done in the design work, significant motivation is moved outside the design room. The participants in the concurrent design team are representatives from their various organizations, coming to the design session as an expert in their particular field. When the various participants in the design session return to their organizations they bring with them a broader understanding of the goal that is being pursued.

There is a need to incorporate the various decision-makers in the design. "Lean philosophy suggests that the values of the end users (such as communications managers and warfighters) should be considered." [47] The previous section mentioned the Army's development of the SMART system for a holistic for acquisition reform, and while it appears that this system will likely make great strides there are even more improvements to this approach that would employ the same techniques of collaboration to ensure that all of the critical stakeholders are considered. SMART does not provide a common aggregation of the multiple preferences of all of the decision-makers, and therefore it is in need of a more formal decision-making tool. The MATE-CON approach of using a utility metric as a means of communication of preferences that

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[47] Dr. Hugh McManus and Dr. Joyce Warmkessel, "Creating Advanced Architectures For Space Systems: Product And Process" AIAA 2001-4738.

can then be wisely aggregated for more effective trades, trades that incorporate all of the driving preferences from all of the driving stakeholders. It is this set of preferences that form utilities that must become the common language for effective collaboration. This utility language allows a common understanding of what *good* means for each stakeholder. Making explicit this notion of good ensures more synergistic collaboration.

Furthermore, in Scenario #3 from the beginning of the chapter it said, "immediately, after completing the adjustments she flips the MATE-CON visualization in her electronic spreadsheet and *she realizes* that *her decision* simultaneously reduced the customer utility and increased the customer expense." In ensuring that there is learning in the design organization it is important that each individual understands his or her actions are having an effect on the whole mission. It should not be a supervisor that tells them that they had an effect and that they could improve the design; rather the internal mechanisms should be in place so that such things are readily apparent to everyone in the design enterprise. Research has shown that the design process necessarily has a conflict resolution facet, and improved means of conflict resolution will result in improved designs. "Design rationale appears to be a crucial prerequisite for conflict resolution. Many of the conflict resolution strategies…require that we be able to identify the reasons for given design actions."[48] Expense and utility inherent in MATE-CON process provide that rationale. Furthermore, during A-TOS, a key finding was that "needs and constraints can be partially uncovered by good up-front work, but during the process they needed continual updating at finer levels of detail."[49] Fundamental to concurrent design is a need to have the decision-makers plugged into the process. The MIST software or similar utility expense software could be

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[48] Mark Klien, Stephen C-Y. Lu, "Conflict Resolution in Cooperative Design" *The International Journal for Artificial Intelligence in Engineering.* Vol. 4, No. 4, pgs 168-180, 1990.

[49] Dr. Hugh McManus and Dr. Joyce Warmkessel, "Creating Advanced Architectures For Space Systems: Product And Process" *AIAA 2001-4738.*

deployed on a network so that design teams could receive continual updates of decision-maker needs and constraints.

Concurrent design in the micro sense is takes place in a networked computer lab with approximately a dozen stations. Each station, or chair, represents a sub-system that will need input into the design. A facilitator, or conductor, leads the session through orchestrated conversation and real-time problem solving. Typically, the customer sits in on the session, though the definition of customer in this context is very nebulous and oftentimes incorrect. For example, the customer for an advanced concept study could be the project manager. Customer in this context meant decision maker as opposed to end user.

Concurrent design sessions are viewed as valuable in that they bring engineers together and facilitate communication through linked tools in real-time. This proximity and interlinking reduces turnaround time from weeks to hours. Typically a design is established over the course of several days. A large report is the output of the study, detailing the investigated point design. The starting point of a concurrent design session varies case-by-case. Sometimes the project manager has a clear idea of what he wants and uses the session to prove his point. Sometimes the customer wants something, but can't articulate it, so he turns to the concurrent team lead to guide the team through a tentative exploration of the tradespace. One thing that characterizes most of the sessions is that the concurrent design team often has packaged answers either waiting in their heads or in a database on the computer. These neat answers are the results of past studies and experience. They inherently *bias* the future solution space.

MATE-CON provides a means to circumvent this bias. Through a large tradespace search prior to the session, MATE-CON will narrow the tradespace to a family of "best" architectures based on utility. These "best" architectures form the starting point of the concurrent design session. Additionally, the presence of the MATE-CON chair, which is linking in real-time the current design back to utility space, ensures that the session output remains consistent with the utility of the decision maker (or whomever the utility represents). Developing MATE-CON as part of concurrent design will symbiotically communicate user utility and expense throughout the design. The concurrent design facilitator will look to the MATE-CON chair to provide the map (of attributes to utility space) to guide the sessions and highlight important trades. It is in this way that the coupling of MATE-CON with the concurrent design environment will result in value-added and ensure that decision theory, probability theory, and economics are integrated into the design environment.

4.5 THE NEED FOR MATE + CON

While it might be clear now the advantage that contemporary concurrent design approaches might gain from the use of MATE-CON, it may not be completely clear the need for the for concurrent engineering in conducting front-end studies. Why not just use MATE, the modeling with utility as an evaluation metric developed in the first and second chapters of part one? Below suggest some rationale for the fundamental need to incorporate all three: 1) modeling; 2) utility; 3) concurrent engineering.

1. You must have humans in the loop, making on the fly decisions, cannot do all automated processes.
2. Higher fidelity models become significantly more difficult to build robustly in the MATE software architecture that is focusing on very large changes associated with broad tradespace exploration.
3. Need a validation of the basic MATE models to ensure MATE study was legitimate, and see how detail affects the tradespace.

4. To build increased fidelity there are increased interactions and you need a concurrent environment to resolve complex system interactions.
5. Lower level trades need a decision-making process for trades that is commensurate with the overall mission; subsystems need utility/expense to enlighten trades.
6. Eventually the information from the MATE study must be passed to lower levels of design. In previous times this was done with CDRs / PDRs, but significant learning is lost in this process. MATE-CON builds a framework for passing learning between every design level
7. Furthermore the verification that comes from passing utility/expense throughout the design enterprise reduces the likelihood of power point engineering by creating greater transparency and accountability with mathematical models that flow from one level of design detail to the next.

4.6 MOTIVATION FROM C-TOS PROTOTYPING WITH X-TOS

While the previous section might seem a bit whimsical the SSPARC design exercises have begun to provide some grounding for these pursuits. To a large degree this work was motivated by the C-TOS study done in the summer of 2001. This study was done using Caltech's Integrated Concurrent Engineering software (ICEMaker). The intent of the study was to provide the details of the B-TOS mission spacecraft design. There was a question then if it would be possible to continue to consider the utility and cost of the architecture as the design proceeded into the conceptual spacecraft design stage. While external factors prevented such an approach, the conceptual spacecraft design stage certainly provided motivation for developing the MATE-CON process, which uses ideas of utility in a concurrent design environment. It was clear throughout that trades could have been better informed with a MATE-CON process.

Reflecting on these lessons the objective was to again use the MIT 16.89 Space System Design course to develop these processes. The course was to go from architecture design, modeling a broad tradespace, to conceptual spacecraft design using ICEMaker and concurrent engineering practices. These processes were connected with a decision-maker utility and showed how the design could respond to changes in decision-maker preference in the middle of the design.

The course began by conducting the modeling and utility interviews similar to the approach in B-TOS. From there a baseline design was selected for further study. This further study was conducted with ICE, and during that process there was one key issue that arose that showed one of the important values of the MATE-CON approach. As discussed in the previous chapter, in order to construct the Multi-Attribute Utility Function it is necessary that the decision maker provide a different weight to the different attributes. Now it is possible for the decision maker's utility preferences to change over time. This might be a result of not completely understanding preferences originally, or it could arise from some exogenous factor. In either case when this change occurs there will be a variation in the small k values that provide the weighting to each attribute. As shown in Figure 14 during the X-TOS study there was a significant change in the k-value for Lifespan.

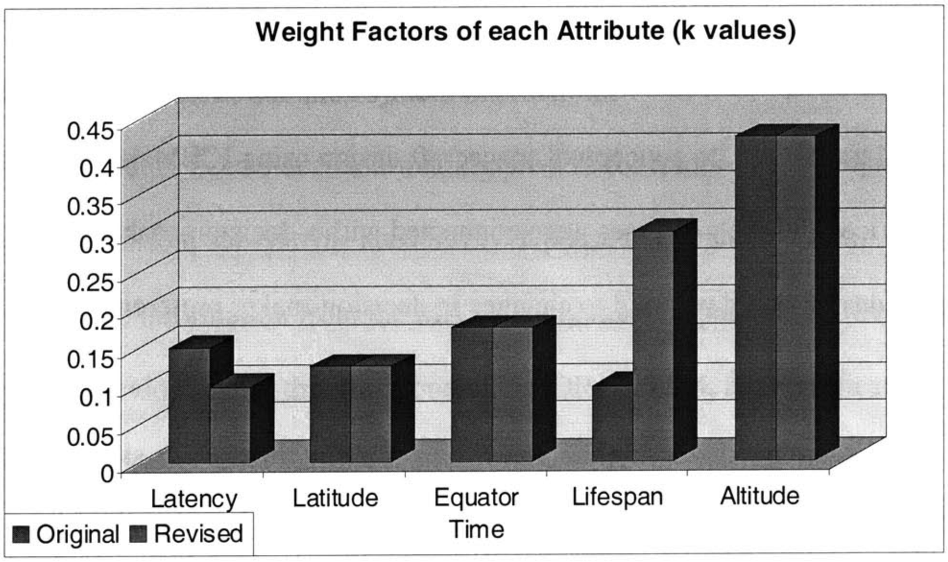

Figure 14 X-TOS Change in k-Values

Recall now that the cost and utility plots rely on these k-values to generate the appropriate utility value for each of the different architectures. Therefore, if there is a change in the k-values there will be a shift in the curve. This is demonstrated in the next two single satellite X-TOS plots.

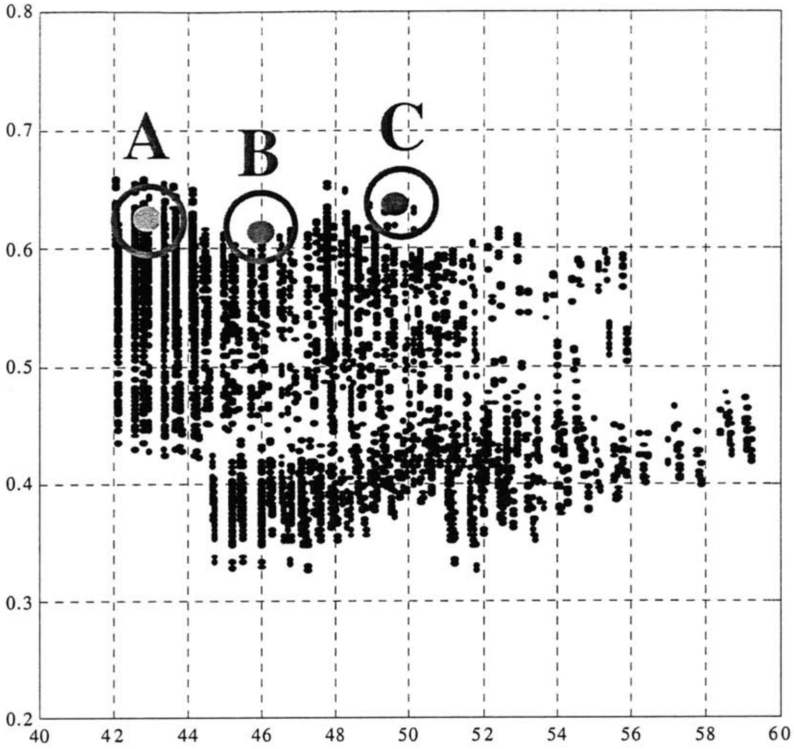

Figure 15 X-TOS Example Architectures with Initial Utility

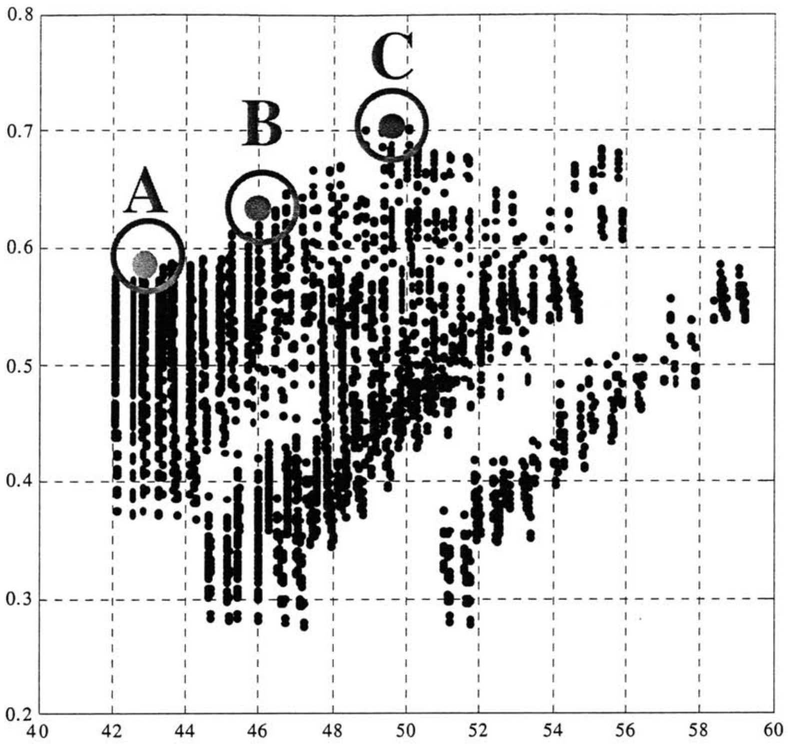

Figure 16 X-TOS Example Architectures with Updated Utility

All of these changes occurred during the concurrent design stage of the course and we can make adjustments to ensure that it will work. Within about thirty minutes the design could be manipulated so that it could accept changes in utility for changing preferences of the decision maker. This was made possible by the incorporation of the MATE-CON chair into the standard concurrent environment, which is depicted below.

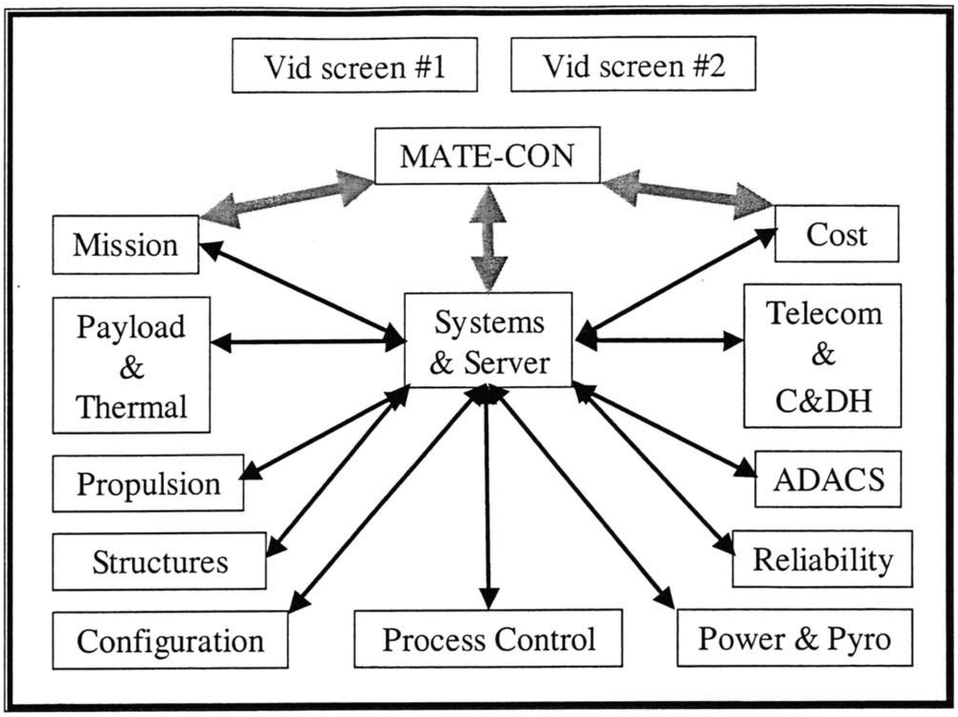

Figure 17 MATE-CON for Integrated Concurrent Engineering

During the course of the design studies in this environment it is possible to maintain the learning from the previous higher-level architecture studies through the MATE-CON chair. It also allows you to monitor progress during the design exercise. Figure 18 shows the type of information that is available to the MATE-CON chair. Use of this information was demonstrated in X-TOS. One of the plots is current USER cost vs. utility. There is also the USER cost vs. Utility plot under the old utilities. The CUSTOMER cost vs. utility plot is also shown. In the bottom right corner is the CUSTOMER vs. USER plotted against each other where the CUSTOMER utilities are considered cost, allowing an expense vs. utility function. All of these can be monitored over time to ensure that the design is progressing towards less expense and more utility. This can be done by looking at better means of trading the hardware components or by using changes in the design variables.

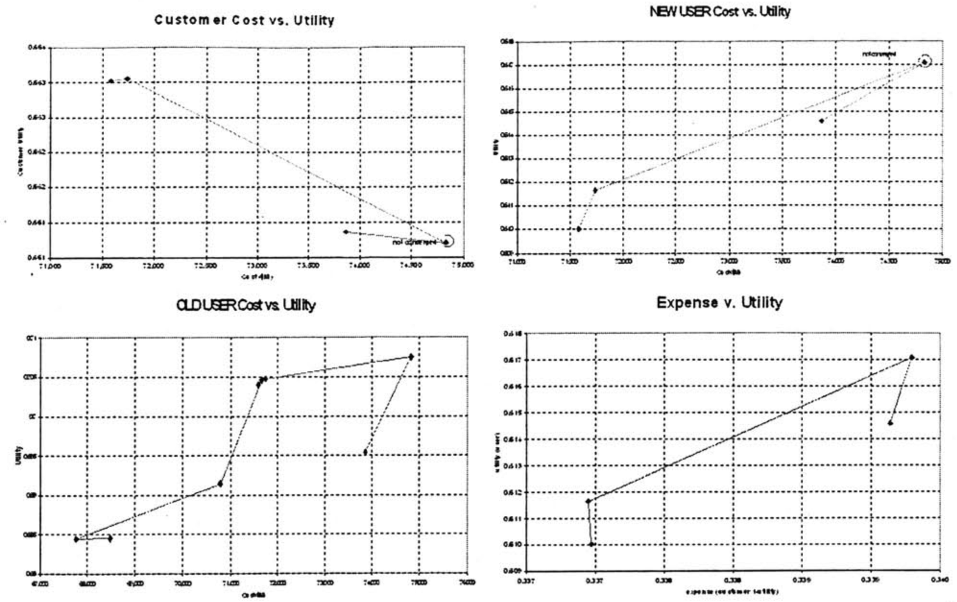

Figure 18 MATE-CON Chair Information Plots

Overall, X-TOS provided a good means of initial testing for the full MATE-CON process. This was the first opportunity to test the potential of using utility in a concurrent design environment for more than one stakeholder. Based on these initial tests is seems likely that MATE-CON could be used to incorporated other stakeholders for improved design for manufacturability, assembly, logistics, reliability, maintainability, usability (human factors), supportability (serviceability), recycleability, disposability, environment, affordability (life-cycle cost). In each case MATE-CON will provide information about the overall expense and utility of each trade to the various stakeholders and to the overall mission design.

5 THE CURRENT MATE-CON PROCESS

This chapter will explicate the current state of the MATE-CON process by giving a quick overview and then proceeding in a step-by-step manner through the fifty MATE-CON activities. The thesis essentially provides the derivation of MATE-CON (Part I), develops the actual process (Part II), and considers the advantages and disadvantages and future possible applications (Part III). If one wants to just quickly apply MATE-CON it would be possible to just refer to Part II, but doing so would be like using an equation without knowing the derivation of the equation that makes explicit the assumptions fundamental to knowing the equation's appropriateness for a given problem. That being said the following fifty steps should provide a baseline understanding of how to use MATE-CON, but it is certainly necessary to do deeper studying into model techniques, MAUT, and concurrent design practices before one could successfully use the whole process. This list then provides the baseline understanding so that one can begin to more deeply explore these questions.

The purpose of Multiple Attribute Tradespace Exploration with Concurrent Design (MATE-CON) is to conceive and evaluate a broad variety of designs by enumerating options and simultaneously aggregating preferences to create a common and continuous metric for evaluation that can be easily communicated throughout the design enterprise.

5.1 INTRODUCTION

MATE-CON should explicitly include the total systems perspective and intent of the system design process into a framework for engineers and designers. The creation of a product necessarily begins with a need from a single or multiple stakeholders. Value can be measured in terms of how many and to what extent each of these needs both current and future, known and unknown, are met. The MATE-CON process keeps the potential solution space as open as possible for as long as possible in order to allow for the discovery of better solutions.

Understanding the objectives of each of the system stakeholders can capture the principle intents for a space system. These objectives can be in the form of concrete goals, such as having a lifetime of no less than 5 years, or of fuzzy aims, such as having data below 1000 kilometers, with lower altitudes better than higher ones. Lifetime and data sampling altitude are examples of attributes, which are quantifiable variables that capture how well an objective is met. MATE-CON uses modeling, decision theory, and a framework for communication to explore the system tradespace through well-defined attributes.

5.2 THE PROCESS

The first part of the MATE-CON process involves understanding the high level issues of the system including the need, mission, scope and relevant stakeholders. This phase precedes any concept exploration and is intended to communicate the origin and context of the need for the system. Since the designers and engineers are in the business of custom product development, with high resource values at stake, it is essential that the high level issues are well understood. It is inherent in the process of discovery that the high level issues will continue to become clarified throughout the process. The art of creation is inherently iterative.

Oftentimes systems are designed in pieces and exposed to the preferences of the decision makers only at important meetings and on an ad hoc basis. This inefficient communication practice results in long time delays due both to rework and waiting. The next phase of the MATE-CON process involves capturing the preferences of the important decision makers. Capturing these preferences creates a proxy for the decision maker, providing guidance on a *continuous basis*, before important and critical design reviews.

Typically the preferences are for how well an objective is met. The preferences are captured through the identification of attributes, which are quantifiable parameters that measure how well a decision maker's objective is met. For example, instantaneous global coverage can be an attribute capturing how well a space system can view the globe at an instant in time. It is important that the *decision maker with the preference* define the attributes. A common mistake engineers make is defining the attributes for the decision maker, thereby introducing personal bias and venturing back into the old method of design.

Once the attributes are known, these are then used to drive the generation of concepts to accomplish these attributes. The purpose of a concept is to provide the best values of these attributes in order to satisfy the wants and needs of the decision makers. It is the transition from the abstract preference space to the concrete design space. The concept can be defined by physical parameters and thereby modeled.

Since the purpose of MATE-CON is to find the designs that will provide the best value for the decision makers, it is essential to understand how the decision maker trades off the various attributes. One method that has been used with some success is Multi-Attribute Utility Theory (MAUT). Utility theory maps preferences for an attribute into a normalized value-under-uncertainty function. MAUT combines single attribute utility functions into a single function that quantifies how a decision maker values different attributes relative to one another, taking into account the levels of each attribute. Having a single utility metric to measure the value of a system to a decision maker helps refine tradespace exploration. The utility value can be expanded back to both to the values of each attribute and to the single attribute utility values for a more detailed comparison. In this way no information is lost from the process, while maintaining manageability through a minimal number of decision metrics.

MAUT has been well studied. As long as the interviewer is aware of the social science issues related to the interview process, a useful utility function can be the result (biases sources). The next phase of the MATE-CON process is to model the concepts. Essentially the model provides the transformation from the design space to the attribute space. Since the design space potentially spans a very large number of possible solutions, it is important to create models that are flexible over a range of concepts and designs. The flexibility allows for the comparison of many possible designs, evaluated by how well they satisfy the preferences of the decision makers.

Once the models are complete, the potential design space, now called the tradespace, is enumerated over different possible designs. The enumerated tradespace is run through the model/simulation, computing the attribute values for each of the designs. Attribute values are then run through the utility function to calculate the value of each design. The resulting evaluated designs can be compared for robustness and ability in meeting the attributes. A typical output plot to show to decision makers is cost versus utility, with each point representing a distinct design.

Analysis of the output is essential for better understanding where the most sensitive areas are for extracting value. Relationships between design parameters and utility values help direct designers to technical issues to concentrate on for the next phase of design. Additionally, it is important to perform sensitivity analysis on the models to increase confidence in the results. Once the models provide reasonable results and the tradespace has been adequately explored, a pareto frontier of cost versus utility can be located, where a gain utility must come at an increase in cost. The frontier represents the best family of architectures, within the uncertainty of the models.

The family of best designs is presented to the decision makers for final selection. It is essential that the utility numbers be converted back to attribute values in order for the decision makers to understand the true value of the system. Because the attribute list is only a subset of the true preferences of the decision makers, it is necessary for direct interaction with the decision maker for higher resolution decision-making. Feedback from the decision makers allows selection of the final set of designs. These designs are then fed forward to the next phase, concurrent design.

5.3 ACTIVITIES: A STEP-BY-STEP TUTORIAL

This section will proceed with a step-by-step description of the MATE-CON process, which includes the fifty activities shown in Table 9. Each activity will be discussed outlining the needed inputs and outputs with a description and an example.

Table 9 MATE-CON Activities List

Identify Need	1
Define Mission	2
Define Scope	3
Identify all relevant decision makers	4
Identify Constraints	5
Propose Attribute Definitions (USER)	6
Solidify attribute definitions (USER)	7
Utility interview (USER)	8
Utility verification and validation (USER)	9

Propose Attribute Definitions (CUSTOMER)	10
Solidify attribute definitions (CUSTOMER)	11
Utility interview (CUSTOMER)	12
Utility verification and validation (CUSTOMER)	13
Propose Attribute Definitions (FIRM)	14
Solidify attribute definitions (FIRM)	15
Utility interview (FIRM)	16
Utility verification and validation (FIRM)	17
Concept generation	18
Organization formation (software teams)	19
Propose Design Variables	20
Solidify Design Variables	21
Map Design variable to attributes	22
Identify I/O for entire simulation	23
Write Model translation from DV to Attributes	24
Decompose code (develop software architecture)	25
Integrate model	26
Enumerate tradespace	27
Navigate enumerated tradespace (intelligent pare down)	28
Run simulation (calculate attributes)	29
Run Utility function	30
Verify Output	31
Analyze output	32
Perform sensitivity analysis (constants/constraints)	33
Perform sensitivity analysis (utility function)	34
Refine tradespace	35
Rerun simulation/utility function	36
Analyze output	37
Locate frontier	38
Select reduced solution set	39
Show to DM(s)	40
Define stakeholder tradeoff function	41
Select design(s) for concurrent design	42
Set selected design as baseline for CE	43
Develop higher fidelity CE models	44
Perform concurrent design trades	45
Converge on final design	46
Show to DM(s)	47
Select final design(s)	48
Create Aerospace System Requirements	49
Establish a MATE-CON Design Decision Support Center	50

5.3.1 Identify Need

Inputs:

This activity is the first of the MATE-CON process, but already requires input from downstream activities. Completion of need identification requires knowledge of all of the important decision makers of the system.

Outputs:

The need feeds forward a general statement of goals.

Description:

The need identification activity involves identifying the initial impetus for the creation of a system. Additional needs may be identified throughout the process, but the initial need is the initial driver for the system. Without a clearly identified need, the designers may find it very difficult to resolve system ambiguity and create a useful product. Need usually involves the addressing some problem with the status quo. Needs can arise from almost any stakeholder with a problem. The key issue is to communicate the need, origin and context of the need to the decision makers in the system architecting and design process.

Dependencies:

Inputs: 4

Outputs: 1-18, 20-21, 23

EXAMPLE X-TOS:

Dr. John Ballenthin of the Air Force Research Laboratory Hanscom gave a lecture to the 16.89 class to describe the problem of inadequate atmospheric drag models for predicting satellite reentry. He described his need to fly his instruments that had been manifested in the early 1990s but ended up in the ocean after a launch failure.

5.3.2 Define Mission

Inputs:

An understanding of the need drives the mission conception.

Outputs:

A concise mission statement provides the vision for the system development and captures the essential characteristics of the need.

Description:

What, why, and how of the need.

Dependencies:

Inputs: 1, 4-5

Outputs: 3-6, 10, 14, 18, 20-22, 24-25, 27-28, 31, 35, 39

EXAMPLE X-TOS

To carry the USER's payload in a space system to measure the atmospheric density of the Earth.

5.3.3 Define Scope

Inputs:

It is necessary to know the mission and the need in order to define the scope. In the past, the mission was diagramed as an information flow network, however this representation can be strongly dependent on the system concept.

Outputs:

A clearer understanding of the system boundaries comes out of this activity.

Description:

In order to make the problem tractable, it is necessary to define the boundaries of the system. Scoping the problem restricts the possible problem and solution space to something that can be specifically addressed by the designers. Scoping defines what is within and without the areas that are to be considered. Scoping should also involve the collection of explicit assumptions of the system.

Dependencies:

Inputs: 1-2

Outputs: 4-7, 10-11, 14-15, 18, 20-22, 24-25, 27-28, 31, 40, 43-44

EXAMPLE X-TOS:

Team decided to not consider the ground stations and operations. They only looked at the space system, collection, and transmission of data.

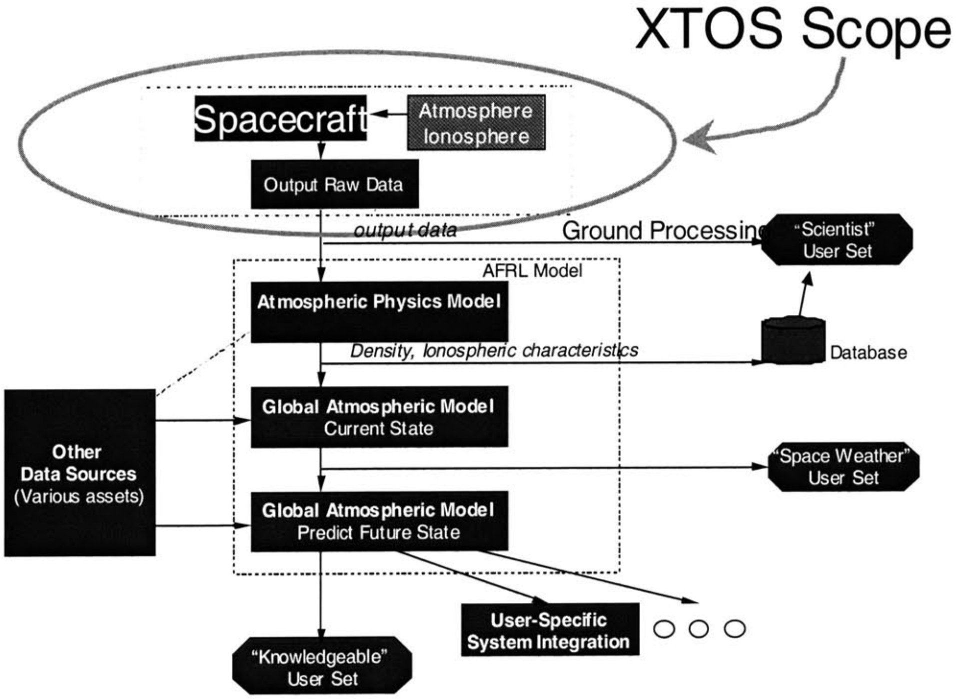

Figure 19 X-TOS Scope

5.3.4 Identify All Relevant Decision Makers

Inputs:

MATE-CON as its essential approach attempts to facilitate communication in order to reduce development time and create a product of greater value. Value means different things to different people. The relevant decision makers are those people who will decide the fate of the system. Other stakeholders with preferences on the system may exist, however, they do not impact the system except through the decision makers. The power of decision-making is consolidated in a few people in order to make the creation of a complex system a tractable endeavor. Identification of these decision makers is essential to successful application of MATE-CON. The more identified, the better prepared the system will be when facing the relevant decision makers. The need, especially the context of the need, provides information on where to locate the decision makers, as does the framework of the system development process for the DESIGNER's organization.

Outputs:

Identifying all of the relevant decision makers is iterative with understanding all of the needs that will drive the system. Additionally this activity is iterative with developing the mission for the same reason.

Description:

As the MATE-CON process philosophy explicitly addresses the nature of product creation as a transformation from resources to a complete system through the preferences of people, it is important to identify all of the stakeholders whose preferences will shape the creation of the system. Through the lifecycle of a system, from the origin of the initial need to the conduction of retirement of the system, human preferences shape the path the system will take. Presumably the direction of this path is guided by the perceived value in the minds of the decision makers who are the originators of these preferences. The MATE-CON process is specifically applied to the beginning of a system lifecycle: from origin of need to deployment. Hundreds of potential decision makers could lie between the beginning and end of this process. One could think of five main categories of decision makers: Designer, Firm, Customer, User, and External. It is important to understand that these are not the only decision makers that will impact the system, making it necessary to consider the other decision makers to help improve the ability to design for manufacturability, assembly, deployment, operations, maintenance, and decommission, some of which might be considered subsets decision makers shown in Figure 20.

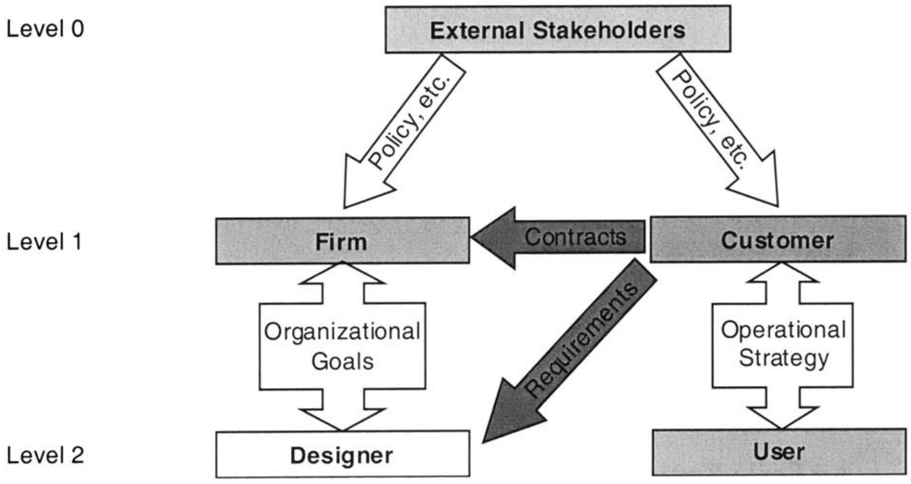

Figure 20 Overview of Potential Decision Makers

Level 2 decision makers (Designer, User) have the closest contact with the end system. Level 1 (Firm, Customer) decision makers deal with the end system through the level 2 decision makers, however, they also have important preferences that determine whether or not the system will be built. These decision makers control the resources necessary for the realization of the system.

Level 0 decision makers (External Stakeholders) may have little to no direct stake in the system, however do have general preferences that may constrain the system.

Typically the User, Firm, or Customer is the originator of need. Science missions typically originate with the User. Military missions typically originate with the Customer. Commercial missions typically originate with the Customer or Firm. In order to simplify implementation, it may be necessary to limit the number of decision makers interviewed in later activities. It is important, however, to identify all important decision makers who will shape the development path of the system. The MATE-CON process engineer will need to be aware of decision makers that are not included in later activities (through utility interviews). Scoping decisions will probably be necessary in order to implement MATE. (This scoping may include limiting the number of interviewed decision makers. If this is necessary, try to get the preferences of the most important people, while noting probable preferences for the other decision makers.)

Dependencies:

Inputs: 1-3

Outputs: 1-2, 5-18, 23, 27-28, 31, 39-42

EXAMPLE X-TOS:

DESIGNER: 16.89 students

USER: Air Force Research Lab (AFRL/Hanscom, John Ballenthin)

FIRM: 16.89 professors, staff

CUSTOMER: Aerospace Corporation

External: The rest of the world (Congress, body of space law/policy)

5.3.5 Identify Constraints

Inputs:

Once the need, mission, scope, and relevant decision makers are identified, they will lend themselves to constraints. Policy, physical, preferential, and other constraints may be imposed on the system. Additionally there is feedback from the concept selection activity. Each concept will also be subject to specific constraints that must be captured in the MATE-CON process.

Outputs:

Constraints will be manifest in restrictions of the design space. It is important to highlight which constraints are hard, which are soft, and which are the result of simplifying assumptions.

Description:

Constraints can be hard or soft requirements on the system. The laws of physics are a hard constraint, as is the necessity of launching U.S. government payloads on U.S. launch vehicles. The chosen concept also defines constraints on performance and operation. Constraints must be adhered to in the eventual modeling of the system and may drive the possible concept space.

Dependencies:

Inputs: 1-4, 18

Outputs: 2, 18, 20-22, 24-28, 31, 33, 39

EXAMPLE X-TOS:

The X-TOS mission carries a government payload and as such is subject to U.S. launch policy that constrains the space of possible launch vehicles to those owned by U.S. companies.

5.3.6 Propose Attribute Definitions (USER)

Inputs:

Once the USER is identified, a conversation can begin. Probe the needs that originated with the USER and try to develop objective statements regarding these needs. The attributes will be quantifiable parameters that measure how well these objectives are met.

Outputs:

A preliminary list of attributes allows the design team to begin to understand the modeling framework for the system. The learning period benefits greatly from thinking about and discussing the attributes with the decision maker. The attributes are meant to replace hard requirements that the decision maker will typically place on the system.

Description:

Oftentimes systems are designed in pieces and exposed to the preferences of the decision makers only at important meetings and on an ad hoc basis. This inefficient communication practice results in long time delays due both to rework and waiting. This activity of the MATE-CON process involves capturing the preferences of the important decision makers. Capturing these preferences creates a proxy for the decision maker, providing guidance on a *continuous basis*, before and between important and critical design reviews. The preferences are captured through the identification of attributes, which are quantifiable parameters that measure how well a decision maker's objective is met. For example, instantaneous global coverage can be an attribute capturing how well a space system can view the globe at an instant in time. It is important that the *decision maker with the preference* define the attributes. The attributes are decision maker-defined metrics that replace the traditional notions of requirements and of solely using engineer-defined metrics, such as mass and power. A common mistake engineers make is defining the attributes for the decision maker, thereby introducing personal bias and venturing back into the old method of design.

It is essential to decide with the USER the definition, the units, the range, the step size, and the direction of increasing "goodness" of each attribute. In order to satisfy the theoretical conditions for Multi-Attribute Utility Theory, which is used in the utility interview, the attributes must form the basis of a monotonic value function (i.e., more is always better or the same, or worse or the same, with the attributes never changing from bad to good to bad).

Dependencies:

Inputs: 1-4

Outputs: 7, 18, 20, 22-25

EXAMPLE X-TOS:

The following list were the proposed USER attributes followed by their units:

Knowledge/Accuracy Altitude	[km]
Mission Lifetime	[months]
Time spent in region	[min]
Latitude range	[degrees]
Latency	[min]
# Simultaneous data pts	[integer]
Data Completeness	[%]
Pointing Accuracy	[degrees]
Pointing Control	[degrees]

5.3.7 Solidify Attribute Definitions (USER)

Inputs:

The proposed list of USER attributes.

Outputs:

The finalized and mutually agreed upon list of USER attributes including their definitions, ranges, units, and direction of increasing value.

Description:

Iteration with the USER results in finalization of attribute definitions. Final attribute definitions capture the preferences of the decision maker for use in the utility functions and for driving the concept generation. These attributes form the core set of drivers for MATE. Finalization must occur before the utility interview and before modeling can commence since these are the primary outputs of the model. The number of USER-defined attributes preferably should be less than seven in order to make the interviewing process tractable. Nested utility functions are possible to capture more than six attributes, however nesting adds complication and requires a sophisticated MATE-CON engineer.

Dependencies:

Inputs: 1, 3-4, 6

Outputs: 8-9, 18, 21-25, 31-32, 34

EXAMPLE X-TOS:

The final attributes for X-TOS USER were:

1. Data Life Span: Elapsed time between the first and last data points. [0 –11 years] (More)
2. Sample Altitude: Height of data sample. [150-1000 km] (Less)
3. Diversity of Latitudes: The spread of latitudes in the data [0-180 degrees] (More)
4. Time Spent at the Equator: Time per day spent near the equator. [0-24 hours/day] (More)
5. Latency: Time from collection to transmission. [1-120 hours] (Less)

5.3.8 Utility Interview (USER)

Inputs:

The list of attributes must be finalized before the utility interview can be given.

Outputs:

The interview data including the indifference points for at least five points along each utility curve and the small k values for each attribute. The indifference points can be used to construct the single attribute utility functions. The small k values can be used to construct the multiplicative multi-attribute utility function. The multi-attribute utility function takes the following form in the case of 6 attributes:

$$KU(\underline{X})+1=\prod_{i=1}^{N}\left[Kk_iU_i(X_i)+1\right]$$

- K is the solution to $K+1=\prod_{i=1}^{n=6}\left[Kk_i+1\right]$, and $-1<K<1$, $K\neq 0$.
- $U(\underline{X})$, $U(X_i)$ are the multi-attribute and single attribute utility functions, respectively.
- N is the number of attributes.
- k_i is the multi-attribute scaling factor from the utility interview.

Description:

MATE-CON currently uses Multi-Attribute Utility Theory[50] (MAUT) to combine decision maker defined preferences of attributes into a single utility metric of value under uncertainty. The utility metric is a dimensionless scalar with a minimum at zero and a maximum at one. Utility in this formulation has the unfortunate property of not being a ratio scale (e.g. 0.8 is NOT four times as valuable as 0.2, just as 80 degrees F is not four times as hot as 20 degrees F). Utility is useful in that it captures the nonlinear preferences of the decision maker on different

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[50] Keeney, R. L., Raiffa, H. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Cambridge University Press: Cambridge U.K. 1993.

levels of an attribute under uncertainty. MAUT also allows for the aggregation of single attribute utility functions into a single metric that takes into account preferences on tradeoffs between the attributes and can be used as a driver for tradespace exploration.

Once the attribute definitions and ranges have been decided, the utility interview can be written. The interview process that is currently recommended is taught in DeNeufville's *Applied Systems Analysis.* The entire interview is a collection of single attribute utility interviews and a corner point interview. The single attribute utility interviews use the lottery equivalent probability method and each question is dependent upon the interviewee's responses. The utility function for each attribute can be derived from the indifference points from the interview. It is important to carefully craft the scenario for each attribute to place the interviewee in the proper mindset to answer lottery questions for the attributes. (Thinking in terms of probabilities is difficult and is a major limitation of the process. It is important to guide the interviewee until the person is comfortable with the question format.) The Multi-attribute Interview Software Tool (MIST), developed by Satwik Seshasai, is a tool to conduct both the single and multi-attribute interviews. The software allows the engineer to enter the attribute definitions, ranges, direction of increasing utility, and scenario. The scenario provides the context for the lottery offered for each attribute. The software is Excel-based and deployable. The attributes for the USER must be finalized before the interview can be conducted, though iteration of the interview is possible and greatly facilitated by computer-based interviewing. It is highly recommended to peruse the literature on the issues involved in utility interviewing as it is inherently a social science experiment and therefore may be outside of the normal experience base of an engineer.[51]

See Delquie, B-TOS report for example interviews.

Dependencies:

Inputs: 1, 4, 7, 9

Outputs: 9, 26, 30-32, 34, 36-37, 41

EXAMPLE X-TOS:

The utility team developed the interview using MIST and emailed it to Kevin Ray (USER). Kevin Ray completed the software-based interview in a couple of hours and emailed it back to the utility team. The team quickly verified that the interview was conducted correctly and was able to call Kevin Ray and request that he redo specific sections. The entire interview was conducted in the span of several hours and the interviewer and interviewee did not need to be co-located. It is important to note that Kevin Ray was familiar with the interview format because he participated in face-to-face utility interviews for B-TOS.

5.3.9 Utility Verification and Validation (USER)

Inputs:

In order to conduct the verification and validation, the attributes need to have been finalized and the initial utility interview conducted. It is possible to conduct the verification immediately after the interview. It is also possible to check the MAUT assumptions have been met prior to conducting the interview.

Outputs:

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[51] de Neufville, R. (1990). Applied Systems Analysis: Engineering Planning and Technology Management. New York, McGraw-Hill Co; Keeney, R. L., Raiffa, H. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Cambridge University Press: Cambridge U.K. 1993.

Verification of the MAUT assumptions regarding utility and preferential independence of the attributes allows for the use of MAU functions. If verification fails, it will be necessary to redefine the attributes, or the simple multiplicative form of the MAU function will be invalid. It is possible to relax the assumptions of MAUT, however it is recommended that any designers considering such a strategy read Keeney and Raiffa's *Decisions with Multiple Objectives* in order to fully understand MAUT. Validation output is the confirmation that the utility functions adequately represent the USER's preferences. Communication of these functions increases both the confidence of the designers and the USER as well. (Often a decision maker may feel uncomfortable being represented by a simplistic proxy function; emphasis on the communication aspect of the function may alleviate some of this anxiety.)

Description:

Once the utility interview has been completed, it is important to verify the MAUT assumptions are met (utility independence and preferential independence). It is also necessary to validate the functions with the interviewee to ensure the functions accurately represent the preferences of the interviewee. Verification questions test the mathematical conditions necessary for the MAU multiplicative function formulation. Validation questions clear up miscommunications between the utility team and the interviewee and add confidence to the function. (In a sense it reduces the error bars on the function.) Verification questions can be done using MIST. Validation questions must be done through a conversation with the interviewee. Validation can be done by showing the utility function to the interviewee or asking preference questions and checking to see if the function gives the same ranking answers.

Dependencies:

Inputs: 1, 4, 7-8

Outputs: 8, 30, 34, 36

EXAMPLE X-TOS:

The utility team showed the utility function results to Kevin Ray (USER) and the USER generally agreed with the results, however decided to change the little k value for Lifetime to a larger number in order to increase that attribute's importance.

5.3.10 Propose Attribute Definitions (CUSTOMER)

Inputs:

Once the CUSTOMER is identified, a conversation can begin. Probe the needs that originated with the CUSTOMER and try to develop objective statements regarding these needs. The attributes will be quantifiable parameters that measure how well these objectives are met.

Outputs:

A preliminary list of attributes allows the design team to begin to understand the modeling framework for the system. The learning period benefits greatly from thinking about and discussing the attributes with the decision maker. The attributes are meant to replace hard requirements that the decision maker will typically place on the system.

Description:

Same as propose Attribute Definitions (USER).)

It is essential to decide with the CUSTOMER the definition, the units, the range, the step size, and the direction of increasing "goodness" of each attribute. In order to satisfy the theoretical conditions for Multi-Attribute Utility Theory, which is used in the utility interview, the attributes must form the basis of a monotonic value function (ie, more is always better or the same, or worse or the same, never changing from bad to good to bad).

Dependencies:

Inputs: 1-4

Outputs: 11, 18, 20, 22-25

EXAMPLE X-TOS:

Proposed CUSTOMER attributes included:

Cost	[$]
# of Additional Missions	[integer]
Lead time	[years]
Leave Behind Capability	[yes/no]
Risk	[bananas]
Science User Satisfaction	[f(Utility)]

5.3.11 Solidify Attribute Definitions (CUSTOMER)

Inputs:

The proposed list of CUSTOMER attributes.

Outputs:

The finalized and mutually agreed upon list of CUSTOMER attributes including their definitions, ranges, units, and direction of increasing value.

Description:

Iteration with the CUSTOMER results in finalization of attribute definitions. Final attribute definitions capture the preferences of the decision maker for use in the utility functions and for driving the concept generation. These attributes form the core set of drivers for MATE. Finalization must occur before the utility interview and before modeling can commence since these are the primary outputs of the model. The number of CUSTOMER-defined attributes preferably should be less than seven in order to make the interviewing process tractable. Nested utility functions are possible to capture more than six attributes, however nesting adds complication and requires a sophisticated MATE-CON engineer.

Dependencies:

Inputs: 1, 3-4, 10

Outputs: 12-13, 18, 21-25, 31-32, 34

EXAMPLE X-TOS:

The final CUSTOMER attributes were given to the class by the course instructors as a proxy for a "real" acquisition customer. The attributes were:

1. IOC cost: Cost to initial operating capability. [0 –250 $M] (Less)
2. USER satisfaction: The degree to which the USER is satisfied. [0-1 utils] (More)

5.3.12 Utility Interview (CUSTOMER)

Inputs:

The list of attributes must be finalized before the utility interview can be given.

Outputs:

The interview data including the indifference points for at least five points along each utility curve and the small k values for each attribute. The indifference points can be used to construct the single attribute utility functions. The small k values can be used to construct the multiplicative mult-attribute utility function.

The multi-attribute utility function takes the following form:

$$KU(\underline{X})+1=\prod_{i=1}^{N}[Kk_iU_i(X_i)+1]$$

- K is the solution to $K+1=\prod_{i=1}^{n=6}\left[Kk_i+1\right]$, and $-1<K<1$, $K\neq0$.
- $U(\underline{X})$, $U(X_i)$ are the multi-attribute and single attribute utility functions, respectively.
- N is the number of attributes.
- k_i is the multi-attribute scaling factor from the utility interview.

Description:

See description under Utility Interview (USER).

Dependencies:

Inputs: 1, 4, 11, 13

Outputs: 13, 26, 30-32, 34, 36-37, 41

EXAMPLE X-TOS:

While no formal utility interview was conducted with the CUSTOMER, the course instructors, familiar both with the general preferences of the CUSTOMER and with utility theory, gave the X-TOS team data in the form of answers to a utility interview. This data set led to the derivation of a CUSTOMER utility function displaying the instructor-perceived preferences for the CUSTOMER.

5.3.13 Utility Verification and Validation (CUSTOMER)

Inputs:

In order to conduct the verification and validation, the attributes need to have been finalized and the initial utility interview conducted. It is possible to conduct the verification immediately after the interview. It is also possible to check the MAUT assumptions have been met prior to conducting the interview.

Outputs:

Verification of the MAUT assumptions regarding utility and preferential independence of the attributes allows for the use of MAU functions. If verification fails, it will be necessary to redefine the attributes, or the simple multiplicative form of the MAU function will be invalid. It is possible to relax the assumptions of MAUT, however it is recommended that any designers considering such a strategy read Keeney and Raiffa's *Decisions with Multiple Objectives* in order to fully understand MAUT. Validation output is the confirmation that the utility functions adequately represent the CUSTOMER's preferences. Communication of these functions increases both the confidence of the designers and the CUSTOMER as well. (Often a decision maker may feel uncomfortable being represented by a simplistic proxy function; emphasis on the communication aspect of the function may alleviate some of this anxiety.)

Description:

See description under 7.3.9 Utility Verification and Validation (USER).

Dependencies:

Inputs: 1, 4, 11-12

Outputs: 12, 30, 34, 36

EXAMPLE X-TOS:

This activity was not performed by the X-TOS team.

5.3.14 Propose Attribute Definitions (FIRM)

Inputs:

Once the FIRM is identified, a conversation can begin. Probe the needs that originated with the FIRM and try to develop objective statements regarding these needs. The attributes will be quantifiable parameters that measure how well these objectives are met.

Outputs:

A preliminary list of attributes allows the design team to begin to understand the modeling framework for the system. The learning period benefits greatly from thinking about and discussing the attributes with the decision maker. The attributes are meant to replace hard requirements that the decision maker will typically place on the system.

Description:

See description under 7.3.6 Propose Attribute Definitions (USER).

It is essential to decide with the FIRM the definition, the units, the range, the step size, and the direction of increasing "goodness" of each attribute. In order to satisfy the theoretical conditions for Multi-Attribute Utility Theory, which is used in the utility interview, the attributes must form the basis of a monotonic value function (ie, more is always better or the same, or worse or the same, never changing from bad to good to bad).

Dependencies:

Inputs: 1-4

Outputs: 15, 18, 20, 22-25

EXAMPLE X-TOS:

This activity was not performed by the X-TOS team.

5.3.15 Solidify Attribute Definitions (FIRM)

Inputs:

The proposed list of FIRM attributes.

Outputs:

The finalized and mutually agreed upon list of FIRM attributes including their definitions, ranges, units, and direction of increasing value.

Description:

Iteration with the FIRM results in finalization of attribute definitions. Final attribute definitions capture the preferences of the decision maker for use in the utility functions and for driving the concept generation. These attributes form the core set of drivers for MATE. Finalization must occur before the utility interview and before modeling can commence since these are the primary outputs of the model. The number of FIRM-defined attributes preferably should be less than seven in order to make the interviewing process tractable. Nested utility functions are possible to capture more than six attributes, however nesting adds complication and requires a sophisticated MATE-CON engineer.

Dependencies:

Inputs: 1, 3-4, 14

Outputs: 16-18, 21-25, 31-32, 34

EXAMPLE X-TOS:

This activity was not performed by the X-TOS team.

5.3.16 Utility Interview (FIRM)

Inputs:

The list of attributes must be finalized before the utility interview can be given.

Outputs:

The interview data including the indifference points for at least five points along each utility curve and the small k values for each attribute. The indifference points can be used to construct the single attribute utility functions. The small k values can be used to construct the multiplicative multi-attribute utility function.

The multi-attribute utility function takes the following form:

$$KU(\underline{X})+1=\prod_{i=1}^{N}[Kk_iU_i(X_i)+1]$$

- K is the solution to $K+1=\prod_{i=1}^{n=6}[Kk_i+1]$, and $-1<K<1$, $K\neq0$.
- $U(\underline{X})$, $U(X_i)$ are the multi-attribute and single attribute utility functions, respectively.
- N is the number of attributes.
- k_i is the multi-attribute scaling factor from the utility interview.

Description:

See description under 7.3.8 Utility Interview (USER).

Dependencies:

Inputs: 1, 4, 15, 17

Outputs: 17, 26, 30-32, 34, 36-37, 41

EXAMPLE X-TOS:

This activity was not performed by the X-TOS team.

5.3.17 Utility Verification and Validation (FIRM)

Inputs:

In order to conduct the verification and validation, the attributes need to have been finalized and the initial utility interview conducted. It is possible to conduct the verification immediately after the interview. It is also possible to check the MAUT assumptions have been met prior to conducting the interview.

Outputs:

Verification of the MAUT assumptions regarding utility and preferential independence of the attributes allows for the use of MAU functions. If verification fails, it will be necessary to redefine the attributes, or the simple multiplicative form of the MAU function will be invalid. It is possible to relax the assumptions of MAUT, however it is recommended that any designers considering such a strategy read Keeney and Raiffa's *Decisions with Multiple Objectives* in order to fully understand MAUT. Validation output is the confirmation that the utility functions adequately represent the FIRM's preferences. Communication of these functions increases both the confidence of the designers and the FIRM as well. (Often a decision maker may feel uncomfortable being represented by a simplistic proxy function; emphasis on the communication aspect of the function may alleviate some of this anxiety.)

Description:

See description under 7.3.9 Utility Verification and Validation (USER).

Dependencies:

Inputs: 1, 4, 15-16

Outputs: 16, 30, 34, 36

EXAMPLE X-TOS:

This activity was not performed by the X-TOS team.

5.3.18 Concept Generation

Inputs:

The need, mission, scope, and relevant decision makers must be identified, as does the list of attributes. The attributes are the metrics by which potential concepts will be measured. The goal of each concept is to perform well in the attributes.

Outputs:

Concepts feedback to the constraint activity as each concept may have unique constraints associated with them. The concepts will provide the template for converting performance in the attributes back to physical design space.

Description:

The concept is the mapping of function to form. This fundamentally requires thinking in physical space. Knowledge of the attributes and how those attributes might be acquired is necessary to begin this activity. Focusing on the fact that all that matters are the attributes, this activity uses the attributes as a focusing tool for creating concepts. During this activity, do not rule out any concepts. At first, look at one attribute at a time and generate concepts that would deliver the range of the attribute desired by the decision maker. Next, look at multiple attributes to generate synergistic concepts. Creativity methods such at TRIZ might be used to generate the concepts.

Mission Examples:

X-TOS attributes (sample altitude, latitude diversity, latency, lifetime, time spent at equator).

B-TOS attributes (spatial resolution, revisit time, latency, accuracy, instantaneous global coverage, mission completeness).

A-TOS attributes (high latitude mission "cookies", low latitude mission "cookies")

For each of these missions, the payload was the fundamental transformer of attributes to real-space since many of the attributes were characteristics of the data returned. Thus the concepts generated involved placement of the payload in different locations in order to perform well in the attributes.

Dependencies:

Inputs: 1-7, 10-11, 14-15

Outputs: 5, 20-22, 24-25, 27, 31, 33, 43-44

EXAMPLE X-TOS:

Attribute: Sample Altitude

Range: 150-1000 km

Direction of increasing utility: toward attribute minimum

Hard constraints: payload design for altitudes >199 km, must be in situ, ram-facing, pointing requirements

Question: How can the mission acquire data over a range of altitudes with lower altitudes better?

Answer: Payload must fly at desired sample altitude. Rest of vehicle does not.

Potential X-TOS concepts: tethered payloads, giant sail, grapefruit-sized satellites, golf-ball satellites on ballistic trajectories. Satellites with supporting subsystems or solely with payloads.

5.3.19 Organization Formation (software teams)

Inputs:

Knowledge of the software architecture will allow the team to divide into functional groups that mirror the software architecture.

Outputs:

Groupings of people to work on software modules, allowing for concurrent development and oversight.

Description:

An essential activity for the creation of the software models is to divide the human resources into teams. The organization of module teams allows for the parallel development of the models. A primary and secondary person for each module ensures no single point failures for the model development. Additionally, it is essential to assign duties to a software integrator and a input/output manager. The input/output manager will ensure the proper interface between the simulation and the overall process, while the integrator ensures the proper interfaces between the modules within the simulation.

Dependencies:

Inputs: 22, 25

Outputs: 23-24, 26

EXAMPLE X-TOS:

The class divided itself into the following software teams:

1. Cost/Schedule
2. I/O
3. Integration
4. Launch/Ops
5. Orbits/Drag
6. Spacecraft
7. Utility

Each team was responsible for the corresponding modules, both development and testing. The integration team, along with the I/O team, provided coherence and leadership for the internal code architecture.

5.3.20 Propose Design Variables

Inputs:

The concept and the proposed attribute list allow for the creation of the proposed design variables. These variables will be the physical space drivers for performance in the attributes and will reflect the selected concept(s).

Outputs:

A list of proposed design variables that will allow for the preliminary creation of the model and simulation.

Description:

The design variables define the concept modeled since this is what differentiates the possible architectures. These are physical parameters that are within the control of the designer.

Mission Examples:

A-TOS design variables [inclination, perigee/apogee altitudes, argument of perigee, number of orbital planes, number of swarms per plane, number of subsats per swarm, number of subplanes per swarm, yaw of subplane, number of suborbits per subplane, size of swarm, Mothership, C2 autonomy, intra-swarm communication], number of design variables: 13

B-TOS design variables [circular altitude, number of planes, number of swarms per plane, number of satellites per swarm, radius of swarm, configuration studies (payload, communication, processing capability)], number of design variables: 9

X-TOS design variables [perigee altitude, apogee altitude, inclination, total delta v, satellite parameters (antenna gain, communication architecture, propulsion type, power generation), mission scenarios (one sat, two sat, series, parallel)] number of design variables: 8 + 2

Dependencies:

Inputs: 1-3, 5-6, 10, 14, 18

Outputs: 21-25

EXAMPLE X-TOS:

The following is a list of proposed design variables for X-TOS:

1. Orbital parameters
2. Number of spacecraft

3. Station keeping
4. Mission Scenario
5. Shape
6. Communication scenario
7. Launch (vehicle, date)
8. Redundancy/Functionality
9. Time/Position determination
10. [Risk/heritage]??
11. spacecraft functionality
12. lifecycle
13. launch sequence
14. data storage

5.3.21 Solidify Design Variables

Inputs:

The proposed list of design variables, plus most importantly, the finalized list of attributes.

Outputs:

The list of finalized design variables, allowing for the creation of the actual software model.

Description:

Finalization of the design variables is necessary before code development can begin. Proposed design variables become finalized after the attributes have been finalized and an understanding of the dependencies between the design variables and attributes has been understood.

Dependencies:

Inputs: 1-3, 5, 7, 11, 15, 18, 20

Outputs: 22-29, 31-33, 35-39, 43-44

EXAMPLE X-TOS:

The final design variables for X-TOS were:

1. perigee altitude,
2. apogee altitude,
3. inclination,
4. total delta v,
5. satellite parameters (antenna gain, communication architecture, propulsion type, power generation),
6. mission scenarios (one sat, two sat, series, parallel)]

5.3.22 Map Design Variables to Attributes

Inputs:

Proposed and final design variables and attributes.

Outputs:

Notional mapping of design variables to attributes to aid the development of the software architecture for the model.

Description:

In order to structure the modeling stage of MATE, it is necessary to understand the relationship between the design variables and the attributes. A QFD can be made to capture the relative impact of each design variable on each attribute. Notional mappings of design variables to attributes allow for the conception of necessary modules for the model. This activity is done in parallel with the proposal and finalization of design variables since it helps prioritize design variables and pare down the proposed list. Only strong drivers of the attributes should be kept as design variables. Other design variables with a weaker relationship to the attributes should be assumed constant and be moved to the constants variable list. This recommended scoping decision arises from the computational limitations of a geometrically growing potential tradespace.

Dependencies:

Inputs: 2-3, 5-7, 10-11, 14-15, 18, 20-21

Outputs: 19, 23-26

EXAMPLE X-TOS:

Table 10 Example QFD for X--TOS is a QFD mapping the final design variables to the final attributes. Extra design variables have already been pared off of the list.

Table 10 Example QFD for X--TOS

		Range	0.5 - 11	150 - 1000	0 - 180	0 - 24	1 - 120		0 - 200 M$	
		Units	Years	Km	Degrees	Hours (per day)	Hours		USD (2002)	
		Attributes	**Data Life Span (Per Satellite!!)**	**Sample Altitude**	**Diversity of Latitudes contained in the Data S**	**Time Spent in Equatorial Region**	**Latency**	**Total**	**Cost**	**TOTAL WITH COST**
			1	2	3	4	5		6	
Variables	**Units**	**Constraints**								
Perigee Altitude	m	150 < hp < 350	9	9	0	0	3	21	9	30
Apogee Altitude	m	150 < ha < 1500	9	9	0	6	3	27	9	36
Inclination	Degrees	0 < i < 90	0	0	9	9	3	21	6	27
delta-V	m/s	0 < mass < 500	9	0	0	0	0	9	9	27
Comm System Type	-	AFSCN or TDRSS	0	0	0	0	9	9	3	12
Propulsion Type	-	Chemical or Hall	6	0	0	0	0	6	6	12
Power System Type	-	Solar or Fuel Cells	6	0	0	0	6	12	6	18
Mission Scenario	-	-	9	9	9	9	3	39	9	48

5.3.23 Identify I/O for Entire Model

Inputs:

Knowledge of the final design variables, attributes, and code structure is necessary for identifying the parameters needed for input and output of the simulation. The design variables and their potential enumeration space will be the inputs.

Outputs:

A listing of the input and output parameters for the entire simulation. This list provides interface requirements for the integrated code and ensures a proper data set for later analyzing. Specified outputs include attribute values, utility values, spacecraft physical parameters such as mass and power, and launch vehicle selected, among others.

Description:

The primary input into the simulation is the set of design variables, or design vector. The primary outputs of the simulation are the utility values of each design vector. Secondary outputs allow for verification of the simulation and a better understanding of the physical systems being modeled. I/O must be identified before the simulation is written in order to provide motivation and guidance for the code developers. Example secondary outputs include the mass and power of the satellites, the intermediate costs, margins, and selected launch vehicle for the system.

Dependencies:

Inputs: 1, 4, 6-7, 10-11, 14-15, 19-22, 25

Outputs: 24, 26-33, 35-37

EXAMPLE X-TOS:

The X-TOS I/O team decided to input the design variables in a different format: an enumerated database. It turned out that the spacecraft design decoupled from the attribute calculations, which ended up being mostly a function of orbit. The outputs included the above-suggested values plus many others. (The output data file was several hundred megabytes.)

5.3.24 Write Model Translation of DV to Attributes

Inputs:

In order to write the final model, it is necessary to have the finalized design variable and attribute lists. The mapping of design variables to attributes helps a little in prioritization and notional effects that need to be captured in the model. The model must also be verified to ensure quality.

Outputs:

Software code that will model and simulate the transformation of enumerated design variables into their attribute values.

Description:

This activity is the core of the modeling stage of MATE. The model is the mathematical translation of the design variables into the attributes. It is the mapping of the design space to the decision maker-perceived space. The utility function then maps the attribute space to the preference space. The models for the TOS projects were composed of separate modules written in Matlab and Satellite Tool Kit, and integrated into a single program. The model typically is capable of iteratively inputting design vectors and dumping to data files the primary and secondary outputs defined in 7.3.23 Identify I/O for Entire Simulation.

Dependencies:

Inputs: 2-3, 5-7, 10-11, 14-15, 18-23, 25, 31

Outputs: 26-37

EXAMPLE X-TOS:

The X-TOS code was mostly written in Matlab. The orbit simulation was done in Satellite Tool Kit (STK) and the data was captured by Matlab and placed in a .mat file. The following is a list of the files used in the simulation of X-TOS with the notional information flow through the model shown in Figure 21:

Adacs.m
Analysis.m

Calc_attributes.m
Calculate_K.m
Comcdh.m
Constants.m
Costing.m
Designvector.m
Launch.m
Mission_scenario_enum.m
Mission_scenario_sim.m
Orbitrun3.mat
OrbitsLookUp.m
Payload.m
Powerpyro.m
Propulsion.m
Scenario1enum.m
Scenario2enum.m
Scenario3enum.m
Scenario4enum.m
Scenario5enum.m
Scenario6enum.m
Spacecraft.m
Structures.m
Thermal.m
Utility.m
XTOS_DATABASE.m
XTOS_MAIN.m

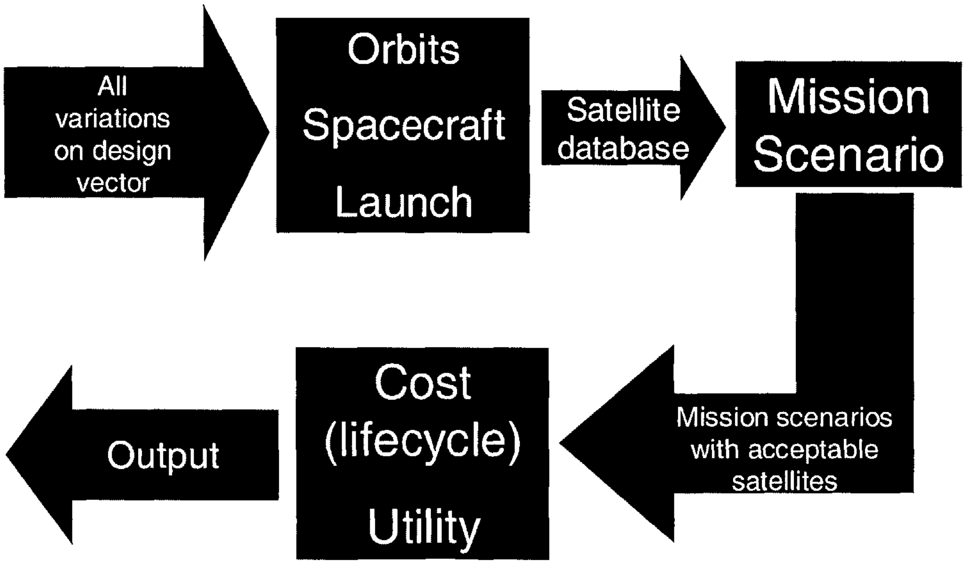

Figure 21 X-TOS Notional Model Flow

5.3.25 Decompose Code (develop software architecture)

Inputs:

After the notional mapping of design variables to attributes is complete, a higher fidelity capture of functional relationships must be done. Finalized design variables and attributes, as well as engineering and physical knowledge of the relationship is needed to complete this activity.

Outputs:

The output of this activity is a software architecture including module names and interface relationships. Typically this information is conveyed in an N-squared matrix.

Description:

Using the mapping of the design variables to attributes, the software architecture can be developed. An N-squared matrix of required inputs and outputs for models necessary to calculate the attributes helps partition the simulation into chunks that can be distributed for parallel development. These chunks, called modules for the TOS projects, have a standardized interface with one another and allow for easy fidelity adjustment through the swapping of newer modules.

Dependencies:

Inputs: 2-3, 5-7, 10-11, 14-15, 18, 20-22

Outputs: 19, 23-24, 26-28

EXAMPLE X-TOS:

The X-TOS team broke up the model into the following modules:

1. Orbits Module
2. Spacecraft Module
3. Launch Module

4. Mission Scenario Module
5. Cost Module
6. Attributes Module
7. Utility Module

	Orbit	Spacecraft	Launch	Cost (TFU)	Mission Scenarios	Calculate Attributes	Cost (Lifecycle)	Utility	Outputs
Orbit									
Spacecraft	X								
Launch	X	X							
Cost (TFU)		X	X						
Mission Scenarios	X	X		X					
Calculate Attributes	X	X			X				
Cost (Lifecycle)		X		X	X				
Utility						X			
Outputs	X	X	X	X	X	X	X	X	

Figure 22 X-TOS N-Squared Diagram

5.3.26 Integrate Model

Inputs:

The software architecture and finished module interfaces are necessary to integrate the model. Knowledge of the simulation Input/Output requirements are as well.

Outputs:

A seamlessly integrated software model that can be run to explore an enumerated tradespace and is capable of outputting data to a data file for later analysis. At a minimum the model can take in a given design vector and output the corresponding utility.

Description:

Once the modules are written and tested, they must be recombined into a working model and simulation. Integration provides interface guidance during module development in order to facilitate the integration process. Integration also includes incorporating the utility function into the simulation. The utility function is written during model development, based on data from the utility interviews. Duties for integrator(s) include maintaining interface control documents, facilitating communication between and among the module developers, and ensuring coherence of the model and simulation.

Dependencies:

Inputs: 5, 8, 12, 16, 19, 21-25

Outputs: 29-30

EXAMPLE X-TOS:

The integration team managed the interface control document, providing coherence for inter-module variable passing. The team also wrote the shell code that called the modules in order to execute the entire simulation.

5.3.27 Enumerate Tradespace

Inputs:

The finalized list of design variables and the ranges over which the model and simulation is valid are necessary to perform the initial enumeration of the tradespace.

Outputs:

A set of design vectors with appropriate values assigned to them.

Description:

The models are developed to accept a particular range of values of the design variables. The tradespace is enumerated by defining particular values of the design variables over model-acceptable ranges. The complete enumeration of a tradespace of even ten design variables may be numerically impossible. A reasonable step size for continuous variables must be determined.

Dependencies:

Inputs: 2-5, 18, 21, 23-25

Outputs: 28-33, 35

EXAMPLE X-TOS:

Table 11: X-TOS Design Variables

A-TOS DESIGN VARIABLES	Range
Mission Scenarios	
Single satellite, single launch	
Two satellites, sequential launch	
Two satellites, parallel	
Orbital Parameters	
Apogee altitude (km)	200-2000
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 Architectures = 50,488	

5.3.28 Navigate Enumerated Tradespace (intelligent pare down)

Inputs:

Inputs for this activity are an enumerated tradespace and some domain knowledge either in MDO techniques or the model functionality.

Outputs:

Similar to the previous activity, the output for this one includes a set of design vectors with associated values, though the size of the set should be much less than the fully enumerated set.

Description:

A completely enumerated tradespace can easily contain 10^10 unique design vector values. Computation capability has increased tremendously in recent years, however the geometric growth of the tradespace with number of design variables and design variable step size prevents an exhaustive search of arbitrary step size resolution. Intelligent pare down of the tradespace, either based on engineering judgment and experience, or through more formal methods like multi-disciplinary optimization techniques, such as simulated annealing or genetic algorithms, reduces the tradespace to a tractable size. There are significant advances made in using techniques for navigating the enumeration that have not yet been incorporated into this list of MATE-CON steps, but should certainly be considered.[52]

Dependencies:

Inputs: 2-5, 21, 23-25, 27

Outputs: 29-33, 35

EXAMPLE X-TOS:

A series of expert rules were developed based on a discussion with the faculty. .

5.3.29 Run Simulation (calculate attributes)

Inputs:

An enumerated tradespace will be fed into a completed simulation model in order to calculate the attributes of the tradespace.

Outputs:

A set of attribute values that correspond to each design vector in the enumerated tradespace will be passed out, in addition to secondary outputs.

Description:

This activity involves the action of running the initial simulation to explore the pared down tradespace of enumerated design vectors. Simulation runs usually are done without human

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[52] Jilla, C.D., Miller, D.W., and Sedwick, R.J., "Application of Multidisciplinary Design Optimization Techniques to Distributed Satellite Systems," *Journal of Spacecraft and Rockets*, Vol. 37, No. 4, 2000, pp. 481-490.

supervision and can be run on parallel computers if the code can select different parts of the tradespace to explore based on user input. The simulation calculates the set of attribute values for each design vector.

Dependencies:

Inputs: 21, 23-24, 26-28

Outputs: 30-36

EXAMPLE X-TOS:

The code for the single satellite case was enumerated in 45 minutes and then simulated in 15 minutes. Since the enumeration was done by scenario, each scenario was run separately (enumeration). After the first scenario and second scenarios were run, it was decided that every other scenario would be dominated by the first scenario and were then not run.

5.3.30 Run Utility Function

Inputs:

Calculated attribute values and a complete utility function are necessary to calculate the utilities of the design vectors.

Outputs:

The utility values, both single and multi-attribute, for each design vector are passed out.

Description:

This activity is the initial running of the utility function over the calculated attribute values from the initial run of the simulation. The utility function calculates the single and multi-attribute values of each design vector.

Dependencies:

Inputs: 23-24, 26-29

Outputs: 31-36

EXAMPLE X-TOS:

X-TOS implemented the utility function for the altitude by taking the utility of a single altitude data point. This gave the normal curve. Then took a vector of a potential orbit's altitudes, sampled at one minute intervals, assigned a utility value for each minute of this orbit (corresponding to each altitude) and summed these utilities up, divided this number by the number of samples in order to renormalize it. For the mission phasing the idea was that it was necessary to recalculate the attributes (and hence the MAU number) for any change in the attribute values. For the one satellite case, it was simple. For the series launch, it was possible to get a utility value for each satellite, then weighted each value by the length of its life time. The same was done for the parallel case, only it was necessary to ensure that there were calculated a new "phase" if one of the satellites died before the other. For two satellites flying at the same time, the attributes simply added. This was done because the attributes were to only be maximized in the case of two satellites. For instance, you couldn't have one satellite that maximized the "time spent in the equator" attribute while simultaneously maximizing the "diversity of latitudes" attribute. However, you can do this with the two satellite case. The problem with that method is that the lifetime attribute won't increase with two parallel satellites...

5.3.31 Verify Output

Inputs:

Output from the simulation and utility function, along with the list of required inputs and outputs and knowledge of reasonable output values are needed to perform the verification activity.

Outputs:

Approval of the simulation model through the verification provides a first order check on the validity of the results.

Description:

It is essential to verify the output of the simulation to make sure it makes sense. If each module is properly tested, the overall simulation output should be relatively error free, however problems due arise when the modules are integrated. (Common problems include unit mismatch and conflicting module assumptions.)

Dependencies:

Inputs: 2-5, 7-8, 11-12, 15-16, 18, 21, 23-24, 27-30, 33-34

Outputs: 24, 32-40, 42

EXAMPLE X-TOS:

This was done internal by the team integrator.

5.3.32 Analyze Output

Inputs:

Verified outputs from the simulation and utility functions, plus the enumerated tradespace are used for analysis.

Outputs:

Plots and statistical analysis of the relationships between the inputs and outputs of the simulation come from the analysis activity. Insight into these relationships directs future tradespace exploration.

Description:

Understanding the structure of the design space-preference space relationship comes out of this activity. Typically analyzing the output involves plotting design variables versus utility or other secondary outputs such as mass or power. Relationships between the design variables and the utilities provide the designers insight into the important drivers of designs of value to the decision makers.

Dependencies:

Inputs: 7-8, 11-12, 15-16, 21, 23-24, 27-31

Outputs: 33-35

5.3.33 Perform Sensitivity Analysis (constants/constraints)

Inputs:

Once the model has been completed and run over an enumerated tradespace, the model can then be subject to sensitivity analysis to determine the stability of the results to uncertainty.

Outputs:

Possible outputs include percent change in output with changes in input. Examples include analysis of the shifting of designs in the utility-cost space with changes in assumed constant values.

Description:

In order to have confidence in the accuracy of the modules, it is necessary to perform sensitivity analysis on the model. Typically accuracy suffers through the assumptions made to perform the calculations. Assumptions take the form of constant values, equations, and algorithms. Sensitivity analysis on constants is relatively straightforward. A list of the constants that have the greatest impact on attribute calculations provide the priority ordering for the analysis. (Sometimes the list comes about after the analysis, but often can be generated through physical insights and engineering knowledge into the system.) Sensitivity analysis can be performed by varying the value of assumed constants and comparing the outputs to the old. This analysis can bring attention to inappropriate model and input assumptions.

Dependencies:

Inputs: 5, 18, 21, 23-24, 27-32

Outputs: 31

EXAMPLE X-TOS:

The X-TOS team derived a parameter-influence tree diagram to determine the important model sensitivities. From the utility function weightings, the USER placed heavy emphasis on data sample altitude and lifetime. Sample altitude is known to a fairly high level of certainty, while lifetime is very uncertain. The greatest uncertainty arises from a large range on the atmospheric density, which was assumed to be a simple exponential distribution in the model, but in reality can vary by an order of magnitude from the idealized distribution. Sensitivity analysis on varying the assumed density model provided insight into impacts on the design. This analysis revealed the real option of using extra onboard fuel to offset the uncertainty in the atmospheric density and ensure a high experienced utility for the USER.

5.3.34 Perform Sensitivity Analysis (utility function)

Inputs:

A completed utility function is all that is needed for sensitivity analysis.

Outputs:

The output of this activity is knowledge of the magnitude of shifts in utility values if the interview data was off or if the decision maker changes preferences.

Description:

Just as sensitivity analysis on the simulation increases confidence in the model, so to does sensitivity analysis on the utility function. Rerunning the utility function under differing values of the little k's and the utility interview data provides insight into how much the utility output answers may change if the decision maker alters his or her preferences. (This analysis captures some of the uncertainty inherent in the interview process and the uncertainty involving the temporal nature of the decision maker preferences. It is important to note that the utility function can be rerun and re-interviewed fairly easily, highlighting the flexibility of the MATE-CON process.)

Dependencies:

Inputs: 7-9, 11-13, 15-17, 24, 29-32

Outputs: 31

EXAMPLE X-TOS:

There was limited sensitivity analysis performed and this proved to be quite problematic in understanding the drivers of the system

5.3.35 Refine Tradespace

Inputs:

Analysis of the previously run tradespace gives insight into regions of the tradespace for further exploration.

Outputs:

An enumerated tradespace of different values than was previously run. These values could be at a higher resolution than previous tradespaces or in a different part of the ranges for the design variables.

Description:

Once the simulation has already been run and the output analyzed, regions of interest will appear on a utility versus cost plot. Regions of interest may include a pareto frontier or other indications of regions for further exploration. A new tradespace is enumerated in this activity to explore the regions of interest. Typically this includes populating the pareto frontier architectures.

Dependencies:

Inputs: 2, 21, 23-24, 27-32

Outputs: 36-38

EXAMPLE X-TOS:

Here there rules which limited the tradespace for a reasonable enumeration for the double sat case were relaxed to allow for sat with lifetimes greater than 6 month as opposed to 1 year. This opened a whole series new low orbits.

5.3.36 Rerun Simulation/Utility Function

Inputs:

Once a new, refined tradespace is enumerated, and the simulation is completely verified and analyzed for sensitivities, all that remains is a final run of the simulation and utility function for more confident exploration.

Outputs:

The enumerated tradespace along with the calculated attributes, utilities, and secondary outputs of the exploration come out of this activity.

Description:

The refined tradespace is run through the simulation and utility functions in this activity. Both the simulation and the utility function are debugged and have sensitivities understood by this point, so the results will have fairly well-understood uncertainties.

Dependencies:

Inputs: 8-9, 12-13, 16-17, 21, 23-24, 29-31

Outputs: 37-40, 42

EXAMPLE X-TOS:

A final data set was produced by the X-TOS team for analysis and presentation at the Preliminary Architecture Review.

5.3.37 Analyze Output

Inputs:

In order to analyze the final output, a data set need to have been generated by the simulation and utility functions.

Outputs:

A final analysis of the tradespace and preference space comes out of this analysis activity.

Description:

The new output is analyzed to find higher order relationships of the frontier architectures between design and preference spaces.

Dependencies:

Inputs: 8, 12, 16, 21, 23-24, 31, 35-36

Outputs: 38-40, 42

EXAMPLE X-TOS:

The team came up with basically the same answer as in the previous analysis. Because sensitivity analysis was not completed until much later, the two runs of the simulation and utility functions occurred sequentially and with little increase in confidence.

5.3.38 Locate Frontier

Inputs:

Once the data set is analyzed, the designs can be plotted in utility-cost space with confidence.

Outputs:

A plot of the designs in utility-cost space with a pareto frontier located. (Designs can be plotted in other spaces as well. The goal is to identify the set of designs that dominate all other solutions.)

Description:

The pareto frontier architectures are identified in utility-cost space. A pareto frontier is defined as one on which an architecture must give up utility in order to reduce cost, or increase cost to gain utility. Economically speaking, the frontier is the efficient set of architectures and dominates all other options.

Dependencies:

Inputs: 21, 31, 35-37, 41

Outputs: 39-40

EXAMPLE X-TOS:

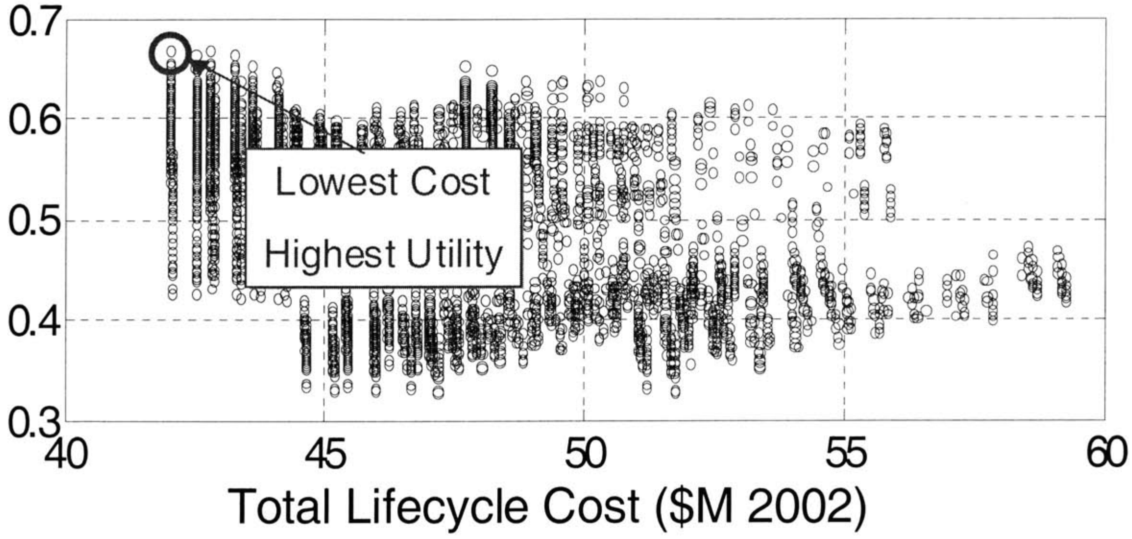

Figure 23 X-TOS Cost vs. Utility

5.3.39 Select Reduced Solution Set

Inputs:

Once the pareto frontier is located, the reduced solution set can be selected.

Outputs:

A set of architectures on the pareto frontier form the reduced solution set, representing the best design vectors in the explored tradespace.

Description:

Along the pareto frontier a small set of architectures are selected for further investigation and demonstration to the decision makers. These architectures can occur at "knees" in the frontier or selected based on other criteria (such as equally spaced points or picked at random).

Dependencies:

Inputs: 2, 4-5, 21, 31, 36-38, 41

Outputs: 40, 42

EXAMPLE X-TOS:

In the X-TOS case, the pareto frontier was chopped due to the constraint of using only U.S. launch vehicles. This cropping led to a clear best solution, i.e. a reduced solution set of one.

5.3.40 Show to DM(s)

Inputs:

Analysis, models, sensitivities, and most important of all, the pareto frontier and reduced solution set are shown to the decision makers for higher resolution decision making.

Outputs:

Information from the decision makers allows for selection of architectures from the reduced solution set or changes in captured preferences, resulting in re-evaluation of the tradespace.

Description:

This activity involves communicating the reduced solution set and analyses to the decision makers. Since the utility functions only capture part of the true preference space of the decision makers, it is important for the decision makers to decide among the reduced solution set architectures or even from the pareto frontier. Feedback from the decision makers improves the architecture delivered value. It is important to convert utilities back to attribute values when communicating reduced solution set architectures. Utility itself has little meaning to the decision makers who can be easily mislead by the multiple nines in utility. The non-ratio scale aspect of utility makes simple interpretation of utility impossible (0.99 utility could actually represent a design that is much worse than one with utility 0.999). Because of the misleading nature of utility, conversion back to attribute space ensures proper communication to the decision maker.

The attributes are by definition decision maker-perceived metrics and thus will have the greatest impact on decision making.

Dependencies:

Inputs: 3-4, 31, 36-39

Outputs: 41-43

EXAMPLE X-TOS:

The only decision makers present at the architecture review was the FIRM and DESIGNER. The USER was not present, and neither was the CUSTOMER. Since only the utility function of the USER was captured for tradespace exploration, this resulted in a disconnect of preferences and communication for selection of the architecture for the next stage of MATE.

5.3.41 Define Stakeholder Tradeoff Function

Inputs:

Input from the decision makers in response to seeing the analysis and reduced solution set from the architecture-level tradespace exploration.

Outputs:

Out of this activity comes a quantitative or semi-quantitative procedure to reconcile multiple utility functions for use in selecting architectures at the end of the architecture-level solution generation and in driving higher fidelity design-level exploration.

Description:

The stakeholder tradeoff function can be an analytical function or a framework for negotiation. The purpose is to reconcile the existence of multiple decision makers with conflicting preferences. The structure of the tradeoff function may reflect organizational structure of the decision makers, such as in the military where rank is clear. The order of the decision makers in the development process could also be used. Rather than using perhaps arbitrary decision maker weightings in an analytic function, the multiple parallel utility functions can be used as a negotiation tool for the decision makers where they can trade utility in order to consensus build. This negotiation allows for incorporation of higher order preferences that may not have been captured through the utility functions. A qualitative tradeoff function will be the result of this negotiation, allowing for the "best" architecture(s) to be selected.

Dependencies:

Inputs: 4, 8, 12, 16, 40

Outputs: 38-39, 42-44

EXAMPLE X-TOS:

This activity was not performed by the X-TOS team.

5.3.42 Select Architecture(s) for Concurrent Design

Inputs:

Feedback from the decision makers regarding the reduced solution set and a stakeholder tradeoff function that will allow for multiple decision maker tradeoffs are needed for selection of architectures for concurrent design.

Outputs:

One or more design vectors and corresponding primary and secondary output parameters from the simulation will feed forward from this activity to concurrent design.

Description:

Once the aggregate preferences of all of the decision makers are known, the "best" architecture(s) can be selected for the next phase of MATE. This activity is the linking point between the architecture exploration and design exploration. Concurrent design will flesh out the architectures to higher fidelity—feasibility studies of a sort.

Dependencies:

Inputs: 4, 31, 36-37, 39-41

Outputs: 43-44

EXAMPLE X-TOS:

Table 12: X-TOS Baseline Architecture

A-TOS DESIGN VARIABLES	Range
Mission Scenarios	
Single satellite, single launch	
Orbital Parameters	
Apogee altitude (km)	200
Perigee altitude (km)	200
Orbit inclination	90
Physical Spacecraft Parameters	
Antenna gain	low
Communication architecture	afscn
Power type	solar
Propulsion type	Hall.
Delta_v (m/s)	1000

5.3.43 Set Selected Architecture as Baseline for Concurrent Design

Inputs:

Once an architecture(s) is selected from the architecture-level exploration and solution evaluation stages of MATE, the selected design vectors can be feed into the concurrent design environment. It is also necessary to know the scope from the architecture design, and the concept from which the design vector originated.

Outputs:

A framework of concurrent design modules (or sheets in the case of Excel-based ICEMaker) that can be used to develop higher fidelity analysis of the baseline design and trades thereof.

Description:

The selected architectures are used to baseline the concurrent design sheets for the next phase of design. This activity is very time consuming and involves creating a concurrent design architecture to be able to make higher fidelity trades on the selected architecture(s).

Dependencies:

Inputs: 3, 18, 21, 40-42

Outputs: 44

EXAMPLE X-TOS:

The X-TOS team reused the ICEMaker sheets developed for the C-TOS design study. Additional sheets of reliability, MATE-CON, and design rationale were added to the set of sheets being reused. X-TOS decided to incorporate the design variables as parameters and drivers of the concurrent design environment.

5.3.44 Develop Higher Fidelity Concurrent Design Models

Inputs:

A developed concurrent design architecture provides the framework for this activity.

Outputs:

This activity adds the computational functionality to the concurrent design framework. Key outputs include fully integrated, higher fidelity subsystem modules (or sheets in the case of Excel-baed ICEMaker) that can trade parameters and allow for human-in-the-loop concurrent design.

Description:

Once the concurrent design architecture has been decided, higher fidelity models necessary to conduct the trades must be developed. These models are written and tested in this activity.

Dependencies:

Inputs: 3, 8-9, 12-13, 16-18, 21, 40-43

Outputs: 45-56

EXAMPLE X-TOS:

The following is a list of sheets developed by X-TOS for the ICEMaker Excel-based concurrent design environment:

MATE-CON
Design Rationale
Systems AND Server
Mission
Power & Pyro
Structures
Reliability
Telecom AND C&DH
Configuration
Payload AND Thermal

Propulsion

ADACS

5.3.45 Perform Concurrent Design Trades

Inputs:

Fully functional and integrated concurrent design tools are needed to begin this activity, as well as a baseline developed from which the trades will diverge.

Outputs:

A set of feasible designs will come out of this activity, each with its associated utility, cost, and physical parameters.

Description:

Directed by the session conductor, the concurrent design team adjusts parameters in their modules in order to develop feasible designs. Trades involve looking at alternative designs that can accomplish the mission. The design trades are navigated through feedback from the MATE-CON chair that continuously calculates the utility of the current design. Typical example trades include looking at alternative sources of power (such as winged solar panels, body-mounted solar panels, or extra batteries) or varying the orbital parameters. It is possible that the higher fidelity models produce different values of the attributes than was calculated in the architecture-level analysis. The purpose of the architecture-level analysis was to focus on the best regions of the tradespace, while the purpose of the design-level analysis is to develop feasible designs that could be physically realized.

Dependencies:

Inputs: 43-44

Outputs: 46-47

EXAMPLE X-TOS:

The X-TOS team developed several designs in the concurrent environment.

5.3.46 Converge on Final Design(s)

Inputs:

Fully functional and integrated concurrent design tools, along with a baseline design parameter set and knowledge of trades together allow for the convergence on final design(s).

Outputs:

A developed higher fidelity design including relevant design parameters, typically including mass, power, and design variable values are passed forward from this activity.

Description:

After the concurrent environment has been baselined and possible trades investigated, the team attempts to converge upon final design(s). A converged design is one that is stable over multiple iterations through the concurrent environment, meaning the parameter set satisfies all of the higher fidelity models and represents a feasible design. The final converged design(s) will take into account knowledge gained through the trade studies and will seek to achieve favorable performance in the decision maker utilities and stakeholder tradeoff function.

Dependencies:

Inputs: 44-45

Outputs: 47

EXAMPLE X-TOS:

The final converged design for X-TOS was the following:

Final design:
Cost: 75,014;

User New Utility:	0.555631116;
U Old Utility:	0.590360564;
Customer old utility:	0.640392756;
customer new utility:	0.584912102;
Wet Mass:	324.2967178;
dry mass w/contingency:	205.5493935;
lifetime:	2.204030227;
DeltaV:	1000;
Perigee:	300;
Apogee:	300;
Launch vehicle:	Minotaur;
Max Power average	162.729

5.3.47 Show to DM(s)

Inputs:

Concurrent design-level analysis and converged design parameters are passed to this activity, as well as knowledge of the relevant decision makers.

Outputs:

Output of this activity is feedback from the decision makers on the analysis up to this activity. This feedback will allow selection of the final design(s).

Description:

Once design-level analysis has been completed, it is necessary to present the results to the decision maker for higher resolution decision-making, just as after the architecture-level analysis. The decision makers typically have an easier time understanding the design-level analysis as it involves physical hardware parameters and can be more readily envisioned. It is important to explain the utility driven designs and verify that these designs capture the important value criteria for each decision maker.

Dependencies:

Inputs: 3-4, 45-46

Outputs: 48

EXAMPLE X-TOS:

The X-TOS team was to present their final results to the "FIRM and USER" on May 13, 2002.

5.3.48 Select Final Design(s)

Inputs:

The set of final converged designs, analysis, and feedback from the decision makers are needed to complete this activity.

Outputs:

The output of this activity is the decision maker selected final design(s) from the MATE-CON process. Typically the fidelity of these designs is at the feasibility level.

Description:

After feedback from the decision makers on the design-level analysis, the final design(s) can be selected. A selected design represents a feasible physical solution to the needs identified in the first activity of MATE. The selected final design can be the baseline for higher fidelity design work in standard engineering design processes. Requirements can be written based on the selected final design and fed forward as standard engineering practice.

Dependencies:

Inputs: 4, 47

Outputs:

EXAMPLE X-TOS:

The X-TOS team will present the selected final design in their final report and mention how requirements could be written based on the final design.

5.3.49 Create Aerospace System Requirements

Inputs:

This step recognizes the need to codify with requirements the particular design that will be pursued by contractors and subcontractors. The fundamental difference is that these requirements are written with the advantage of a formalized process that helps ensure that the requirements that are written:

- have considered a broad set of options
- are quantitatively verified for determining the feasibility of the requirements
- have a basis in a formal process of measuring requirements based on preference
- after helping the decision makers clarify and verify their preferences
- understand the effects of design details on larger system mission
- include inputs from interdisciplinary stakeholders and particular systems experts

Therefore, the whole MATE-CON process provides input into this step, and therefore ensures that there is learning within the design enterprise.

Outputs:

The output of this activity is a requirements document that can be carried forward for the full system design and production.

Description:

Having moved through the MATE-CON process it is now necessary to codify the learning of the process and proceed to the development of the aerospace system. In order to do this it is necessary to write requirements for the various organizations that will be developing the system. The particular details of the writing the requirements will be dependent on the organization, but in general the items deemed necessary for mission success will be written down to provide a common baseline for design.

Dependencies:

Inputs: 1-48

Outputs:

EXAMPLE X-TOS:

These design exercises did only a very limited implementation of the requirements generation since it was known that the designs were not going to be continued in the near-term, but again it would have been possible to make much more sensible requirements for the particular systems having gone through this systematic process.

5.3.50 Establish MATE-CON Design Decision Support Center

Inputs:

The input should be all facets of the MATE-CON process to include specific models, and if possible specific design team that carried out steps 1-49.

Outputs:

The output of this step will be an organization within the design enterprise that will continually monitor the increased level of detail of the design.

Description:

As different details of the design are worked out they will be input into the MATE-CON concurrent design platform. This will allow a continual monitoring of the changes in expense and utility of the design throughout the design process. This also provides decision support for the decision makers so that they can adjust to changes in the environment with the advantage of expense and utility decision support. Unforeseen design difficulties will be reflected on the overall expense and utility to the mission to help understand the impact as uncertainty becomes certainty. It is then possible to make adjustments to mitigate potential of higher expense or lower utility. Ideally this organization would be made up of the team that conducted steps 1-49, but it is not completely required since the learning from these steps should have been broadly captured throughout the whole organization. Furthermore, in the best case this support would provided continued support for the system once it is fielded and through decommission to provide the various stakeholders continued decision making support so that learning continues and is built upon for maximum utility and minimum expense to all stakeholders that interact with the system.

Dependencies:

Inputs: 1-49

Outputs:

EXAMPLE X-TOS:

These design exercises were not carried out for a sufficient time to warrant the need for such a support organization. In a university environment this could be demonstrated if the students were actually building the satellite.

6 MEASURING MATE-CON

Having now discussed the three components of MATE-CON in Part I, and developing the MATE-CON process in Part II, it is now important to consider whether this process can improve current practices of creating aerospace system requirements. This Chapter will not propose a mathematical proof of MATE-CON as an optimal process, but it will instead discuss its strengths and weaknesses. In particular it will use a maturity matrix developed by a researcher in the Lean Aerospace Initiative (LAI), Captain J. Robert Wirthlin, USAF. This is critical to understand where MATE-CON fits into a generalized framework used by most product development organizations, and it is expected that MATE-CON will to some degree or another map to the general approaches used in current practice.

The Headquarters Air Force 2002 Requirements Reengineering Team facilitated this research, and it was then used to analyze the front-end design processes for eight military organizations and eight corporations in addition to the U.S. Air Force. The framework focuses on the activities required for the development of requirements needed for a business case decision, and it was developed through a thorough examination of the literature relating to product development. The framework uses the maturity matrix to evaluate the organizations (commercial and military) relative to an idealized and mature front-end process. Having now developed MATE-CON as new approach to front-end processes the matrix will be used to determine the maturity of a MATE-CON organization. This chapter assumes this as a legitimate framework and does not attempt to fully critique or prove its validity or completeness.

Wirthlin's analysis shows that that military organizations in general will need to reevaluate the current practices in the front-end and the application of process enablers within their organizations. Further, military organizations should reexamine if the current process structure for system development in the front-end needs significant changes.[53] If MATE-CON meets the criteria of this analysis the implications might be that it could provide a useful means for facilitating these significant organizational changes.

6.1 MATURITY MATRIX FOR EVALUATION

The maturity matrix is made up of four phases that include the Identification of Requirements, Initial Screening, Concept Development, and the Business Case Development Phase. Additionally, the matrix includes two enablers the Organizational Enablers and the Business Foundation Enablers. These different phases and enablers are depicted on the flow chart in Figure 24, and the level to which an organization meets that stage is characterized on a scale from one to four with four being the most complete alignment with best practices. The approach here will be to show how MATE-CON does or does not match these various phases based upon the criteria established in each matrix. It is very important to not some fundamental differences in language between MATE-CON and current practices. For instance, requirements and needed flexibility in requirements will be mentioned in the matrix development. MATE-CON does not use the traditional language of requirements until it is absolutely necessary. In the sequence developed in Part II, the writing of requirements comes at the very end. In doing this comparison one should remember that MATE-CON was developed as a systematic approach for design by addressing the following problems:

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[53] J. Robert Wirthlin, *Best Practices in User Needs/Requirements Generation.* S.M. in ESD Thesis, MIT, February 2000.

1. A priori design selections without analysis or consideration of other options
2. Inadequate technical feasibly studies in the early stages of design
3. Insufficient regard for the complete preferences of all decision makers
4. Disconnects between perceived and actual decision maker preferences
5. Pursuit of a detailed design without understanding the effects on the larger system
6. Limited incorporation of interdisciplinary expert opinion and diverse stakeholder interest

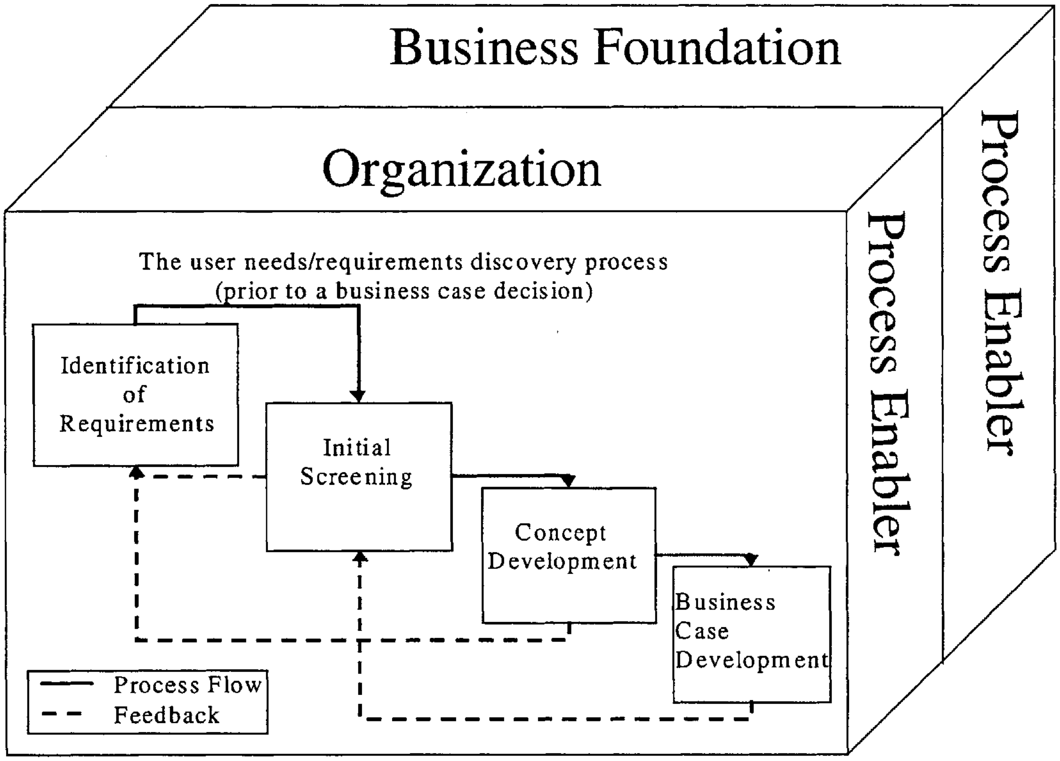

Figure 24 The Front-end Framework and the Process Enablers

It therefore might be the case that it does not necessarily fulfill each of the different phase requirements, but these cases are also important to examine so that one will more clearly understand where MATE-CON might improve the overall front end processes and how these processes might be implemented into current practices among a variety of commercial, civil, intelligence, or military aerospace systems cases.

6.1.1 Identification of Requirements Phase

Overall this stage is the initialization of the product. It is the time when a solution to a need is first pursued. In practice these sources of realizing the need can be consumer feedback, market studies, research, or surveys. To a large degree this step is recognizing that there is a problem and realizing that there might be a new system that could provide a solution. Meeting level four criteria for this phase requires that the organization meet three fundamental criteria. Right from the beginning MATE-CON is going to have difficulty in completely fitting this mold since MATE-CON does not consider requirements until after developing a tradespace, evaluating it based on utility and expense, and then confirming the validity of the point design and its ability to meet decision maker preference with concurrent design. In fact the MATE-CON philosophy would critique any process that began with requirements. Nevertheless it is important to continue through these three criteria to continue to elucidate differences.

6.1.1.1 Multiple structured methods are used to elicit and gather needs for the different stakeholders / customers. Relates to extensive market research and analysis.

The level to which MATE-CON meets this standard quite effectively by beginning any discussion with the stakeholder with preference language that is easily converted into the more structured methods of utility analysis so that the focus is on true customer value.

6.1.1.2 Requirements are specified to describe a desired end-state, or a capability desired.

Again, the MATE-CON philosophy would take issue with the terminology, requiring instead that the discussion be in terms of preferences (attributes). By using this terminology it is much more likely that the communication will describe a desired end-state or capability as opposed to a point design.

6.1.1.3 Structured methods used to develop required capabilities or end-states into potential solutions.

Certainly MATE-CON meets this criterion by establishing very explicitly the definitions of the attributes, and using rigorous methods to convert those methods into different design variables that will eventually allow the creation of a concept (potential solution).

6.1.2 Initial Screening Phase

In this stage the framework discusses the refinement of the needs list by drafting a document and creating it as the baseline of discussion that will be continually refined. It also mentions that in addition the needs listed on the document the list of potential solutions should also be included.[54] This stage has four more explicit criteria for meeting a level four maturity for initial screening. The last two criteria are outside the realm of the MATE-CON direct process, but would certainly be required within an organization for effective implementation of MATE-CON.

6.1.2.1 The portfolio of development projects (potential solutions) plans for required technology development. The portfolio is controlled by one group / organization.

This portfolio of potential solutions would be similar to the selected design vector, which explicitly contains the main design variables that will be included in the enumeration of the tradespace. MATE-CON does not explicitly address the organizational management of the

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[54]

modeling team that would develop the design vector, but certainly the MATE-CON philosophy would say that the group with the expertise in engineering would be providing the design vector so that the decision maker is less likely to jump to a point solution.

6.1.2.2 Development project risk and potential return must satisfy pre-negotiated criteria before approval to pursue further development.

This form of initial screening is achieved through a series of different processes. First the utility interview process is fundamentally a means of analyzing value under uncertainty. This is a function of the utility assessment mechanism of using lottery assessment techniques. This step would likely be performed at the architecture selection phase of MATE-CON where the decision makers and the design team would be in the same room to decide the baseline for proceeding to the integrated concurrent engineering phase.

6.1.2.3 Decision for further development guarantees resources. Resources are dispersed at the discretion of the portfolio management.

This criterion is a function of organizational management that is not in the realm of MATE-CON, but is nonetheless an important consideration.

6.1.2.4 Required technology research and development is given necessary resources upon approval for further development. Portfolio management controls resources.

Similar to the last, being simply a function of the organization.

6.1.3 Concept Development Phase

Of all phases this one probably most closely matches the MATE-CON process. As discussed earlier one of the main differences is in the use of the requirements term. Just to reiterate, the MATE-CON process does not use the requirements language until after the integrated concurrent engineering phase when it is clear what the optimal requirements might be. Until that point the discussion is in terms of constants, design variables, and attributes. All of these that can be easily varied to quickly show the effect on overall value to the mission, quite unlike requirements. So again it seems that while the terminology might change to some degree MATE-CON provides a means of reaching this high-level of maturity.

6.1.3.1 Clear and concise product requirements with measurable outcomes and acceptable ranges on all requirements.

This will be a clear and finalized definition of attributes that included not only the minimum and maximum tolerances, but it also includes a means of determining the varying level of value between the decision maker defined ranges. This also includes a complete list of the constraints that go into the constants vector.

6.1.3.2 Trade-off analysis on multiple requirements mix and 'sets' of solutions.

If best practices used today score at a level four here MATE-CON would be at level five through implementing the advances in tradespace exploration discussed in part I of this thesis. It is the enumeration of these potential solutions and conducting the tradeoff analysis in terms of decision maker utility that makes MATE-CON so valuable. If MATE-CON is not a complete front-end process then as a minimum it should be employed in this stage of current practice.

6.1.3.3 All product features are prioritized. Additional information to 'delight' the customer is also included.

As discussed already MATE-CON reaches the highest levels for this criteria through the use of Multi-Attribute Utility Theory. Indeed it is the interim single attribute utility values that are determined through the single attribute interviews that allow one to understand this level of 'delight,' and then the overall aggregation of those attributes that create the most 'delightful' solution.

6.1.3.4 The architecture of the solution is clear and precise. It embraces open standards and future growth where appropriate.

This criterion is likely not met until entering the integrated concurrent engineering phase of the MATE-CON process. It is here where the internal and external interfaces are made explicit and are more completely modeled and understood. It is also at this phase where future growth can be most quickly recognized.

6.1.3.5 This step conducted by front-end process group.

This criterion is a function of organizational management that is not in the realm of MATE-CON, but is nonetheless an important consideration. It is certainly important to have a single group that performs this step to manage the complex software architecture. However, it should be understood that this phase should not be by this group in a vacuum. High iteration with external stakeholders is still very important.

6.1.3.6 Service / support / maintenance concepts must be explicitly described to include estimated costs over the lifetime of the solutions.

To pick up on the previous point, all stakeholders must have some input into this process, as specifically addressed by MATE-CON. Only by employing concurrent design practices is it possible to reach the appropriate level of detail to ensure that the conceptual design is really being designed for the full system lifecycle.

6.1.3.7 Appropriate prototypes along dimensional axes of 'physical-analytical' and 'comprehensive-specific' are used; developed according to defined methodology (Ulrich and Eppinger).

This level four criterion is met through the integrated concurrent design environment, and is explicitly done by the chair that is given the task, but the overall integrated concurrent team provides the initial prototype and going even above the standard of this criterion, it quantitatively evaluates the prototype with respect to the preferences established in the earliest phases of the design.

6.1.4 Business Case Development Phase

The overall goal of this phase is to explicitly categorize and define efforts to be pursued by the organization. To conduct this phase well it is critical that the learning from the previous phases be clearly captured, and it is in creating and propagating the learning that MATE-CON has such distinct advantages. However, as in some of the previous criteria, many of these various levels are completely a function of organizational management and therefore are not explicitly addressed by MATE-CON.

6.1.4.1 Approval of concept commits organization to launch of product and commits resources of organization.

While to a large degree this is an organizational management function MATE-CON can certainly provide insights into the decision to commit resources, particularly if one considers the sensitivity analysis that are possible. Furthermore, MATE-CON provides a framework for more clearly understanding technological risk.

6.1.4.2 Description of the Product Concept exists; is clear, precise, and concise; and is integrated with the concept of operational employment.

Upon completing the integrated concurrent engineering phase the details of the design have been clearly determined and the interfaces have been carefully worked out using the advantages of the concurrent design environment. Furthermore since MATE-CON has established the preferences and the constraints of all stakeholders that will be interacting with the system, it takes little effort to annotate that the proposed system has been integrated with the concept of operational employment.

6.1.4.3 The business plan contains detailed information how the product will contribute to the objectives of the corporate strategy, including specific information of how much, when, and for how long

The corporate executives will have already defined for the design team the fundamental preferences that ensure that the product meets the overall mission needs. The level to which the product then meets those objectives was then explicitly quantified using utility theory and can be aggregated as a single expense utility point or can be disaggregated in the more comprehensible terms of expense and utility attributes defined by the decision maker. Furthermore, the MATE-

CON mandate of designing for total lifetime will provide the "specific information of how much, when, and for how long."

6.1.4.4 The product replacement strategy is outlined with specific information regarding the costs and benefits to the organization with a timeline giving the necessary predevelopment work that must occur for a successful transition.

The product replacement strategy is something that is necessarily developed in the concept through the design vector. MATE-CON can provide a clearer explanation of the costs and benefits to the organization through iterating various product replacement strategies and showing their relative merit both in terms of attributes and in aggregated terms of utility and expense, terms that would be quite difficult to quantify without the advantage of a process that did not incorporate Multi-Attribute Utility Theory.

6.1.4.5 Technology planning, maturation and insertion are outlined in detail along with defined process(es) that will be used for each to occur.

Again the MATE-CON process could provide a very clear means by which to recognize needed technology and more importantly the cost of not acquiring that technology or the benefit of acquiring better technology. One such case was developed in the C-TOS implementation of the integrated concurrent engineering process. As part of the MATE-CON process it would have been quite possible to get a clear understanding of the defined processes for technology insertion.

6.1.4.6 Architecture of concept is explicit in its relationship to the architecture of the existing company products or the 'next' generation of products.

Like a previous criteria, these interfaces are made explicit in the concurrent engineering phases of the design through the incorporation of the full product lifecycle approach.

6.1.4.7 Contingency planning a regular business activity.

This is one area that has not yet been completely incorporated into MATE-CON but has been part of the SSPARC[55] research and is in the process of being integrated with the full MATE-CON process. The possibilities for of such planning were addressed qualitatively in the X-TOS exercise. Essentially, during the integrated concurrent engineering phase it become possible to see which design decisions can be put off for a later time. The cost of providing this so called real option can be captured though the utility and expense language that is integrated into the integrated concurrent design environment to provide such contingency planning for the design enterprise managers. Actual use of this capability then relies on the management.

6.1.4.8 Relationships to other development projects are explained by including information that indicates the value of the relationships in terms of all affected resources.

MATE-CON seems to provide level four maturity, and is done by ensuring that all stakeholders are included in the front-end design process. Among these stakeholders must be the decision maker interested in nurturing the relationship between the new product and other development projects. This would be realized through the attributes of said decision maker.

6.1.5 Organizational Enablers

As Wirthlin states in discussing organizational enablers, "the overall focus of the organization's people is on understanding user needs. The goals and strategy of the organization are known and understood by all employees and is explicit for the front-end of product development (Cooper 1996; Cooper and Kleinschmidt 1996). They understand how their

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[55] Myles Walton, *Managing Space System Design Uncertainty Using Portfolio Theory.* Doctoral Thesis, Aeronautics and Astronautics, MIT, June 2002; Annalisa Weigel, *Bringing Policy into Space System Conceptual Design: Qualitative and Quantitative Methods.* Doctoral Thesis, MIT, June 2002.

specific job relates to achieving those goals."[56] This is one of the fundamental advantages that comes from combining Multi-Attribute Utility Theory and concurrent design practices. The individual can see the effect that they can have on the overall expense and utility of the system, ensuring that the focus is on value. This section will again address the various means that MATE-CON meets the standards for a mature front-end process. However, this more than the other sections requires particular human resources management by the leader that is not explicitly addressed in MATE-CON but could be surmised from the MATE-CON philosophy.

6.1.5.1 The organization's product development strategy is explicit for the front-end and contains specific measures that drive the behavior of the front-end.

Simply by making the choice in implement MATE-CON the organization would be meeting level four maturity for this parameter as MATE-CON is explicitly a front-end process and as indicated from part II of the thesis includes specific measure that drive the behavior of the front end.

6.1.5.2 The organization is structured to automatically generate cross-functional inputs.

To correctly implement MATE-CON an organization would necessarily need to have representative from the various functions that would participate in and provide input for concurrent engineering activities. This also means that these representatives from the design enterprises various stakeholders would provide input for utility interviews.

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[56] Wirthlin, 76.

6.1.5.3 The Integrated Product Team consists of a small 'core' group with less than 10 members.

Such Integrated Product Teams were similar to the teams that conducted the TOS exercises, so MATE-CON in its most current instantiation is done with teams of this size. This should not allow one to forget the importance of brining in stakeholder representatives throughout the process that will participate in some of the activities of this core group.

6.1.5.4 Clear roles and responsibilities for the preferred organizational structure are negotiated as part of the front-end process.

This is not an issue directly addressed by MATE-CON, but like other criteria are a function of organizational management that is not explicitly considered by the process structure alone.

6.1.5.5 The preferred organizational structure relies on self-selected and self-directed teams.

This is the same as 5.4.

6.1.5.6 Entire team remains intact for the duration of the front-end process.

As mentioned earlier it is almost required do to the complexity of the models needed to effectively conduct the MATE-CON process.

6.1.5.7 Leadership of development efforts given to senior employees based upon technical & managerial skill evaluations.

This is an interesting point as it relates to MATE-CON. Certainly, like any process the effectiveness of MATE-CON is dependent on the technical competence of those conducting the MATE-CON activities. However, it is a process developed explicitly to reduce the need of individuals with intuition for finding a good design. Certainly these old and wise employees are a great advantage to the process. Unfortunately, if one reviews the current demographics of the aerospace engineering corps, there is a looming human capital crisis, that is sure to reduce the number of these senior employees. This inevitable trend makes the emergence of MATE-CON evermore timely.

6.1.5.8 Employee participation in development effort is not restricted.

Depending on the different organization employee participation will almost inherently be tied to MATE-CON, in that it makes it clear how each different stakeholder will be interacting with the system. So essentially every employee that is part of a stakeholder organization will be participating in the process to one degree or another.

6.1.6 Business Foundation Enablers

This final section of the framework discusses the way in which the organization should arrange itself with respect to the incorporation and management of a front-end design process. This section much like the last is to a large degree a function of organizational management. This is not to say that MATE-CON cannot assist in these decisions. Certainly, in the first case it is quite clear how MATE-CON's value might be realized.

6.1.6.1 A formal process exists and is consistently followed and measured.

To meet this level the organization is much more likely to consistently follow a process if it has the full development and is pre-existing. It is unlikely that the organization is going to spend the time developing a completely new process. The focus of the organization is on the product, leaving little resources available to approach the academic question improving processes (this might explain to a large degree why there has been little process improvement, and why the government sponsor was interested in a government, university, and industry partnership—

SSPARC—to approach this problem). MATE-CON is an existing process that could be picked up and consistently followed and measured.

6.1.6.2 Management has active interaction with the front-end in a coaching and/or advisory role. There is a distinct lack of organizational layers between management and the front-end process.

Inherent in the MATE-CON process is the need to incorporate the preferences of all of the main decision makers. Certainly, among these is the management. MATE-CON mandates direct contact with the management for the purposes of accounting for the preferences in the product design.

6.1.6.3 Employee training is required in the specialty of each employee. Other training in areas of interest that may not be related to specialty of each employee is given in a 'holistic' fashion giving the employee an opportunity to understand the different functional areas of the company. Training is directed towards continuous improvement.

Among all of the criteria in the matrix this particular one seems least pointed to front-end development process, but rather just a statement of good management practices.

6.1.6.4 Understanding resource capacity vs. flexibility in front-end considered in portfolio management. Tradeoffs between resource-starving projects and development speed are understood. The relationships between short-term and longer-term development projects are key to management decisions.

As mentioned earlier, this is one of the least developed areas of research under MATE-CON, but certainly one of the most important. This is not to say this research has not been done, it simply has not been sufficiently incorporated into the MATE-CON framework. It is undoubtedly necessary to be able to characterize the dynamic nature of the development processes so that portfolios and real options can be developed providing management with tools for mitigating risk among the multitude of projects in it purview.

6.1.6.5 One organization shepherds ideas from the beginning of the front-end process until product launch.

This would be the MATE-CON organization. It is up to the management to establish such an organization.

6.1.6.6 A common database or IT tool is used by all process participants in the organization. It also contains decision assistance methodologies based upon predetermined criteria.

While MATE-CON is not required to be used on only one IT tool, it certainly provides the framework for using such a tool and incorporating others. The second part of this criteria is also sufficiently satisfied by using the Multi-Attribute Utility Analysis, however, as was mentioned in the introduction MAUA should not be considered the end state for determining and characterizing preferences nor should it be used exclusively if other possibilities are available. These decision methodologies should however meet a very high level of mathematical, statistical, and psychometric rigor lest they be counter-productive.

6.1.6.7 R&D is tightly coupled with the current product concepts in the front-end.

In the case of R&D this tight coupling comes from the concurrent engineering facet of MATE-CON, whereby the R&D would be tied in directly via the IT tools to the current product concepts that are being considered in the front-end. This again demonstrates the importance of the combination of concurrent design with MAUA, is that the R&D would be able to more quickly and easily justify the purpose for pursing a particular technology because they would be able to model the existence of that technology and show how the new design would have an increased utility or a decreased expense.

6.2 MATE-CON MATURITY CONCLUSIONS

In virtually all of these six metrics MATE-CON scores very high in terms of maturity. Unfortunately, since MATE-CON has not yet been implemented into a particular organization it is not possible to say with certainty that at MATE-CON organization would necessary provide greater value than all other possible organizations. It is however possible to use this matrix as a baseline to compare MATE-CON. As a minimum an organization could gain by considering the precepts of the various points in the matrix and considering how MATE-CON approaches a method to achieve those metrics. In doing so one is almost sure to find significant benefits of employing some of these process practices. Again, this does not claim mathematical proof of MATE-CON as a best process. Instead, Wirthlin proposes a maturity matrix based on interviews, literature, and experience with the processes. One could certainly argue the legitimacy of some of the points, but overall it provides a very solid baseline for measuring front-end design processes. When one looks at MATE-CON under this light it seems to perform better that the sixteen other organizations that Wirthlin considered, among these were the top Air Force organizations along with a couple of other military organizations and the other half was composed of businesses.

7 CONCLUSION

In Part I of this these Chapter 2 showed how it was possible to avoid establishing design requirements a priori with by considering a tradespace of options. Furthermore, these options could be systematically evaluated in the early stages of design. This Broad Tradespace Modeling was derived from GINA and used in A-TOS with expected benefit, but a more generic metric for modeling value to the user was still needed. Lack of regard for the complete preferences of the decision maker and inaccurate characterization of decision maker preferences led the to a need for Multi-Attribute Utility Analysis in B-TOS. IN B-TOS there was analysis of value based on decision-maker preference and there was intelligent aggregation of multiple preferences, yet there was a need higher fidelity to see how detail impact total tradespace and for an improved method for enumerating the tradespace. While the later was not directly addressed C-TOS and more clearly X-TOS approached the problems of pursuing a detailed design without understanding the effects on the larger system and failing to incorporate interdisciplinary expert opinion and diverse stakeholder interest. The concurrent environment proved to resolve complex system interactions and the MATE-CON chair showed impact of low-level trades on the overall mission. After developing this discussion in Part I, Part II established a fifty-point process by which MATE-CON could be implemented. Finally in Part III MATE-CON was evaluated by a front-end maturity matrix and qualitatively showed to have high potential as a mature process.

7.1 KEY FINDINGS

Based on this development, explication, and first cut at evaluating the process it is important now to consider some of the main factors to remember about the process. Some of these are advantages, some are disadvantages and some are simply cautions. Since each subtitle could be the initiation of another thesis the attempt will be to just briefly brush over the issue.

7.1.1 Need Scripts for Integrated Concurrent Engineering Sessions

With the complex problems that are being tackled in each session it is critical to have a clear method for conducting the session. It is probably best to develop a single baseline design based on one of the pareto architectures. During this development it is possible to use expense and utility for subsystem trades, and once the baseline is established it is then possible to look at perturbations. Remember that the goal of the session is to increase fidelity and utility and reduce expense.

7.1.2 Utility Language is Difficult and Expense is More Difficult

While the MIST software significantly decreased the time on the utility interview in X-TOS there is significant questions about the widespread acceptance of utility interviews based on lotteries. It is quite likely that people will feel that these interviews are mundane and waste time. Additionally, utility metrics on a scale of 0 to 1 are very difficult to present to those who are not familiar. Explaining the notion of expense as an aggregate of negative attributes is even more difficult. Replacing requirements language with attributes or utility language will be very difficult.

7.1.3 Utility Language is Useful

Utility theory here contributed to the field by reducing a 6-dimensional decision to only two dimensions by asking 1) how many resources can you afford to give up? 2) how much benefit must you extract? Fundamentally, it reduces highly complex decisions into a cost-benefit analysis. However, in performing this service there is not loss of completeness of weighing the n-dimensional problem, for the multiple variables of the decision have been aggregated into single two single numbers. Information is not lost in this aggregation, and therefore it is possible to do quick transformations between the utility expense space of zero to one values and the attribute space of performance ranges defined by the decision-maker. This allows a decision-maker to make decisions base on two variables expense and utility.

7.1.4 Utility has Limitations

Currently, it is not clear how to include many more than six attributes. This however should not be overly limiting since most psychological data suggests that humans cannot keep more than about seven parameters in their head at one time. Additionally, if one considers six separate expense attributes then it would be possible to have two single aggregations of twelve numbers still reducing a twelve dimensional problem down to a two dimensional problem. This does not overcome all of the limitations. If one considers the possibility of using utility theory for purchasing a house, they may have completed a full set of attributes and these attributes point towards a particular house, when in fact the decision-maker (purchaser in this case) arrive and finds out that the rooms are arranged far to awkwardly for his or her liking. The bottom line here is that this approach is not going to uncover all possible preferences of the decision-maker, but the premise is that in the process of defining attributes the decision-maker critically considers the specifics of his or her preferences (with the hope that new ones are not uncovered later) and the designer begins to develop why he or she is designing.

7.1.5 Frequent Communication with the Decision Maker is Key

Even with perfect utility expense metrics it is absolutely necessary to keep close communications with the decision maker. The decision maker's environment is constantly changing and if the designer is not aware of that he or she will be designing a solution to an old problem. Utility does not get around this, but if used correctly concurrent engineering can help mitigate these dangers.

7.1.6 Attributes Must have Clear Definitions Early

In every case so far significant problems have arisen from poorly defined attributes. The attribute definitions seem to continually change. Attributes and their definitions are controversial discussions. Force these discussions earlier rather than later and ensure that the definition is developed in such a way that an equation can be readily developed for calculating that attribute. An attribute that cannot be calculated is of no value.

7.1.7 Technical Expertise is Irreplaceable

It is important to underline in the methodology the importance of having a strong technical background to ensure that the designs being developed under this new process are actually technically legitimate. This process can never be considered good if it does not create designs that undergo strict technical scrutiny. Thus, individuals working in this research must not spend excessive time on processes, which seem to be the "fuzzy" end of the research at the expense of the technological legitimacy of the products, which the process should produce. You must have individuals who are engaging the math, science, and engineering if there is any hope of changing the way in which mathematicians, scientists, and engineers create design products to fulfill a social need.

7.1.8 Helping the Decision Maker Determine Preferences

It is important to understand that one of the greatest advantages of using utility is that it helps the decision makers learn what they want, and the more this is explored at the front, the more probing the questions the less likely that those desires will be misstated. In order to do this it is fundamental to have designers that have a greater appreciation for interdisciplinary processes. Utility allows the designer to understand what the decision maker desires maybe even before the decision maker knows. The value-added by MATE in the B-TOS project was its explicit focus on communication between the decision-maker and the design team. The utility assessment process forced the decision-maker to better understand his wants and needs. Additionally, the utility function, and the information it conveyed, provided the design team with a much better understanding of the holistic context of the system. This communication function of MATE coincided well with the role of tools as an information channel between disciplines.

7.1.9 Concurrent Design Validation is Necessary

In modeling there are three goals. They are to create a model 1) quickly, 2) that has high fidelity, 3) is flexible for broad trades. Unfortunately not all can be met simultaneously leaving one with a reduced fidelity. At some point the perturbations are going to knock you off of what the model will allow and you can then either expand the model to continue to try to optimize the spacecraft or depending on time you stay within the given range. In any case it is necessary to understand how to pass the learning on to the next level of design. The transition from the system architecture modeling to the concurrent spacecraft modeling show means of maintaining that learning between levels.

The rationale for using concurrent design with MATE:

1. It puts all of the experts in the room
2. It allows learning in the design group
3. It motivates everyone toward common desired end for team cohesion
4. It allows group exploration of the tradespace

5. It makes trades depending on the effect that those trades have on cost and utility
6. Everyone cans see the effect of loosening architecture requirements
7. It is possible to quickly consider how to get the most from technology development

7.1.10 Rationale Capture is Key

In conducting these exercises one must capture learning and understandings of how to create increased value as the design increases in detail. This can be done by a good rationale capture tool, and SSPARCY is one such tool (see Satwick's Thesis)

7.2 FUTURE WORK

Since this thesis provided an introduction into the MATE-CON process it is quite clear that further work is necessary to make MATE-CON a more complete front-end process. The sections below outline some of the basic research areas that are needed to make MATE-CON a more viable design process.

7.2.1 Multiple Stakeholders and Value in Broader Application of Concurrent Design

For architecture development it seems similarly important to get all of the key stakeholders in the room. We continually have the problem of not being able to get the attributes. This is because there are not single decision-makers and if there is a single decision-maker that decision-maker must somehow aggregate the interests of many others. Pedagogically, it might be that in the first portion of the class it is critical for the group to divide into the various stakeholders and become representatives for those stakeholders. They can then try to determine a good means of aggregating those preferences. MATE-CON can become a means of improving negotiations. It seems that it would be possible to find all of the individuals that are hope to get drag data. One could do different utility functions for each individual and aggregate those multiple attribute utilities of each individual into a single multiple attribute for the entire system. Much work is necessary to check the validity of such an approach.

7.2.2 Networked Decision Makers

In order to stay in better contact with the decision make it might be useful to establish a regularly scheduled time for updates to utility interviews. It is not clear if it is necessary to do the complete interview again. Perhaps after a while the decision maker would begin playing games with the utility question undermining the interview system. In any case it seems that research is need to find better means of extracting more exact preferences with higher frequency.

7.2.3 Dynamic Decision Making Management Tools Real Options

Following up on the previous point, it is inevitable that a decision maker will change his or her preferences. This is a result of the changing environment, and should be expected. It is possible to prepare for these changes by developing dynamic decision tools for the manager so that when there is better information it is possible to make better decisions. It seems that MATE-CON could provide a means to develop such tools and understand their expense and utility to the overall mission design.

7.2.4 Need Better Catalysts for Innovation

Modeling tradespaces is difficult and the increased complexity through broadening the trades between concepts can in the end discourage innovation. It simply becomes too difficult to include many of the interesting trades in the model so they are dropped from the tradespace. Techniques must be developed to improve modeling practices so that greater innovation can come from considering more diverse designs.

7.2.5 Expense Functions

While these were develop just briefly in Chapter 3 there is still more work. One of the first advantages seems that it provides a means to include more attributes, but there are very serious questions about the legitimacy of using this particular approach. In any case more work should be done on the Multi-attribute Utility Theory to determine how to include more attributes so that the definitions are not so difficult and so that interview processes are not as painful.

7.2.6 Need fidelity chair in the room

One recurring theme is the inability to ensure that the entire model is of the same fidelity. This problem arises in both in the architecture studies using MATLAB and in the ICE sessions. One person may be developing perfect models, but if their models rely on inputs from someone else whose models are of much lower fidelity the final answer this has a high deal of uncertainty. The uncertainty in the outputs could potentially invalidate the entire study. At least in the case of the ICE sessions it is possible to develop a fidelity chair that understands the range of legitimacy of the model outputs.

7.2.7 Change Requirements Processes

As already discussed the purpose it to eventually get to the point that requirements are not established until absolutely necessary. The problem is that right now requirements language is used right from the beginning of a program. Field research should be done to consider how this language barrier might be overcome, and more importantly to see if MATE-CON could actually be applied to organizational practices.

7.2.8 Need to Improve Tradespace Exploration

While the work of Cyrus Jilla has been briefly discussed it is worth reemphasizing the importance of doing more thorough tradespace studies. Given current computing power this is going to take much more clever means of looking at a diverse tradespace in modeling. Furthermore, there are potential advantages of considering some notions of pursuing optimality from the outset. This comes from doing better enumerations of the tradespace.

7.3 IN SUM

As a first cut MATE-CON, while not yet deemed an optimal process by mathematical proof, had made great strides in confronting major problems in system design. First, by incorporating the GINA advances in modeling tradespaces, it has increased the breadth of options considered in the early stages of design. These advances have also increased the level of technical rigor for determining system design feasibility. Additionally, by employing Multi-Attribute Utility Theory, MATE-CON has developed a mathematically rigorous approach to aggregating decision maker preferences. This approach provides a metric to equitably evaluate different system design options. It also attempts to quantify and track decision maker preferences instead of assuming a decision maker preference based on invalid metrics and fixed requirements. Finally, by utilizing advances in concurrent design, it is possible to propagate this utility metric throughout the various levels of design preventing the use of resources to pursue a detailed design without understanding the effects on the total mission. It also incorporates interdisciplinary expert opinion and diverse stakeholder interest throughout the design. While significant work remains in formally proving best process metrics, preliminary findings show that MATE-CON possesses a set of benefits that will significantly improve space system design.

8 GLOSSARY

Terms	Definition	Source
Architecture	1. The structure, arrangements or configuration of system elements and their internal relationships necessary to satisfy constraints and requirements. 2. The arrangement of the functional elements into physical blocks. 3. The embodiment of concept, and the allocation of functionality and definition of interfaces among the elements. 4. The structure -- in terms of components, connections, and constraints -- of a product, process, or element.	1. 16.882, Fall 2001, Lecture 1 (attributed to Boppe) 2. 16.882, Fall 2001, Lecture 1 (attributed to Ulrich & Eppinger) 3. 16.882, Fall 2001, Lecture 1 (attributed to Crawley) 4. The Art of Systems Architecting, 2nd ed., Maier and Rechtin
Attribute	1. Quatifiable variable that measures how well a decision-maker defined objective is met, must be complete, operational, decomposable, non-redundant and minimal	1. SSPARC internal and Keeney and Raiffa, Decisions wth Multiple Objectives 1993
Benefit	1. Value derived the from the use of a good or service	1. SSPARC internal
Complexity	1. A measure of the numbers and types of interrelationships among system elements. Generally speaking, the more complex a system, the more difficult it is to design, build, and use.	1. The Art of Systems Architecting, 2nd ed., Maier and Rechtin
Concept	1. A product or system vision, idea, notion or mental image which maps function to form and embodies "working principles".	1. 16.882, Fall 2001, Lecture 1
Concurrent Design	1. An engineering process in which experts from various distinct disciplines design systems through real-time interaction	1. SSPARC Internal
Constants Vector	1. The set of untradeable parameters in a design. The Constants Vector contains physical constants, constraints of the problem, and variables deemed less important due to scoping decisions.	1. SSPARC internal
Cost	1. Economic resources expended in production of a good or service	1. SSPARC internal
Design	1. The detailed informationof the plans or instructions for making a defined system element; a follow-on step to systems architecting and engineering.	1. The Art of Systems Architecting, 2nd ed., Maier and Rechtin
Design variables	1. The tradeable parameters in the Design Vector.	1. SSPARC internal
Design Vector	1. The set of tradeable parameters in a design. The Design Vector along with some components of the Constants Vector define the Concept. The values of the variables in the design vector constitute a particular design.	1. SSPARC internal
Expense	1. Value lost as described by preferences of a decision-maker	1. SSPARC interal
Exploration	1. An investigation, analysis, or study to highlight drivers and quantify comparisions as opposed to formal mathematical optimization techniques	1. SSPARC internal
Form	1. The structure, layout or arrangement of the physical/logical embodiment or configuration. 2. The sum of the parts. 3. What is formed, manufactured, implemented, written, sculpted, or drawn.	1. 16.882, Fall 2001, Lecture 1 2. 16.882, Fall 2001, Lecture 1 3. 16.882, Fall 2001, Lecture 1

Terms	Definition	Source
Function	1. The process and behavior of the system 2. The operations and transformation that contribute to performance. 3. The intent for which a thing exists.	1. 16.882, Fall 2001, Lecture 1 2. 16.882, Fall 2001, Lecture 1 3. 16.882, Fall 2001, Lecture 1
MATE	Multi-Attribute Tradespace Exploration	1. Ross-Diller 2001
MATE-CON	Multi-Attribute Tradespace Exploration with Concurrent design	1. Ross-Diller 2001
Multi-Attribute Utility Theory	1. The theory of quantifying and aggregating decision-makers preferences using an ordered metric scale	1. De Neufville Applied Systems Analysis
Objective	1. Client needs and goals, however stated.	1. The Art of Systems Architecting, 2nd ed., Maier and Rechtin
Objective function	1. A preference fuction that one desires to optimize, it defines the quantity to optimize	1. De Neufville Applied Systems Analysis
Requirement	1. An objective regarded by the client as an absolute; that is, either passed or not. [see goal]	1. The Art of Systems Architecting, 2nd ed., Maier and Rechtin
Risk	1. The level of hazard combined with the likelihood of the hazard leading to an accident, and the duration or exposure of the hazard; a combination of the likelihood, severity and lack of detectability of an accident or loss event.	1. ESD Terms and Definitions (Version 11), May 24, 2001
System	1. A set of interacting components having well-defined (although possibly poorly understood) behavior or purpose; the concept is subjective in that what is a system to one person may not appear to be a system to another. 2. A physical or virtual object that performs a function which cannot be fulfilled by its constituent parts alone and that is distinct from its environment through a system boundary. 3. A collection of things or elements which, workign together, produce a result not achievable by the things alone.	1. ESD Terms and Definitions (Version 11), May 24, 2001 2. 16.882, Fall 2001, Lecture 1 (attributed to de Weck) 3. The Art of Systems Architecting, 2nd ed., Maier and Rechtin
Systems architecting	1. A process for creating a design at a high, abstract level, whereas systems engineering is often associated with refining such a design; by blending the two processes one accomplishes the assignment of functions to physical or abstract entities, and the definition of interactions and interfaces between the entities. 2. The art and science of creating and building complex systems. That part of systems development most concerned with scoping, structuring, and certification.	1. ESD Terms and Definitions (Version 11), May 24, 2001 2. The Art of Systems Architecting, 2nd ed., Maier and Rechtin
Systems engineering	1. A process for designing systems that begins with requirements, that uses and/or modifies an architecture, accomplishes functional and/or physical decomposition, and accounts for the achievement of the requirements by assigning them to entities and maintaining oversight on the design and integration of these entities; systems engineering originally aose in the context of aerospace projects in the 1950s, but has been applied more broadly since then. 2. A multidisciplinary engineering discipline in which decisions and designs are based on their effect on the system as a whole.	1. ESD Terms and Definitions (Version 11), May 24, 2001 2. The Art of Systems Architecting, 2nd ed., Maier and Rechtin
Tradespace	1. The the enumeration of all design possibilities	1. SSPARC internal

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