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MULTI-ATTRIBUTE TRADESPACE EXPLORATION IN SPACE SYSTEM DESIGN

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The inability to systematically approach the high level of ambiguity present in the early design phases of space systems causes long, highly iterative, and costly design cycles. This paper introduces and describes a process to capture decision maker preferences and use them to generate and evaluate a multitude of space system designs, while providing a common metric that can be easily communicated throughout the design enterprise. Communication channeled through formal *utility interviews* and *analysis* enables engineers to better understand the key drivers for the system and allows for a more thorough exploration of the design tradespace. *Multi-Attribute Tradespace Exploration with Concurrent Design* (MATE-CON), an evolving process incorporating decision theory into model and simulation-based design, has been applied to several space system projects at MIT. Preliminary results indicate that this process can improve the quality of communication to more quickly resolve project ambiguity, and enable the engineer to discover better value designs for multiple stakeholders. MATE-CON is also being integrated into a *concurrent design* environment to facilitate the transfer of knowledge of important drivers into higher fidelity design phases. Formal utility theory provides a mechanism to bridge the language barrier between experts of different backgrounds and differing needs (e.g. scientists, engineers, managers, etc). MATE-CON couples *decision makers* more closely to the design, and most importantly, maintains their presence between formal reviews.

INTRODUCTION

Space system engineers have been developing effective systems for about fifty years and their accomplishments are a testament to human ingenuity. In addition to tackling the complex technical challenges in building these systems, engineers must also cope with the changing political and economic context for space system design and development. The history, scope, and scale of space systems results in a close tie with government and large budgets. The post-Cold War era has resulted in much smaller budgets and a space industry that needs to do more with less. Time and budget pressures can result in corner cutting (such as the Mars Program), and careless accounting (such as Space Station Program).

Space system design often starts with needs and a concept. Engineers perform trade studies by setting baselines and making minor changes to seek improvement in performance, cost, schedule, and risk. The culture of an industry that grew through an Apollo race to the moon and large defense contracts in the 1970s and 1980s is slow to adapt a better way to design systems to ensure competitiveness in a rapidly changing world.

Current approaches to creating aerospace systems requirements do not adequately consider the full range of possible designs and their associated costs and utilities throughout the development and lifecycle. These approaches can lead to long design times and designs that are locally optimized but may not be globally optimized. This paper develops a systematic approach for space system design by addressing the following problems:

1. A priori design selections without analysis or consideration of other options
2. Inadequate technical feasibility 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

The purpose of Multi-Attribute Tradespace

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Exploration with Concurrent Design (MATE-CON) is to capture decision maker preferences and use them to generate and evaluate a multitude of system designs, while providing a common metric that can be easily communicated throughout the design enterprise. To achieve this end, a framework is established that uses advances in tradespace modeling in addition to Multi-Attribute Utility Theory for the aggregation of preferences to create a common metric for evaluation in those models, and finally employs concurrent engineering for simultaneous (immediate), common (inclusive of all stakeholders), and continuous (inter-temporal) propagation of the metric.

MATE-CON creates a single and complete framework by which conceptual design may be systematically approached through broader technical and non-technical improvements to conceptual design. MATE-CON provides structure for developing technical, political, market, and budgetary uncertainty analysis of a proposed system. It also allows consideration of several beneficial design theories during the conceptual phase, i.e., design for: manufacturability and assembly, deployment, operations, maintenance, and decommission. It is expected that these design choices will flow through the development and procurement processes. These fundamental facets of design are easily forgotten in the initial phase, when the focus is on optimizing performance, but all of these facets affect overall system success.

Throughout the system lifetime, aggregate system success will be dependent upon the interactions of multiple stakeholders with the system. It is therefore quite useful to design a system from the outset with models that evaluate systems based on utility and cost. Allowing the stakeholders in the system to interact concurrently enables them to understand the impact that details of the design have on the overall utility and cost. This process ensures that decisions are made based upon their effect on the whole system. Through improving front-end processes, MATE-CON promotes learning throughout the design enterprise, enhancing aerospace system value.

MATE-CON employs decision theory to provide useful tools for bridging the gap between engineers and the individuals that will interact with the engineered product. Such tools have been used for evaluation, but not as a driver for concept generation and selection.[1] A formal mapping process from decision maker cost and utility preferences (attributes) to engineer technical choices (design vector) is imperative to improving system design. Decision-based design and concurrent engineering have received increased attention, but while these efforts have identified key improvements to the design process, none of them couple decision theory with broad tradespace exploration and concurrent design.[2,3,4,5,6,7,8,9,10,11]

MOTIVATION

Cost committal at the beginning of the design process makes early attention a high leverage point for improving system cost.

Long iteration times and communication bottlenecks extend project duration longer than they need to be, resulting in higher costs. Advances in academic research on product development processes suggest methods for improving and streamlining development processes.

Counter to the past tendency for engineers to specialize, there is growing demand for systems engineers to manage the growing complexity of space systems. The general lack of “systems thinking” in industry results in shortsighted decisions that may result in increased system rework. Stakeholder analysis and inclusion into system design and development may force systems-level thinking and direct engineers to focus on the more important regions of the complex tradespace.

TAXONOMY

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

Utility is a dimensionless parameter that reflects the “perceived value under uncertainty” of an attribute. Often used in economic analysis, utility is the intangible personal goal that each individual strives to increase through the allocation of resources.

Design variable is a designer-controlled quantitative parameter that reflects an aspect of a concept. Typically these variables represent physical aspects of a design, such as orbital parameters, or power subsystem type. Design variables are those that will be explicitly traded in the MATE-CON analysis.

Design vector is a set of design variables that, taken together, uniquely define a design or architecture. The vector provides a concise representation of a single architecture, or design.

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

Tradespace is the space spanned by completely enumerated design variables. It is the potential solution space. 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. Building upon the Generalized Information Network Analysis (GINA) technique developed at the Space System Laboratory at MIT, MATE-CON takes advantage of advances in computation to enumerate a set of design variables for cross-design comparisons.[12] The enumeration of a large tradespace helps prevent designers from starting with point designs, and allows them to recognize better design solutions.[13]

Exploration is the utility-guided search for better solutions within a tradespace. This approach is not an optimization technique, but is instead a means for investigating a multitude of options, thus deriving information that will become the basis of decision-making. The "action of examining; investigation, or scrutiny" is where the designer begins to creatively consider the various possibilities contained in the tradespace, and how that tradespace might be broadened.[14] Many times this requires human interaction that is simply not conducive to optimization techniques in the strict sense. The exploration of a multitude of 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. This technique of design, conceived in the early 1990s, entails teaming experts in the various fields affected by a design and providing information technology to facilitate these experts in designing the system for development, production, operation, maintenance, and retirement. The addition of concurrent design to the MATE-CON process ensures that the various stakeholders and experts are being driven by a common goal—utility. Providing a clear, common metric creates motivation and cohesion among the stakeholders without relying on the variable experience of a particular manager.

Decision Maker is a person that makes decisions that impact a system at any stage of its lifecycle. In particular, the decision maker is a person that has significant influence over the allocation of resources for the project.

Pareto Frontier is the set of efficient allocations of resources forming a surface in metric-space. Movement along the frontier requires making one metric worse off in order to improve another.

PROCESS

The MATE-CON process overlaps the first few phases of product development: Concept Development and System-Level Design.[15] As practiced, MATE-CON output will result in system requirements for the Detail Design phase to follow.

Decision makers

In order to formalize inclusion of various upstream stakeholders typically not considered by the design engineer, several classifications of decision makers, or roles, have been identified based upon their impact type on the space system product. Figure 1 shows the roles and their notional relationship to the product.

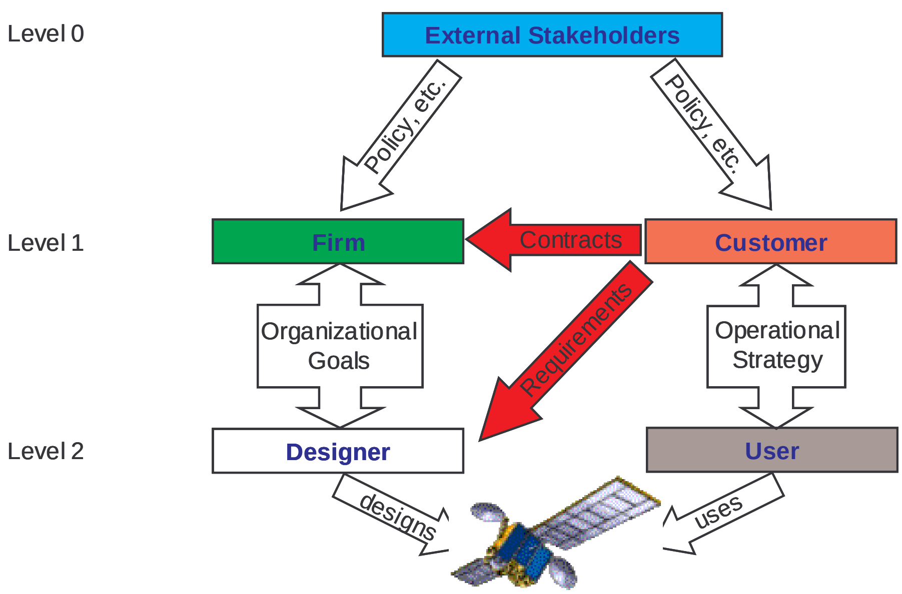

Figure 1 Decision Maker Roles and Levels

Level 0 decision makers are classified as External Stakeholders. These stakeholders have little stake in the system and typically have control over policies or budgets that affect many systems. An example of an External Stakeholder for a space system is Congress or the American people. Level 1 decision makers include the Firm and the Customer. The Firm role includes those who have organizational stakes in the project and manage the Designers. This decision maker may have stakes in multiple projects, but has specific preferences for the system in question. An example of a Firm is an aerospace company. The Customer role includes those who control the money for financing the project. This decision maker typically contracts to the Firm in order to build the system and provides requirements to the Designer. Level 2 decision makers include the Designer and the User. The User role has direct preferences for the system and typically is the originator of need for the system. (Need can originate within an organization, such as the Firm, as well. See Ulrich and Eppinger for discussions on firm strategies and enterprise opportunities.) An example of a User is a scientist or war fighter. The Customer typically has preferences that balance product performance meeting User needs, cost of the system, and political considerations. The Designer role has direct interaction with the creation of the system and tries to create a product that meets the preferences of the Firm, Customer, and User roles. An example of a Designer is the system engineer within the aerospace company building the system.

Process Description

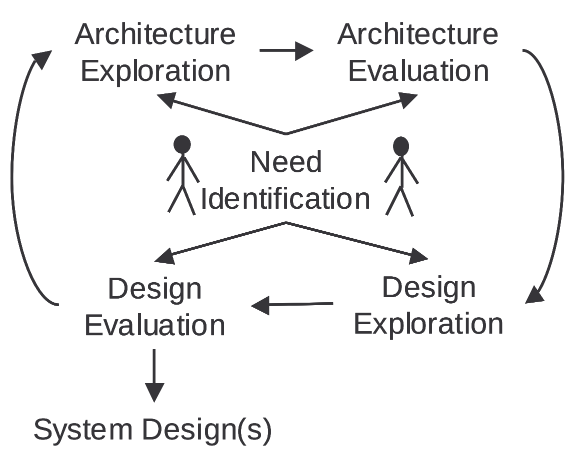

Figure 2 MATE-CON Process

At a high level, MATE-CON has five phases: Need identification, Architecture Solution Exploration, Architecture Evaluation, Design Solution Exploration, and Design Evaluation, shown in Figure 2. The Need Identification phase motivates the entire project, providing the needs, mission, and scope for the project. MATE-CON is the marriage of the architecture-level exploration and evaluation (MATE) with the design-level exploration and evaluation (CON). Architecture-level exploration and evaluation is accomplished using models and simulations to transform a large set of design vectors to attributes and then evaluating each set of attributes in utility-cost space. The set of modeled design vectors, or architectures, are analyzed in utility-cost space and the best architectures are selected for the design-level exploration and evaluation. Design-level work is done in a concurrent design environment using ICEMaker, a process and product from the Caltech Laboratory for Space Mission Design.[16] Knowledge gained from the design-level analysis is flowed back to the architecture-level analysis to improve the fidelity of the models and architecture selection.

Need identification

MATE-CON begins with a set of decision makers with needs and preferences about a system. These decision makers can come from any one of the roles depicted in Figure 1, as needs can be motivated by market pull, technology push, or customized needs.[17] Discussions with the Designer attempt to increase awareness of each roles' knowledge and preferences. The driving preferences of the decision makers are captured through attributes using Multi-Attribute Utility Analysis and form the Preference-space through which potential systems will be evaluated.

Translating Preferences

Since the purpose of MATE-CON is to find the set of designs that will provide the best value for the decision makers, it is essential to understand how the decision makers trade the various attributes. One method that has been used with some success is Multi-Attribute Utility Theory (MAUT).[18] Utility theory maps preferences for an attribute into a normalized value-under-uncertainty function, known as *utility*. 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 reflect the decision maker preferences on a system helps to refine tradespace exploration. The utility value can be expanded back to both the values of each attribute and 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. One must understand the many underlying assumptions of MAUT in order to correctly implement the theory.[19]

Among these assumptions, if both the preferential and utility independent assumptions hold, then the multi-attribute utility function for each decision maker can take the following form:

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

- K is the solution to $K+1=\prod_{i=1}^{N}\left[Kk_i+1\right]$, and

$$\sum_{i}^{N}k_i<1 \qquad K>0$$

$$\sum_{i}^{N}k_i>1 \qquad -1<K<0$$

$$\sum_{i}^{N}k_i=1 \qquad K=0$$

- $U(\underline{X})$, $U(X_i)$ 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.

If there are no cross-term benefits for the attributes, then the simpler additive multi-attribute utility function can be used (this is the case where K=0). The simple weighted sum is the typical method for aggregating metrics in design.

$$U(\underline{X})=\sum_{i=1}^{N}k_iU(X_i) \tag{2}$$

- $U(\underline{X})$, $U(X_i)$ 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.

The process of constructing these utility functions involves the determination of the single attribute utility curves and the k_i multi-dimensional weighting factors. Performing this utility assessment is fundamental to successfully constructing these multi-attribute utility functions.

Utility Assessment (MIST)

Once the attribute definitions and ranges have been decided, the utility interview can be written. 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 lottery equivalent questions. 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. From the initial implementation one finds that thinking in terms of probabilities is difficult and is a major limitation of the process. Therefore, it is important to guide the interviewee until the person is comfortable with the question format.

Prior research has addressed the issue of utility assessment.[20,21,22] Based on this research, the Space Systems, Policy, and Architecture Research Center at MIT (SSPARC) has developed its own Excel-based utility assessment tool in order to simplify, standardize, and expedite the interviewing process. The tool, the Multi-attribute Interview Software Tool (MIST), is deployable and has been shown to reduce by half the time required for an interview.[23]

Regarding Multiple Decision Makers

At this point it is necessary to make some comments regarding the assessment of multiple decision makers. While in many cases a single decision maker can be identified, there is nonetheless a strong possibility that other significant stakeholders will influence key decisions. Often this influence is implicit through the main decision maker having preferences regarding the satisfaction of other stakeholders. An example of such a relationship would be that of an acquisition customer wanting the end users to be satisfied, such as the Air Force wanting the scientists and war fighters satisfied by a particular satellite system. In an ideal world, the decision maker would have complete knowledge of the multifaceted preferences of each stakeholder, however in reality this knowledge is incomplete and obfuscated by politics. The role framework mentioned above helps the Designer explicitly incorporate the important sets of preferences that shape the needs for the space system.

The strength of Multi-Attribute Utility Theory lies in its ability to capture in a single metric the complex preferences of a single decision maker. The preferences of multiple decision makers, however, cannot be aggregated into a single metric.[24] Instead of aggregation, the multiple utility functions are

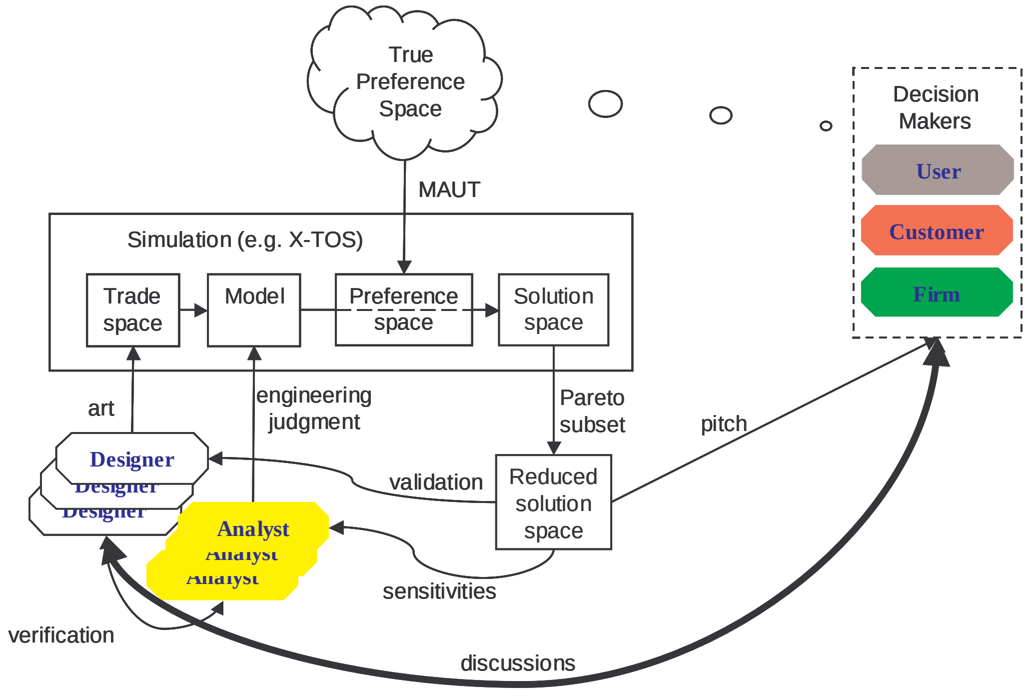

Figure 3 Need Identification and Architecture-level Analysis

continuously assessed and can be used for negotiation among the decision makers. In addition, knowledge of these utility functions enables Designers to avoid exploring regions of the tradespace that are clearly dominated solutions, thereby finding better designs for all decision makers. A multidimensional Pareto efficient surface will define the best sets of architectures. Deciding which designs to pursue is a human process that combines negotiation, politics and other exogenous factors. MATE-CON enlightens participants by focusing on higher value solutions.

Architecture-level analysis

As preferences are being captured, the Designer is developing the Tradespace through the creation of design variables that will achieve the preferences expressed by the decision makers. No formal theory has been used to develop the design variables, but QFD has been used to organize and prioritize suggested variables. Engineering expertise and experience drives the creation of these variables. Figure 3 depicts the relationships discussed in this section.

Once the Tradespace and Preference space have been defined, the Analyst develops software models and simulations to map the design variables to the attributes. Once the models are verified, the Designer enumerates the design variables and evaluates hundreds or thousands of design vectors by calculating their attribute values and subsequently their utility values and costs. The Solution space contains the mapping of the design vectors to Utility-cost space. The Pareto frontier designs are selected as the Reduced solution space and are used to validate and perform sensitivity analysis on the tradespace and models. After analysis, a Reduced solution set of designs is presented to the decision makers for higher fidelity decision-making. Because MAUA only captures the driving preferences and not all preferences, it is necessary to use the actual decision makers for final evaluation, rather than their proxy preference functions. Selected designs are then flowed down to the design-level analysis.

Design-level analysis

The design-level analysis involves a concurrent design team analyzing the selected architectures at a higher fidelity in a real-time environment. Subsystem engineers each have their own set of design tools at a computer terminal and these chairs are linked to a central server. Representatives of downstream stakeholders, such as manufacturing and operations, take part in the concurrent design session to ensure that their expertise is incorporated into the design. The systems engineer maintains system-level information. Additionally, the MATE-CON chair incorporates all of the knowledge and models from the architecture-level analysis for real-time analysis of the designs. The baseline design provided from the architecture-level analysis is fed into ICEMaker and

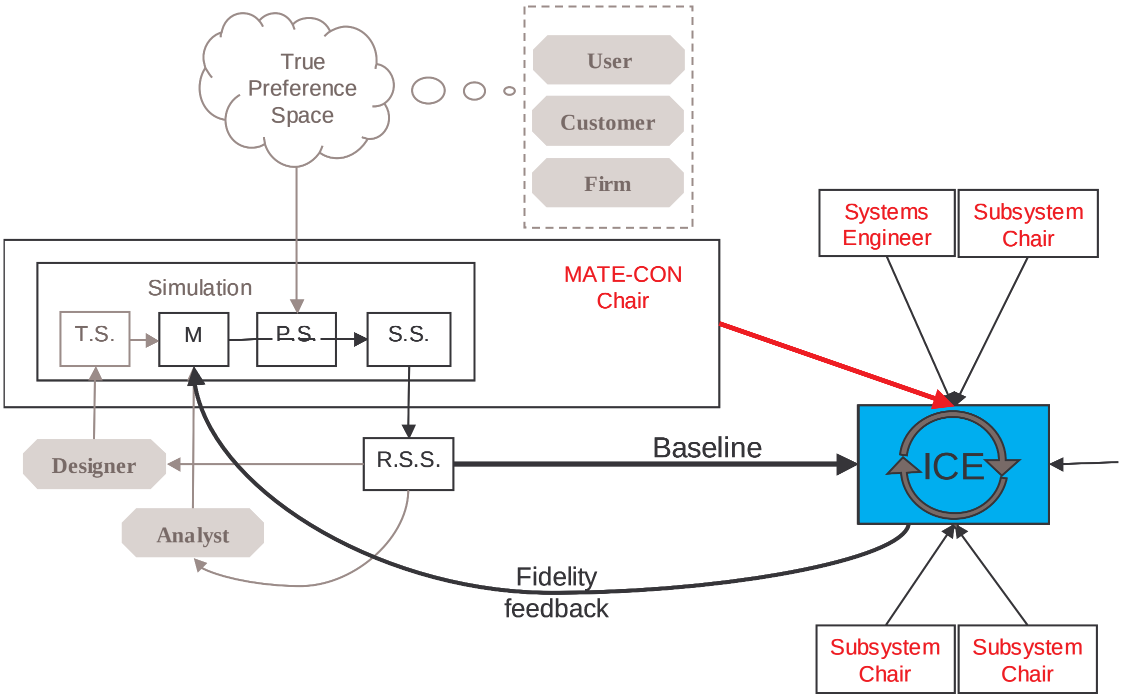

Figure 4 Design-level Analysis with Integrated Concurrent Engineering (ICE)

the team converges upon a feasible design through iteration and design trades. The MATE-CON chair directs the session by continuously monitoring the utility and cost of each design. Lessons learned during the concurrent sessions are incorporated into the MATE-CON chair by improving the models used in the architecture search. The appropriate level of fidelity for the architecture-level analysis is reached when results do not conflict with the design-level analysis. Figure 4 depicts the connection between the Architecture-level analysis and Design-level analysis through the MATE-CON Chair.

PROJECT X-TERRESTRIAL OBSERVER SWARM (X-TOS)

The first application of the entire MATE-CON process to a design took place in the Spring of 2002, in the graduate space system design course at MIT. The class explored 50,488 architectures and performed about a dozen higher fidelity concurrent design trades before the semester ended. The process not only allowed the class to move rapidly from needs to system design, but also provided important insights into creative solutions of and drivers for the system.

Problem

Scientists from the Air Force Research Laboratory/Hanscom (AFRL/VSB) had a suite of instruments designed to take in situ measurements of the neutral density of the atmosphere in order to improve satellite drag models. The User role was fulfilled by the payload designer who had presented the drag model problem to the class.

Process application

Need Identification

The class began by understanding the needs, mission, and scope. For this particular project, the mission was to fly the AFRL/VSB Atmospheric Density Specification (ADS) payload through the Earth's atmosphere to collect drag data. The scope was decided to solely include the space segment.

Architecture-level analysis

Attributes

The identified roles for X-TOS were the User (payload scientist), the Designer (design class), the Firm (teaching staff), and the Customer (Aerospace Corp). The design team explicitly determined the preferences of the User and was given the preferences of the Customer. The Designer preferences were implicit in the design process and the Firm preferences involved performance evaluations of the team at regular reviews. For pedagogical reasons, the class was instructed to focus solely on the User needs for X-TOS, though the class could have incorporated the other preferences as well by adding more attributes.

After iterative discussions with the User about his true needs, the X-TOS mission User attributes were determined as in Table 1.

Data Life Span: Elapsed time between the first and last data points of the entire program measured in months.

Sample Altitude: Height above standard sea-level reference of a particular data sample, measured in kilometers. (Data sample = a single measurement of all 3 instruments)

Table 1 X-TOS User Attributes

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

Diversity Latitudes Contained Data Set: The maximum absolute *change* in latitude contained in the data set. The data set is defined as data taken from 150 – 1000 km.

Time Spent at the Equator: Time per day spent in the equatorial region defined as +/- 20 degrees off equatorial.

Latency: The maximum elapsed time between the collection of data and the start of transmission downlink to the communication network, measured in hours. This attribute does not incorporate delays to use.

X-TOS used the MIST tool to interview the User at AFRL/VSB and construct the single and multi-attribute utility functions. The interviewed User was able to complete the interviews in two hours, with feedback from the interviewer over the phone.

Tradespace Formation

Once the attributes for the system have been finalized, concepts for the realization of those attributes must be generated. The concept is a high level mapping of function to form. The design variables are a parameterization of the concepts modeled and comprise the design vector that differentiates among possible architectures. These design variables must be independent parameters that are within the control of the designer.[25]

The design vector excludes model constants and focuses on those variables that have been identified to have significant impact on the specified attributes. Rapid geometric growth of the tradespace results with increasing number of variables and the values over which they are enumerated. Computational considerations motivate keeping the list curtailed to only the key elements, while still maintaining the ability to keep the tradespace as open as possible in order to explore a wide variety of architectures.

The process of paring down the design vector occurs after the brainstorming of all significant design variables. A QFD-like matrix has been employed to rank the strength of impact of the design variables on the attributes. Scoping decisions to manage modeling complexity and computation time lead to the elimination of weakly driving design variables. Later in the process, sensitivity analysis can be performed on these variables to validate the assumption of weak impact.

The concept for the X-TOS architectures was enumerated based on the design variables in Table 2.

Table 2: X-TOS Design Variables

X-TOS DESIGN VARIABLES	Range
Mission Scenarios	
Single satellite, single launch	
2 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

Building upon inherited design processes from GINA and previous design studies, the X-TOS team decided to create a modular software architecture. To first order, the simulation takes as input the design vector and outputs the attribute, utility, and cost values for each design vector. The simulation consisted of a Satellite database, a Mission Scenario module, a Utility, and a Cost module. The Satellite

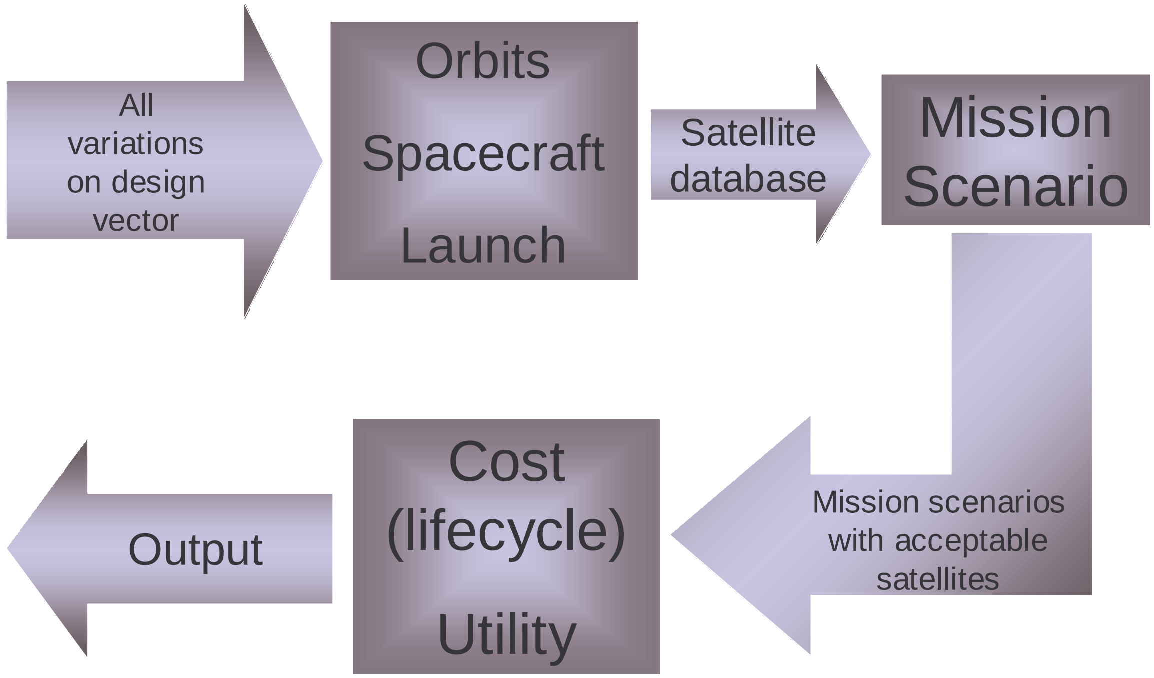

Figure 5 X-TOS Software Flow

database contained the Orbits, Spacecraft, and Launch modules. The Spacecraft module enumerated the possible satellites by varying the different physical spacecraft parameters. The Orbits module simulated the orbital dynamics of a satellite by calling Satellite Tool Kit and keeping track of position and time information.[26] The Launch module determined the launch vehicle, insertion orbit, and physical launch constraints for the satellite. The Mission Scenario module traded the scenarios given in Table 2 by pulling the appropriate combination of designs from the Satellite database. The Utility and Cost modules then calculated the utility and cost for a given design vector. Figure 5 shows the X-TOS software flow.

The modular software architecture allowed the design team to divide the software among teams for concurrent development. It also allowed the team to readily change individual modules in order to improve the simulation following sensitivity analysis.

Results

The design variables were enumerated to provide a tradespace of architectures that were measured against the preferred performance (attributes) set defined by the User. Figure 6 shows the utility-cost representation of the analyzed designs. A Pareto frontier with increasing utility for increasing cost is not readily apparent on the plot. It is believed that a Pareto frontier would exist with a more complete enumeration of the tradespace. The policy constraint of launching only on U.S. launch vehicles prevents the enumeration of architectures that would lie on the frontier. This Solution space has a clear set of "best" architectures where high utility for low cost can be realized.

A key result discovered in this analysis is depicted in Figure 6. The X-TOS Solution space is plotted in small, filled circles. In open circles are possible STEP-1 architectures.[27] In 1994 the User flew a similar payload aboard the Space Test Experiment Platform 1 (STEP-1), but lost the satellite soon after launch. The X-TOS mission is intended to accomplish at least the same as the failed STEP-1 mission. All of the potential STEP-1 architectures are dominated, meaning they fall inside the Pareto frontier. Better design decisions would result in a better design at the same cost. One consideration for STEP-1 was the fact that the Atmospheric Density Specification payload shared the satellite with another payload and thus may have had to sacrifice some performance. Knowledge of the tradespace such as that in Figure 6 would provide valuable information for negotiating such sharing arrangements and makes clear exactly how much value is being sacrificed and if it is worth the cost savings.

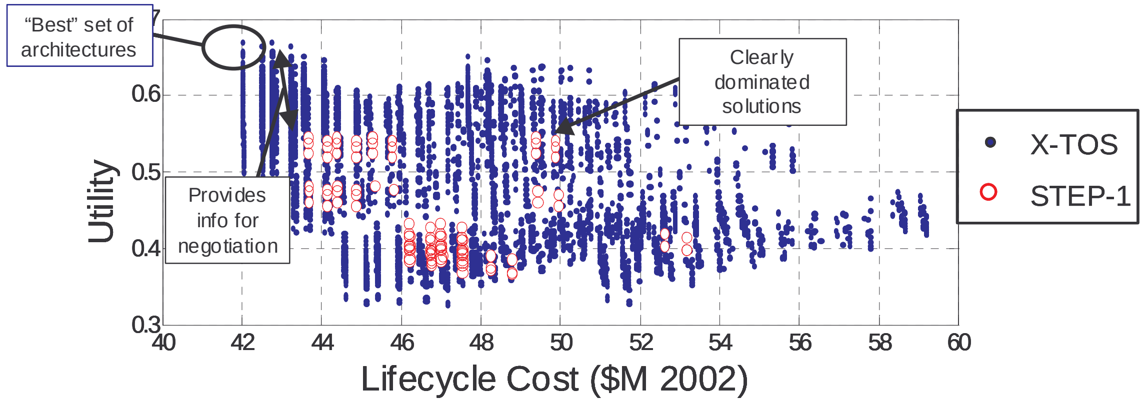

Figure 6 X-TOS Solution Space with STEP-1

Design-level analysis

At some point, a system design must be selected for more detailed design. The fundamental rationale of using concurrent engineering in MATE-CON is to ensure that that as many stakeholders as possible are included in the design and to propagate the notion of overall mission value throughout the design enterprise as the design begins to take on finer detail. Essentially this flow down is equivalent to having soft requirements that reflect preferences, allowing technically feasible designs to be created, and the various design enterprise decision makers to decide based on mission value. Furthermore, it allows a design rationale capture, so that if higher-levels of detail reveal that the selected design is not feasible, it is a simple matter to move up one design level and select an alternative high value solution set.

In the pursuit of this flexibility, the X-TOS team spent the second half of their semester designing the satellite in an integrated concurrent design environment. As shown in Figure 7, the design room was equipped with networked computers for real-time design interaction between the various spacecraft subsystems, also known as chairs, and common display screens for group visualizations. The sharing of networked design parameters was facilitated by Caltech's ICEMaker software, which allows communication between various Excel spreadsheets. The primary distinction between the design network used by X-TOS and other integrated product development or concurrent design centers is the incorporation of the MATE-CON chair.[28] This chair is able to compare the spacecraft and architecture designs that come from using ICEMaker against the same preference metrics established for the initial design. This continuity allows more informed trades at these higher levels of design detail—trades that focus on mission value instead of more common metrics such as mass and power.

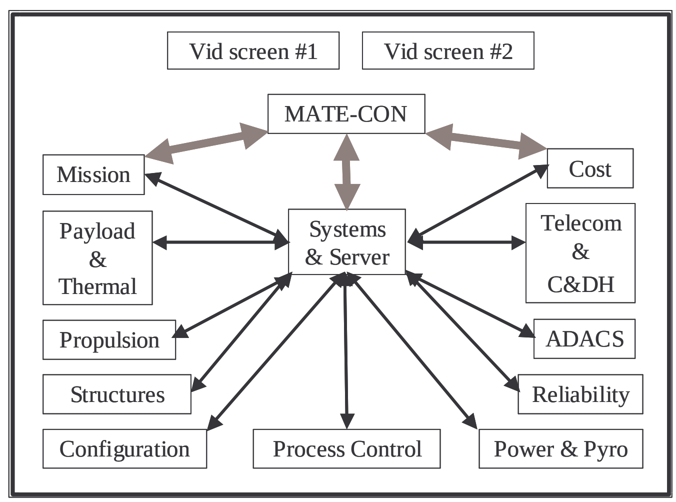

Figure 7 MATE-CON in ICE

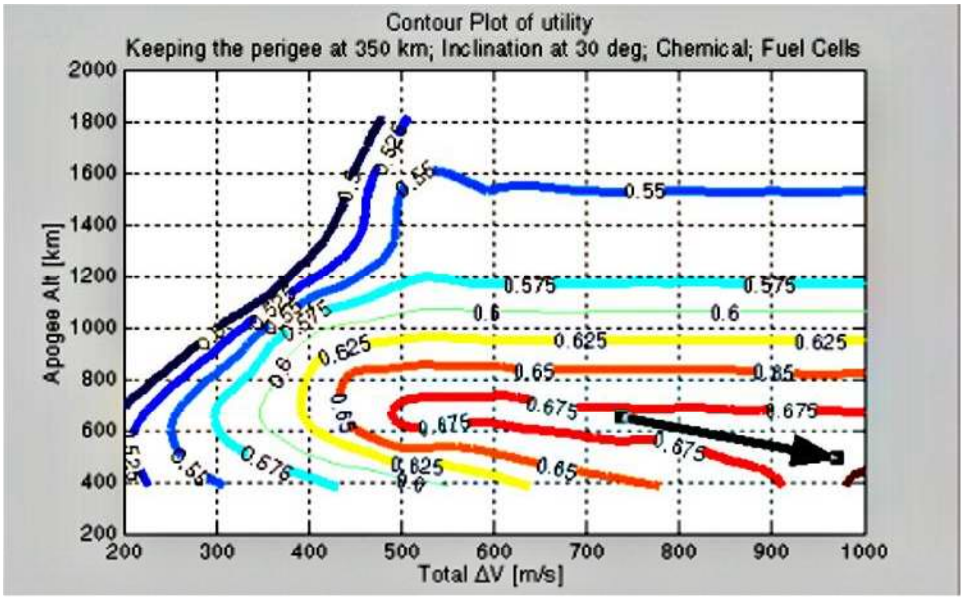

Figure 8 Iso-utility Contours for X-TOS Design Trades

As the design trades were performed, the MATE-CON chair continuously monitored design parameters and utilities, creating large data sets for further analysis. Contour plots showing directions of increasing utility, such as Figure 8, provided motivation and direction for trades in near real-time.

This exercise also demonstrated the ability of the MATE-CON process to rapidly account for and adapt to changes in decision maker preferences. Once the ICEMaker design sessions had begun, the utility team returned to the User to show the selected baseline architecture. Upon seeing the results, the decision maker realized that his preference for lifetime had not been captured. The difference in the utility space is shown in Figure 9 (r). Comparing this plot with Figure 9 (l), under the original utility there was virtually no difference between architectures A, B, and C, but under the revised utility there is enough difference to lead the ICE team to explore the emerging regions of higher utility.

Since X-TOS was the first attempt at implementing the MATE-CON process with concurrent design, a number of benefits of the process came to light that had previously been under-appreciated.

1. Changes in decision maker preferences could be quickly and easily quantified for rapid analysis and adjustment in the design process.
2. Subsystem trades could be navigated and motivated by quickly referencing their impact on overall mission utility.
3. Organizational learning could be improved by wisely flowing down information from previous design study work.

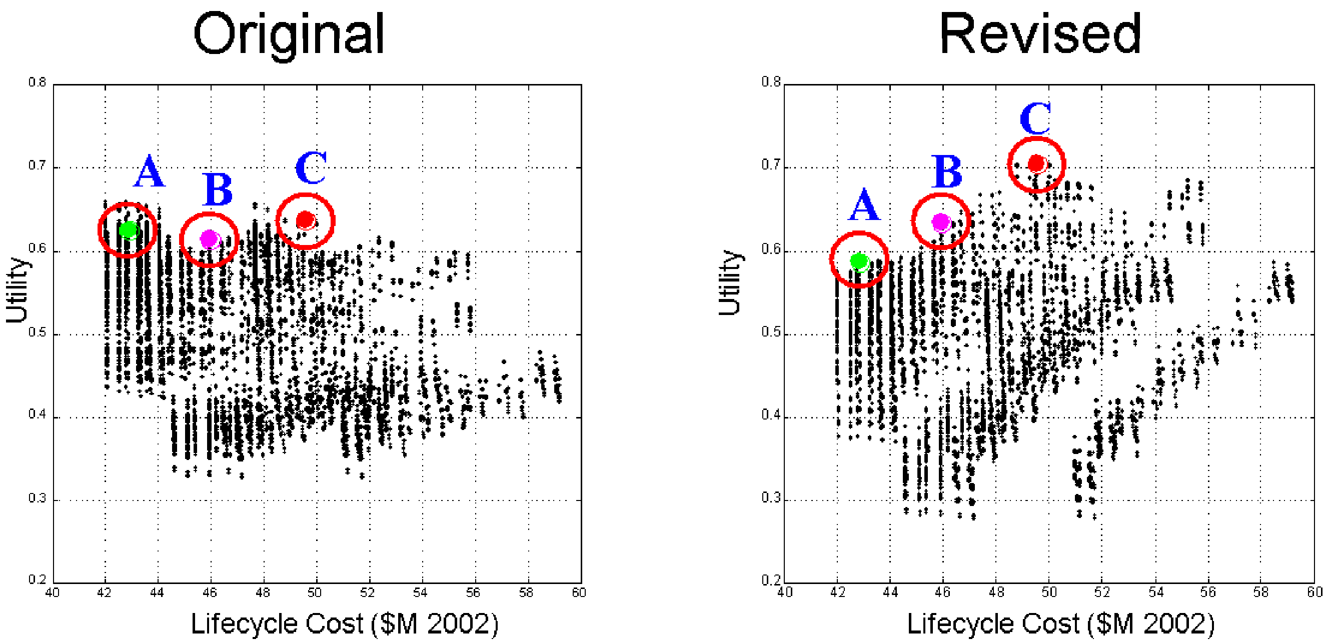

Figure 9 X-TOS Cost vs. Utility Original (l) and Revised (r)

<u>Insights</u>

During the X-TOS project, several key insights were realized. Firstly, the process is robust and flexible to changing preferences. If the models do not need modification following changes in preferences, the entire tradespace can be recalculated in minutes to hours. Minor code modification may result in additional hours of work. When the User changed preferences while the class was performing concurrent design trades, the team was able to rapidly adapt to the new drivers by recalculating the utility of the designs. Further sensitivity analysis to the global tradespace under the new preferences revealed some architectures that were robust to the changes in preference and some that became much more valuable. The changing preference and resulting quantitative representation of this change on the tradespace strengthened the communication of needs and possibilities between the designers and the User. Gaining the ability to design for robustness in changing preferences may result in cost savings.

Secondly, if time had permitted, the team realized that they could just have easily modeled space tethers or other such "exotic" concepts for flying the User's payload. And more significantly, be able to compare these concepts on *the same utility-cost plots*. The utility metric is concept independent and thereby allows the designers to make apples-to-apples comparisons across concepts. Time constraints limited X-TOS to traditional satellite designs, but they were able to look at different scenarios.

<u>CONCLUSIONS</u>

MATE-CON has made great strides in confronting major problems in system design. 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.

By utilizing advances in concurrent design, it is possible to propagate the 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. Additionally, by incorporating interdisciplinary expert opinion and diverse stakeholder interest throughout the design, MATE-CON reduces the likelihood of miscommunication throughout the system design process. 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.

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