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Multi-Attribute Tradespace Exploration as Front End for Effective Space System Design

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The inability to approach systematically the high level of ambiguity present in the early design phases of space systems causes long, highly iterative, and costly design cycles. A process is introduced and described 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, a process incorporating decision theory into model- and simulation-based design, has been applied to several space system projects at the Massachusetts Institute of Technology. Preliminary results indicate that this process can improve the quality of communication to resolve more quickly project ambiguity and to enable the engineer to discover better value designs for multiple stakeholders. The process is also 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, for example, scientists, engineers, managers, etc. Multi-attribute tradespace exploration with concurrent design couples decision makers more closely to the design and, most important, maintains their presence between formal reviews.

Nomenclature

K = multi-attribute utility normalization constant
k_i = multi-attribute utility scaling factor for attribute i
N = number of attributes
$U(\boldsymbol{X})$ = multi-attribute utility function
$U_i(X_i)$ = single attribute utility function i
$\boldsymbol{X}$ = set of multiple attributes $1, \ldots, N$
X_i = single attribute i

Introduction

SPACE system engineers have been developing effective systems for about 50 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 the International 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 life cycle.[1] 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 preferences of key 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, and 6) limited incorporation of interdisciplinary expert opinion and diverse stakeholder interest.

The purpose of multi-attribute tradespace 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 (intertemporal) propagation of the metric.

MATE-CON creates a single and complete framework by which conceptual design may be systematically approached through broader technical and nontechnical improvements to conceptual design. The framework provides a structure for developing technical, political, market, and budgetary uncertainty analysis of a proposed system. It also allows for the consideration of several beneficial design theories during the conceptual phase, that is, design for manufacturability and assembly, deployment, operations, maintenance, and decommission through the inclusion of key downstream

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stakeholders. These facets of the system life cycle are easily forgotten in the initial design phase, when the focus is typically on optimizing performance, but all of these facets affect overall system success.

Throughout the system lifetime, aggregate system success will be dependent on 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, decision maker perceived value under uncertainty, 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 on 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 who will interact with the engineered product. Such tools have been used for evaluation, but not as a driver for concept generation and selection.[2] A formal mapping process from decision maker cost and utility preferences (attributes) to engineer technical choices (design variables) is imperative to improving system design. Decision-based design and concurrent engineering have received increased attention in the literature, but, although these efforts have identified key improvements to the design process, none of them couple decision theory with broad tradespace exploration and concurrent design.[3–7]

Motivation

Cost committal at the beginning of the design process makes early attention a high-leverage point for improving system cost. The additional need for getting the project right because space systems usually cannot be repaired or upgraded adds significant cost as well. (The Hubble Space telescope is a notable exception, although the servicing cost would make this option infeasible for almost any space system.)

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 results in shortsighted decisions that may result in increased system rework. Stakeholder analysis and inclusion into system design and development should force systems-level thinking and direct engineers to focus on the more important regions of the complex tradespace with a broader perspective.

Taxonomy

Much of systems engineering is spanning the gaps between systems: When the interface is defined and managed, language is an important part of that interface and must be properly defined to prevent miscommunication and misunderstanding. Because the MATE-CON process incorporates concepts from decision theory and novel Massachusetts Institute of Technology (MIT) system design methods that may be unfamiliar to most, this section will define several of the key terms used in this paper. The following definitions are intended to match the context and usage in the MATE-CON process.

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.

Attribute is a decision maker perceived metric that measures how well a decision maker defined objective is met. The characteristics of an attribute are definition, a range (from least to most acceptable value), units, and direction of increasing value. It is imperative that the decision maker and not only the designer define the attribute.

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 who makes decisions that impact a system at any stage of its life cycle. In particular, the decision maker is a person who has significant influence over the allocation of resources for the project, or the origination of the need for the system.

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.

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 consider creatively the various possibilities contained in the tradespace and how that tradespace might be broadened.[8] 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.

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 to improve another. Dominated solutions can be made better off by moving to the frontier.

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 that never before existed. Built 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.[9] The enumeration of a large tradespace helps prevent designers from starting with point designs and allows them to recognize better design solutions.[10]

Utility is a dimensionless parameter that reflects the "perceived value under uncertainty" of an attribute (Ref. 11, Chapters 1 and 4). Often used in economic analysis, utility is the intangible personal goal that each individual strives to increase through the allocation of resources. In the context of this paper, utility reflects the ordering preferences of a decision maker for levels of an attribute or a set of attributes.

Process

The MATE-CON process overlaps the first few phases of product development: concept development and system-level design.[12] As practiced, the MATE-CON output at the end of concurrent design will result in system requirements for the detailed design phase to follow, to ensure a clean transition to traditional engineering practice. The impact of the discovery of technical infeasibilities during the detailed design phase can be mitigated by making appropriate design changes based on knowledge of the larger tradespace performed during MATE-CON.

Decision Makers

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 on their impact type on the space system product. Figure 1 shows the roles and their notional relationship to the product. Although most of the

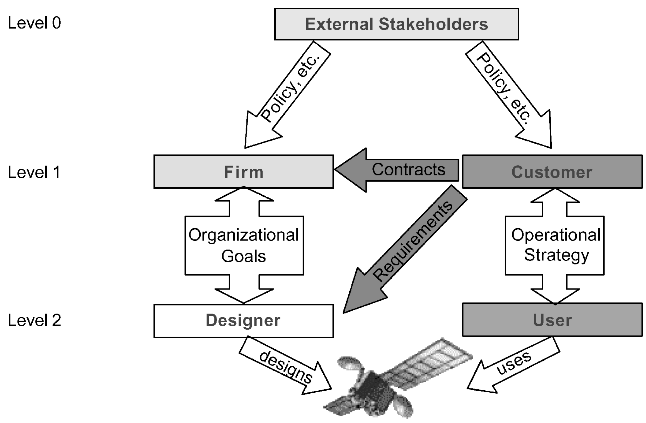

Fig. 1 Decision maker roles and levels.

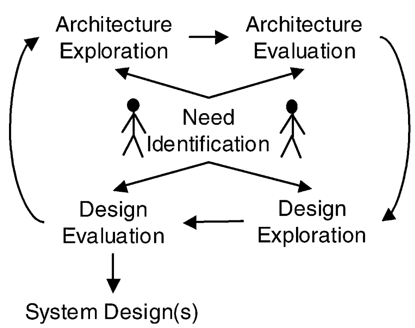

Fig. 2 MATE-CON process.

information flows are bidirectional, the direction of the arrows in Fig. 2 indicates the primary (majority) information flow.

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 public. 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 the firm 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.[12]) 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

At a high level, MATE-CON has five phases: need identification, architecture solution exploration, architecture evaluation, design solution exploration, and design evaluation, as shown in Fig. 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), while maintaining focus on the need throughout. 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 California Institute of Technology (Caltech) Laboratory for Space Mission Design.[13] 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 shown in Fig. 1 because needs can be motivated by market pull, technology push, or customized needs.[12] Discussions with the designer are an attempt to increase awareness of each role's 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

Because 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) (Ref. 11, Chapters 5 and 6). 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. If option A has a higher utility value than option B, option A would be preferred to option B, and in this way, the utility function is a continuous ranking function. 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 to implement the theory correctly, however.[7]

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:

$$KU(\boldsymbol{X}) + 1 = \prod_{i=1}^{N} [Kk_i U_i(X_i) + 1] \tag{1}$$

where K is the solution to

$$K + 1 = \prod_{i=1}^{N} [Kk_i + 1]$$

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

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

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

This form of the utility function captures the tradeoffs among attributes, something that a linear weighted sum function neglects. As

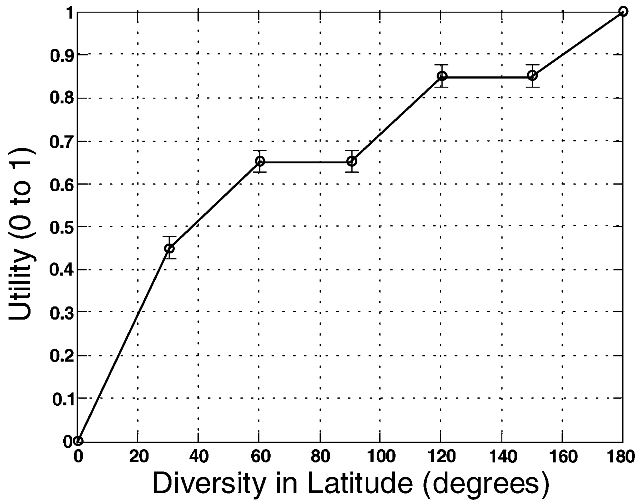

Fig. 3 Example single-attribute utility curve.

with complementary and substitute goods in the economic literature, attributes also can complement or substitute for one another in a system design.

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 $K = 0$.) This simple weighted sum is the typical method for aggregating metrics in design:

$$U(\boldsymbol{X}) = \sum_{i=1}^{N} k_i U_i(X_i) \tag{2}$$

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

Utility Assessment

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 (LEP) method, and each question is dependent on the interviewee's responses.[14,15] The utility function value for each attribute can be derived by determining the point at which the interviewee is indifferent between the lotteries offered in the LEP questionnaire. Figure 3 is an example single-attribute utility curve with the indifference points shown with error bars. It is important to craft the scenario carefully for each attribute to place the interviewee in the proper mindset to answer lottery questions for the attributes. Experience from the initial implementation of this process found that thinking in terms of probabilities is difficult and is a major limitation of formal utility assessment methods. Therefore, it is important to guide the interviewee until the person is comfortable with the question format.

Prior research has addressed the various technical and social issues related to utility assessment[14,16] (also Ref. 11, pp. 188–211, 219–223, 261–270, and 297–309). Based on this research, the Space Systems, Policy, and Architecture Research Center at MIT has developed an Excel-based utility assessment tool 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.[17]

Regarding Multiple Decision Makers

At this point, it is necessary to make some comments regarding the assessment of multiple decision makers. Although 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 U.S. 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 earlier helps the designer explicitly incorporate the important sets of preferences that shape the needs for the space system.

The strength of MAUT 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.[18] Instead of aggregation, the multiple utility functions are 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 matter of determining which decision makers dominate the preferences and may need to be resolved through negotiation, politics, and other exogenous factors. Note that MATE-CON does not create the problem of trading off among multiple decision makers, but rather makes the tradeoffs more explicit.

Architecture-Level Analysis

Figure 4 shows the interactions among decision makers within the need identification and architecture-level analysis of MATE-CON. The numbers indicate the rough sequence of relationships in these phases of the process. A- and B-labeled interactions with the same number occur approximately in parallel.

The process begins with the initial need identification (1a; Fig. 4) and discussions (1b; Fig. 4) between the key decision makers and the designers. As preferences are being captured (2a; Fig. 4), the designer is developing the tradespace (2b; Fig. 4) through the creation of concepts that will achieve the preferences expressed by the decision makers. The concept is a high-level mapping of function to form. Comprising the design vector that differentiates among possible architectures, the design variables are a parameterization of the concepts modeled. These design variables must be independent parameters that are within the control of the designer.[9] No formal theory has been used to devise the design variables, but quality function deployment (QFD) has been used to organize and prioritize suggested variables. Engineering expertise and experience drives the creation of these variables.

Once the tradespace and preference space have been defined, the analyst develops software models and simulations (3a; Fig. 4) to transform design variable values into attribute values. Once the models are verified (3b; Fig. 4), the designer enumerates the design variables and evaluates (4; Fig. 4) 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 (5; Fig. 4) as the reduced solution space and are used to validate (6a; Fig. 4) and perform sensitivity analysis (6b; Fig. 4) on the tradespace and models. After analysis, a reduced solution set of designs is presented (7a; Fig. 4) to the decision makers for higher fidelity decision making (7b; Fig. 4). Because MAUT 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

Figure 5 shows the connection between the architecture-level analysis and 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

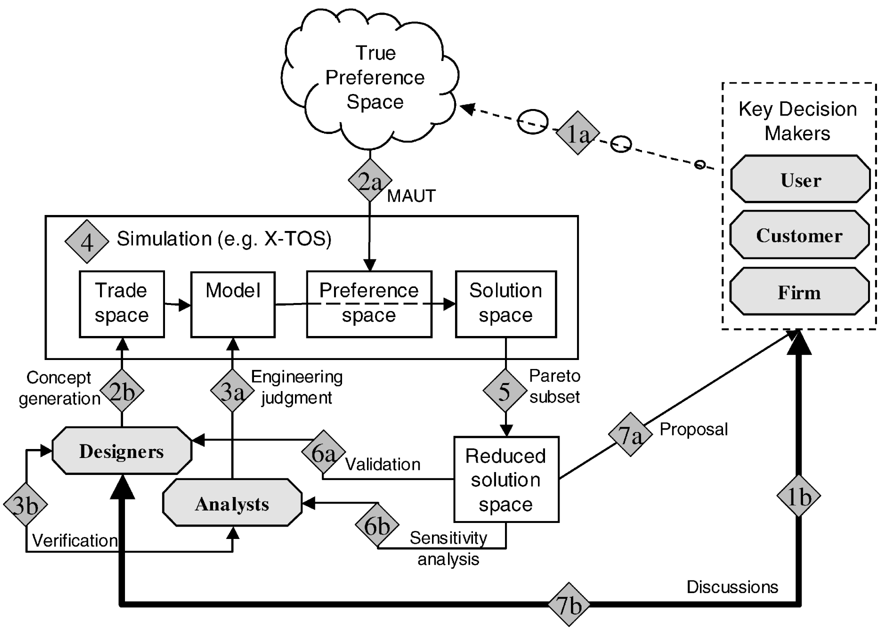

Fig. 4 Need identification and architecture-level analysis interactions.

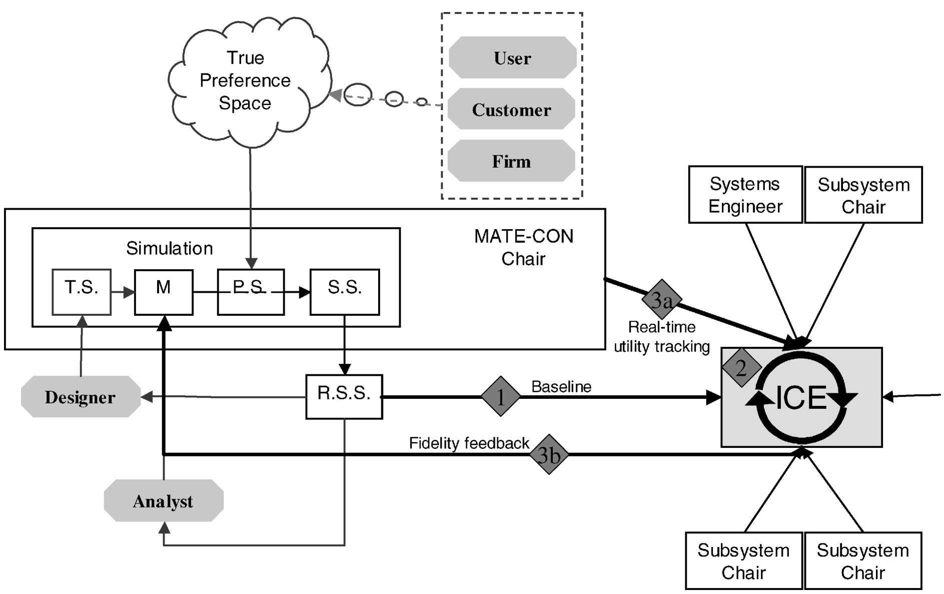

Fig. 5 Design-level analysis interactions with integrated concurrent engineering (ICE).

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 (1; Fig. 5) provided from the architecture-level analysis is fed into ICEMaker, the concurrent design server, and the team converges on a feasible design through iteration and design trades (2; Fig. 5). The MATE-CON chair directs the session by continuously monitoring the utility and cost of each design (3a; Fig. 5). Lessons learned during the concurrent sessions are incorporated into the MATE-CON chair by improving the models used in the architecture search (3b; Fig. 5). The appropriate level of fidelity for the architecture-level analysis is reached when results do not conflict with the design-level analysis. This explicit connection between broad architecture-level analysis and more detailed design-level analysis through the MATE-CON chair coupled with utility-driven concurrent design is a unique contribution of the MATE-CON process.

Even though many of the components of MATE-CON have been done before, such as parametric design, concurrent design, and applications of MAUT, no space system design process integrates these components to realize the holistic benefits that can accrue from preference-driven broad tradespace exploration. From a process structure perspective, MATE-CON has been analyzed for both its efficiencies and key differences from other design processes, and has been shown to require less time and effort for a given project,[19] for example, the terrestrial observer swarm, iteration X (X-TOS).

Project 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

Table 1 X-TOS user attributes

Attribute	Best	Worst
Data life span, mo	132	0
Sample altitude, km	150	1000
Diversity of latitudes,°	180	0
Time spent at equator, h	24	0
Data latency, h	1	120

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 U.S. Air Force Research Laboratory/Hanscom (AFRL/VSB) (Battlespace Environment Space Vehicles Division) had a suite of instruments designed to take in situ measurements of the neutral density of the atmosphere to improve satellite drag models. The user role was fulfilled by the payload engineer who 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 include the space segment only.

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 (The Aerospace Corporation). 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, although the class could have incorporated the other preferences as well by adding more attributes.

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

Data life span is the elapsed time between the first and last data points of the entire program measured in months. Sample altitude is the height above standard sea-level reference of a particular data sample, measured in kilometers. (A data sample is defined as a single measurement of all three instruments.) Diversity latitudes contained data set is the maximum absolute change in latitude contained in the data set. The data set is defined as data taken from 150–1000 km. The time spent at the equator is the time per day spent in the equatorial region defined as $\pm 20^\circ$ off equatorial. Latency is 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 2 h with feedback from the interviewer over the phone.

Tradespace formation. Once the attributes had been determined, the X-TOS team could then develop concepts to perform the mission, which are reflected in the construction of a design vector. 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 to explore a wide variety of architectures.

Table 2 X-TOS design variables

Variable	Range
Mission scenarios	
Single satellite, single launch	
Two satellites, sequential launch	
Two satellites, parallel	
Orbital parameters	
Apogee altitude, km	200–2,000
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/chemical
Delta V, m/s	200–1,000
Total number of explored architectures	50,488

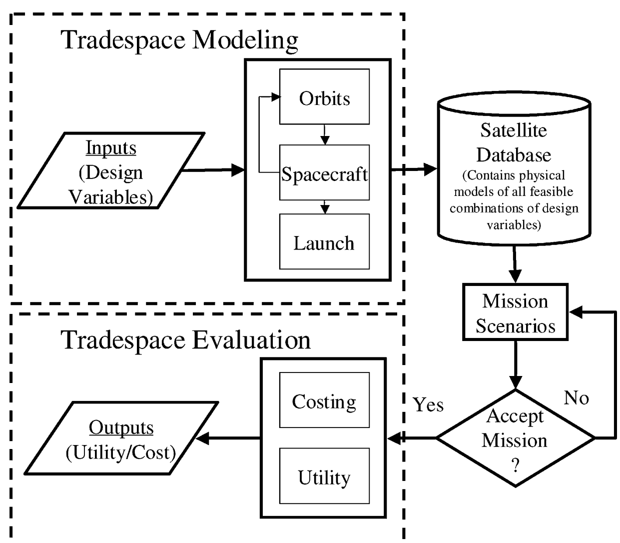

Fig. 6 X-TOS software flow.

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.

Building upon inherited design processes from the GINA method 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 database contained the orbits, spacecraft, and launch modules. The orbits module simulated the orbital dynamics of a satellite by calling Satellite Tool Kit and keeping track of position and time information.[20] The spacecraft module enumerated the possible satellites by varying different physical spacecraft parameters based on parametric design rules.[21] The launch module determined the launch vehicle, insertion orbit, and physical launch constraints for the satellite using sizing algorithms and launch vehicle performance data.[22] 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 using the utility function given in Eq. (1) and the small satellite cost model.[11,21] Figure 6 shows the X-TOS software flow.

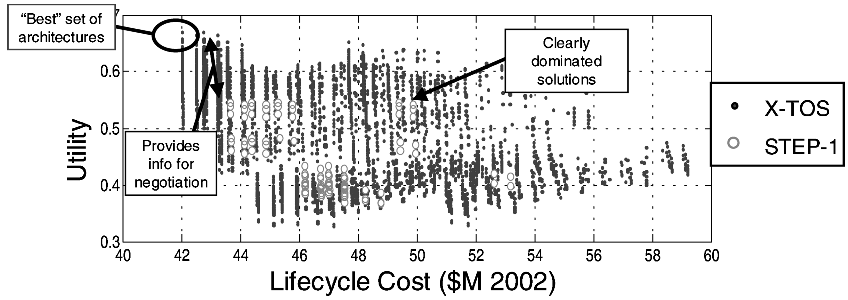

Fig. 7 X-TOS solution space with STEP-1.

The modular software architecture allowed the design team to divide the software among teams for concurrent development and also allowed the team to readily change individual modules, without needing to redesign the entire code, to improve the simulation following sensitivity analysis.

Results. The design variables (given in Table 2) were enumerated to provide a tradespace of architectures that were assessed through the software simulation code in terms of the preferred performance (attributes) set defined by the user. Figure 7 shows the utility–cost representation of the analyzed designs. A Pareto frontier with increasing utility for increasing cost is not readily apparent in Fig. 7. It is believed that such a tradeoff 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 shown in Fig. 7. The X-TOS solution space is plotted in small, filled circles. In 1994 the user flew a similar payload aboard the Space Test Experiment Platform 1 (STEP-1), but lost the satellite soon after launch. In open circles are possible STEP-1 architectures.[¶] The X-TOS mission is intended to perform at least as well as the failed STEP-1 mission. All of the potential STEP-1 architectures are dominated, meaning they fall inside the Pareto frontier. (Some of the design variable values were unknown for the actual STEP-1 mission, so that the unknown variables were enumerated over all possible values, resulting in the set in Fig. 7.) Better design decisions would result in a better design at the same cost. One consideration for STEP-1 was that the ADS payload shared the satellite with another payload and, thus, may have had to sacrifice some performance. Knowledge of the tradespace such as that in Fig. 7 would provide valuable information for negotiating such sharing arrangements and makes clear exactly how much value is being sacrificed and whether it is worth the cost savings.

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 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 Fig. 8, 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. (A similar design environment using ICEMaker is employed by Team X at the Jet Propulsion Laboratory.) 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.[23] This chair is able to compare the spacecraft and architecture designs that come from using ICEMaker using the same preference metrics established for the initial design. Figure 8 shows the MATE-CON chair in the role of information integrator, providing continuity that allows more informed trades at these higher levels of design detail, trades driven by mission value metrics instead of the more common metrics of mass and power.

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 Fig. 9, provided motivation and direction

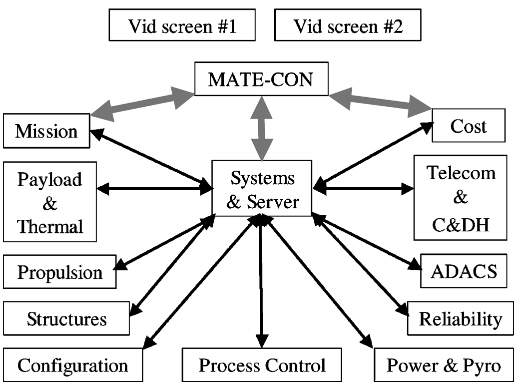

Fig. 8 MATE-CON integrated with ICE.

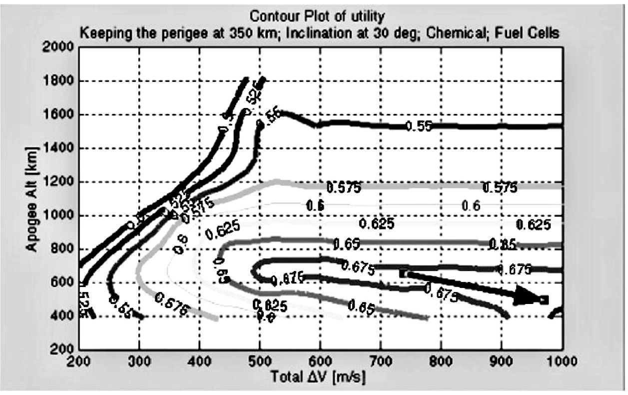

Fig. 9 Isoutility contours for X-TOS design trades.

¶Data available online at Small Satellites Homepage, URL: http://www.ee.surrey.ac.uk/SSC/SSHP/mini/mini94.html [cited 20 July 2002].

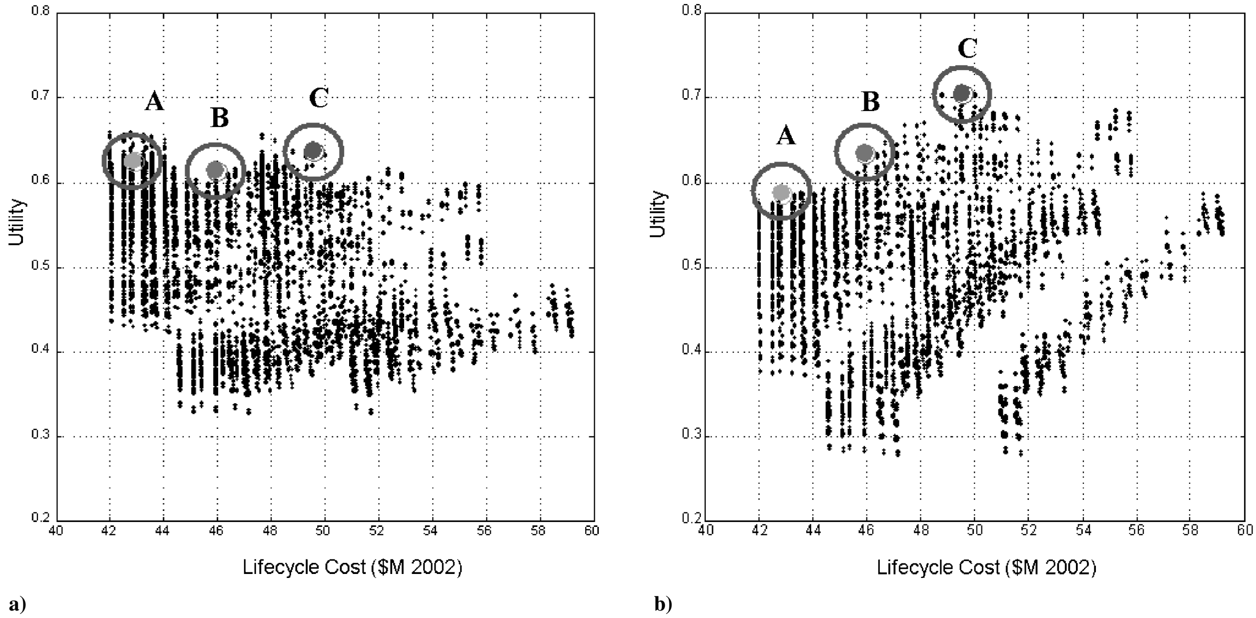

Fig. 10 X-TOS cost vs utility: a) original and b) revised.

for trades in near real time. Often the trades conducted during a concurrent design session are dictated by the technical experience of the session leader. The isoutility contour information supplements that experience with an explicit parameter-value map for directing trades, sometimes revealing counterintuitive information. In the X-TOS study, increasing mass tended to lead to more utility due to an increased ability to remain longer in a high-drag environment. Usually design sessions are directed to minimize mass, but in this mission minimized mass does not necessarily lead to a more valuable mission.

This exercise also demonstrated the ability of the MATE-CON process rapidly to 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. When the results were seen, the decision maker realized that the preference for lifetime had not been accurately captured. A new utility function was assessed, and the architectures were reevaluated in terms of the new preferences. The difference in the utility space is shown in Fig. 10b. When Fig. 10b is compared with Fig. 10a, 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.

Because 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. These benefits are as follows: First, changes in decision maker preferences could be quickly and easily quantified for rapid analysis and adjustment in the design process. Second, subsystem trades could be navigated and motivated by quickly referencing their impact on overall mission utility. Third, organizational learning could be improved by wisely flowing down information from previous design study work.

Insights

During the X-TOS project, several key insights were realized. First, 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 adapt rapidly to the new drivers by recalculating the utility of the designs. (A change in preference results in a new utility function.) 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 the face of changing preferences may result in cost savings.

Second, 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. More significantly, the team would have been 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, the duration of the semester, limited X-TOS to traditional satellite designs, but they were able to look at different scenarios (single vs multiple satellites operated and deployed in parallel or in series). The inability to consider radically different concepts may have prevented the discovery of valuable systems; however, as shown in the comparison to the STEP-1 designs, the team was still able to determine more valuable systems within the traditional satellite concept.

Conclusions

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 the employing of MAUT, MATE-CON has developed a mathematically rigorous approach to aggregating decision maker preferences. This approach provides a metric to evaluate equitably 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 the utilization of 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 the incorporation of interdisciplinary expert opinion and diverse stakeholder interest throughout the design, MATE-CON reduces the likelihood of miscommunication throughout the system design process. The key value of MATE-CON lies in its synergistic combination of techniques to explore tradespaces and communicate preferences among experts. Although 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.[19]

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