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New Methods for Rapid Architecture Selection and Conceptual Design

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New methods for rapid front-end development of complex systems are introduced. New tradespace exploration techniques, advances in integrated concurrent engineering, and application of risk analysis methods early in the design process allow rapid progress from poorly defined user needs to fairly detailed conceptual designs. An overview is provided of the methods. A process is described that allows thousands of system architecture alternatives to be quickly and quantitatively assessed vs user needs. The result is an understanding of the tradespace, including its key constraints and sensitivities, as well as an optimum architecture. This architecture is used to specify needs for space vehicles, which are designed using integrated concurrent engineering techniques. Research in risk and uncertainty, policy impacts, and information technology methods allows quantitative consideration of these factors, resulting in designs that are robust to uncertainties and policy impacts and potentially more versatile and flexible. Eight systems designed to date using the method are briefly reviewed. Key literature and a number of companion papers that go into depth on various aspects of the method are cited.

Introduction

THIS paper and its companion papers address the increasing national need for rapid acquisition of complex systems with a space component and the increasing acquisition times for such systems. Recent events have dramatically demonstrated the use of systems with space, air, and ground components to execute rapidly complex military missions. Space components are a key link in civil communication systems as well, but recent experience has pushed that industry away from reliance on individual vehicles or even constellations and toward a view of space components as one of many possible ways to move information. Even in science missions, the trend has been away from single big-bang missions such as Galileo and Cassini and toward integrated systems of many missions, for example, the Mars explorers. Rapid shifts in both the world geopolitical situation and the commercial markets for space services require a capability to rapidly understand and design complex systems with space components. The same forces place a premium on flexibility and adaptability in the design of such systems.

Here we focus on the early stages of product development, from the determination of a user need, through the determination of a system architecture, to the completion of a conceptual or preliminary design. At the end of this process, the basic solution approach to the problem has been determined, and major design decisions have been made. These decisions will determine up to 80% of the eventual program cost and schedule.[1] It is in these stages that major innovations and/or technology breakthroughs can be realized. It is also in these stages that mistakes can be made that can be very expensive to fix later, or even doom a program to failure.

Traditional approaches, still widely used in the U.S. aerospace industry, tend to settle on a preconceived design early in the process without tools to consider the full range of possible designs and their associated costs. The approaches are also limited in their ability to assess how needs might change during development and operation. As a result, traditional trade study methods lead to systems that are locally optimized but may not be globally optimized. Problems with traditional practices include a priori design selection and pursuit of that design in detail without understanding its effects on the larger system; requirements instability, often based on insufficient early understanding of the complete preferences of all decision makers, or development times so long that real needs have changed before the design is complete; poor understanding of risks and uncertainties (which are almost always high in early design phases); difficulties with technology transition and maturity; lack of understanding of the impact of future budgeting and policy decisions; and lack of ability to create and evaluate designs for flexibility and upgradability.

In response to this challenge, the Space Systems, Policy, and Architecture Research Consortium (SSPARC) was formed. This consortium consists of academics at the Massachusetts Institute of Technology (MIT), the California Institute of Technology (CalTech), Stanford University, and the U.S. Naval War College, with a research staff and funded graduate students. The academic effort is assisted by government personnel, primarily from the Air Force Research Laboratory (AFRL) at Hanscom Air Force Base in Lincoln, Massachusetts. Contacts have also been maintained with similar efforts at the Naval Postgraduate School. To assure the relevance and rapid applicability of the work, the consortium has been assisted by an Industrial Advisory Board (IAB) of senior engineering personnel at most major U.S. space systems manufacturers.

To address the issues raised earlier, the consortium has created a new front-end architecture and design process and brought advanced risk, reliability, and uncertainty analyses into the early design phases. An architecture selection tool was created based on the concept of exploring the tradespace of possible architectures rather than settling quickly on an optimum. This architecture selection tool was linked to advanced integrated concurrent engineering (ICE) methods. Quantitative spacecraft reliability calculations have been integrated into ICE. Advanced assessments of the uncertainties implicit in design margins, launch vehicle reliabilities, and the risks of geographically separated design teams are also explored. These methods have been used to analyze eight candidate space missions and several other systems to date. They have also been

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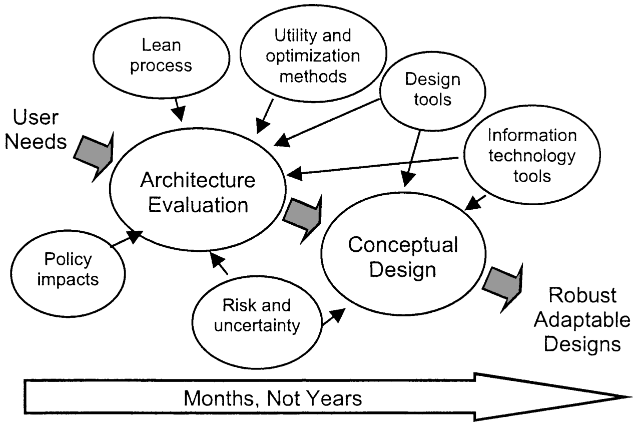

Fig. 1 Process overview.

used to provide a framework for applying further research in managing risk, uncertainty, and policy impacts on space programs.

The new front-end design process consists, broadly, of an architecture segment and a conceptual design segment (Fig. 1). In the architecture segment, the organization of the system is determined, including major choices such as whether a space segment will be included, where the space segment should be (how many vehicles, in what orbits, and with what vehicle lifetimes), and what its basic capabilities and operating modes will be, for example, instrument types, communications modes. Perhaps more important, the architecture segment, multiattribute tradespace exploration (MATE), includes an exploration of the available design space, which yields many benefits. In the conceptual design segment, the vehicle(s) are designed using ICE in sufficient detail to determine technical feasibility of the architecture, improve cost estimates, and understand if the architecture is constrained by issues, for example, configuration for launch, that do not come up when the spacecraft is regarded as a black box. MATE and ICE together are referred to as the multiattribute tradespace exploration and conceptual design (MATE-CON) process.

The power of the method comes primarily from the ability to assess quantitatively many design choices very early in the design process. This ability allows designers and users/customers to explore many design options, and prevents focusing on a single point design too early. The designs considered can be assessed by analysis, rather than by qualitative, experience-based methods. This is particularly valuable for new systems, or for assessing new design alternatives or new technologies, for which there is little or no experience. This capability enables quantitative assessment of factors such as risks and uncertainties in technical performance and cost, and the impacts of changes in markets or government policy, by allowing exploration of a large number of possible situations, including speculative (what if) scenarios.

Several methods for assessing risks, reliabilities and uncertainties have been advanced as part of this work. Some of these have been integrated into the MATE-CON process, whereas others stand alone or work with other analysis frameworks. The estimation of spacecraft system and subsystem reliability based on probabilistic risk analysis (PRA) techniques has been incorporated into ICE. The estimation of the failure risk of complex systems (such as launch vehicles) considered as a whole has been studied independently, as has the question of correct design margins. The risks involved in managerial or organizational practices, in particular the used of geographically dispersed design teams, have been assessed using the system–action–management (SAM) framework.

This paper is intended as an overview of the MATE-CON process and an introduction to the related research topics covered in the companion papers. It does not attempt to fully review the topic of advanced design methods, but the advanced design methods emerging in aerospace and closely related fields will be reviewed, along with fundamental background work relevant to the research topics covered in this and the companion papers. The paper will then review the new processes, focusing on the MATE-CON method and an example taken from a graduate design class. The paper will also briefly describe the research which has both aided in the generation of the processes and extended their capabilities. These research topics are expanded in depth in the companion papers. The paper will also summarize the applications of the methods to date. The lessons extracted will illustrate how the new capabilities gained can be used to understand user needs, quantitatively evaluate proposed designs to satisfy them, uncover the key trades that will affect program success, and allow consideration of risk and policy impacts, all at a very early stage of product development.

Background

The traditional processes critiqued in the Introduction have been inherited from a time when the national needs were very different from those of today.[2] In the past 10 years or so, advanced methods and tools have emerged in response to this challenge. Penetration of advanced tools, for example, computer aided design, has been fairly widespread and will not be reviewed here. New design methods are now frequently used in government and quasi-government settings, for example, NASA, the Jet Propulsion Laboratory, and The Aerospace Corporation, and are also starting to make inroads into industry.[§] This paper will review relevant examples of advanced design methods used in the aerospace industry (and, in one case, the similarly complex design of undersea vehicles), with an emphasis on the work that has provided the foundations for this effort. The companion papers go into considerably greater depth on the relevant backgrounds of their specific topics.

The most widespread advanced design method in the aerospace industry goes by several names. Here, it will be referred to as ICE. The key to ICE is the linking of both computer tools (using common databases and other data-sharing technologies) and human experts in a design environment that maximizes communication. This allows complex, linked, and often iterative design analyses to be performed extremely rapidly. This method is currently used for preliminary designs of complex space vehicles and systems, and for detailed design and fabrication of components such as instruments. Its practitioners are developing the method with the eventual goal of allowing requirements-to-hardware development of complex systems.

The Jet Propulsion Laboratory (JPL) Advanced Projects Design Team (team X) uses this method for preliminary space system design.[3] The method as used by team X is particularly suited to the exploration of novel missions using simple vehicles.[4] The related Next Generation Payload Development Team (NDPT, or team I) uses essentially the same method for detailed design of components such as instruments; this work has gone as far as creating the electronic specification of a component that was then produced and used.[5,6] The Aerospace Corporation has also done extensive work of this type, referring to their efforts as the concept design center (CDC).[7] The CDC has five teams, spanning a wide range of analysis types, from system architecture to electrooptical payload design. The teams trade scope for level of detail to keep the problems examined tractable.[8] The CDC experience has emphasized the role of human engineers and their efficient, tool-enabled interaction as the key to the ICE method.[9] ICE techniques are also in use at ESA for preliminary assessment of space science missions.[10,11] These techniques have seen some use in industry, with Saab, AB, TRW, The Boeing Company, Ball Aerospace, and probably others all using variants on the ICE environment.[12,13] The adoption of these methods by companies with traditional design cultures has not been easy, however, and the practice is in most cases considered experimental.

ICE methods require complex, multidisciplinary models of the systems of interest. This is a large field of study that this paper will not attempt to review. However, SSPARC has directly benefited from fundamental work of this type that has been carried out at NASA Research Center,[14] NASA Goddard Space Flight-Center,[15] and NASA Ames Research Center[16] focusing on the analysis of

[§]For example, see data available online at http://NewDesignParadigms.jpl.nasa.gov/ and http://nsd2001.jpl.nasa.gov/.

advanced launch and reentry vehicles. These works have explored alternatives or complements to the ICE method for solving multidisciplinary problems.

The ICE component of this effort is directly descended from the JPL and The Aerospace Company techniques, which have undergone further refinement at CalTech.¶ The SSPARC program uses the ICEMaker tool for linking computational models and related techniques for problem decomposition, modeling, and design session facilitation.[17,18] The program has also benefited from the design and creation of a modern design environment at the MIT Aeronautics and Astronautics Department, using the experience cited earlier as a guide.[12]

The exploration of architectures has been carried out using many of the described methods. These methods can be used to explore design alternatives, or optimize certain parameters in a given design. However, handing large numbers of open design parameters can lead to very large design spaces, which are often very uneven in the sense of having many locally optimum designs far from the true optimum. Architecture selection is also complicated by uncertain or even conflicting evaluation criteria. These features pose challenges for optimization methods[19–22] and have motivated the use of innovative collaborative optimization[23,24] and tradespace visualization and customer choice techniques.[25]

The MATE analysis of spacecraft architectures is a direct descendent of the generalized information network analysis (GINA) method.[26] The GINA method used concepts and tools from information theory to allow analysis of complex space systems as information transfer networks. These networks have quantifiable attributes that determine the quality of service that they deliver: signal isolation, information rate, information integrity, and availability. The GINA methods have been expanded to include systems that cannot be simply defined in terms of information networks. The concept of attributes of the system has been generalized to include those characteristics most important to decision making stakeholders such as users, acquirers, sponsors, and developers.[27] Recognizing what attributes might be important to relevant decision makers requires understanding of these stakeholders and their interactions. Here, we are guided primarily by the work of the Lean Aerospace Initiative.[2]

The ability to use GINA-type methods on systems whose functionality goes beyond information handling is enabled by the use of evaluation concepts borrowed from the business world. Multiattribute utility theory,[28] real options methods,[29] and portfolio theory[30,31] are well-understood methods. Recently, they have been successfully applied to complex aerospace systems, albeit in a piecemeal fashion.[32–35] In this work, they are brought together to enable quantitative evaluations and comparisons of complex systems, handling of the uncertainty inherent in early design, and dealing with the uncertainty in a rational way.[36–38]

Quantifying uncertainty can be accomplished using existing methods for risk, reliability, and uncertainty analysis. Often, few data are available for assessing important risks, such as launch vehicle failure, necessitating the use of Bayesian techniques.[39] Even in the case of good reliability data, the complexity of space systems requires a systematic approach to reliability estimating, which has not typically been exercised in conceptual design.[40] As a surrogate for understanding risks and uncertainties, or as a mitigation technique for understood risks, large margin budgets are typically mandated in early design. Incorrectly estimated, margins can lead to major development problems; conversely, they can lead to overly conservative designs.[41] Currently these margins are based only on experience; systematically understanding the margins needed at each stage of development is part of this effort.[42] Finally, the risks of mission failure due to managerial decisions such as the structure and makeup of development teams has recently been highlighted by mission failures.[43,44] Understanding these risks, and how they change with new development processes,[45] is also a part of this effort.[46]

Multidisciplinary optimization (MDO) offers a wealth of powerful techniques for finding optimal solutions when faced with a large tradespace. In some sense, this work offers an alternate approach to MDO, in that the ultimate goal is to understand the tradespace itself, including as much complexity as can be used by decision makers, whereas MDO techniques tend to boil down the complexities of the tradespace to optimal solutions and perhaps sensitivities in the neighborhood of them. MDO techniques have been evaluated for use in GINA tradespaces.[47] As part of this work, a simulated annealing MDO technique was extended to handle multiple objectives and find Pareto fronts as well as optima and was incorporated into a method called multi-objective multidisciplinary design optimization systems architecting (MMDOSA).[48]

Finally, a great deal of information is generated during early design that may impact the later steps of the design process. Thus, it is very important to handle this information carefully and collect and analyze it rigorously. In this, we are aided by existing expertise in knowledge management, covered in a companion paper.[49]

MATE-CON Method

Here we will walk through the process used in MATE-CON. The intent is to give the reader a conceptual understanding of the method and its aims so that the examples and lessons covered in the next sections can be understood and the work in the companion papers put in an overall context. More details are in Refs. 36 and 50. In the latter, the process is defined in terms of 50 distinct steps.

MATE

MATE at the system architecture level is a process for understanding complex solutions to complex problems. Figure 2 shows the conceptual flow of the MATE process, and Fig. 3 is an expansion in terms of a specific study, the terrestrial observer system X (TOS-X) carried out at MIT in cooperation with the AFRL Hanscom.

The first step is selection and bounding of a mission concept. Here, the basic issue to be addressed, that is, the user needs to be satisfied, the broad scope of the solution space, that is, what kinds of systems will be considered, and the scope of the analysis to be performed must be decided. In our example, the X-TOS project was scoped fairly narrowly: The customer needed a system that could deliver and support a set of three preexisting instruments designed to take in situ measurements of ionospheric conditions. The solution space was restricted to conventional-technology space vehicles and the scope to the design and operation of these vehicles.

The next step is a critical one for reducing qualitative user needs to quantitative metrics. A limited number of attributes of the system need to be specified. Attributes have been described as what the decision makers need to consider and/or what the user truly cares about; they must also be quantifiable and capable of being predicted with reasonable fidelity by fairly high-level models. In the example, it was the characteristics of the data collected that concerned the users, not the characteristics of the system itself. This lack of concern for the physical system is typical and illustrates a key feature of the entire method, that it is driven by a set of quantified user needs, rather

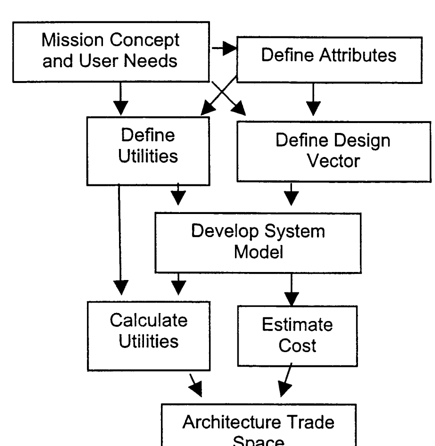

Fig. 2 Outline of MATE process.

¶Data available online at http://www.lsmd.caltech.edu/

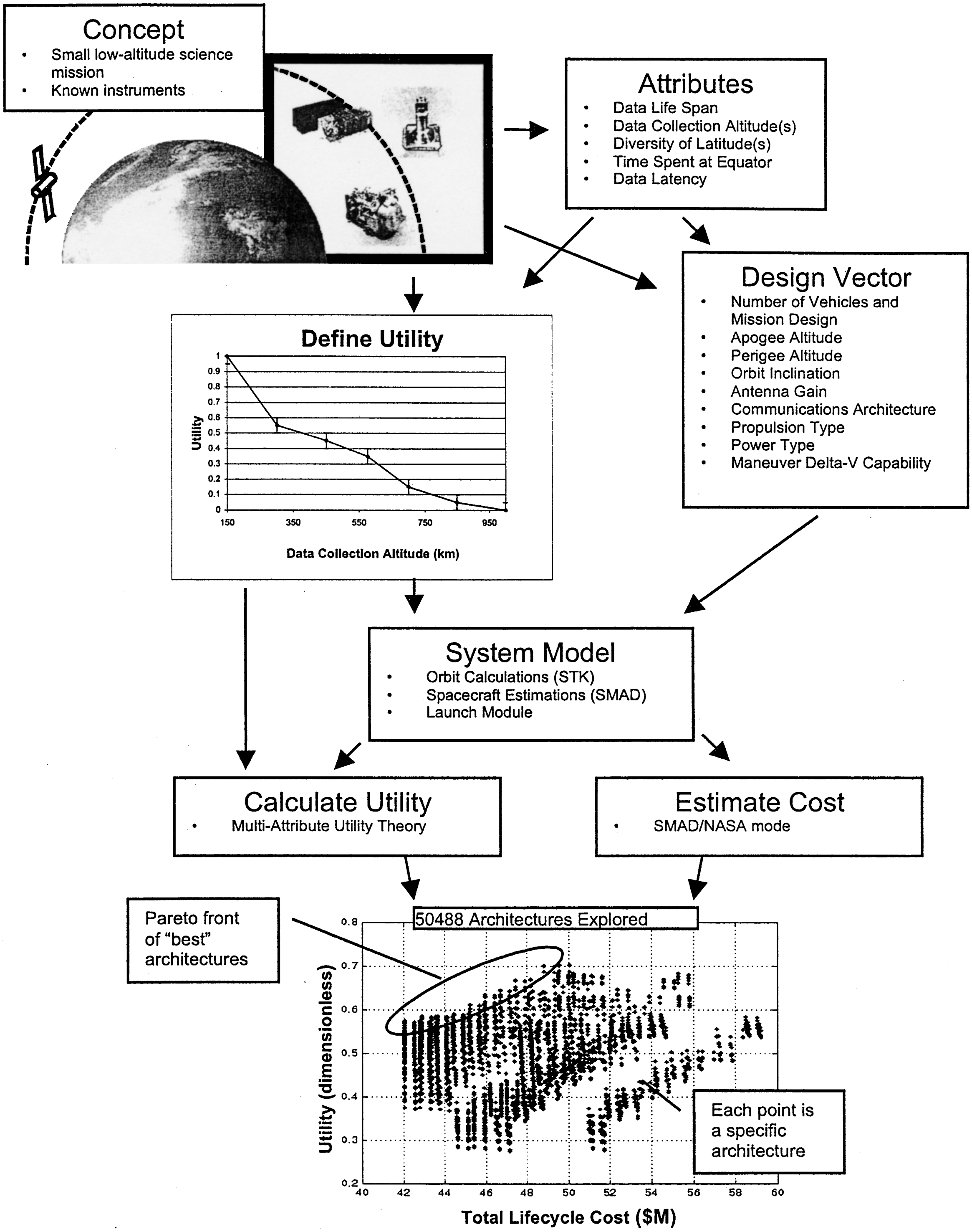

Fig. 3 MATE process: X-TOS example.

than requirements pertaining to a specific system. The attributes ideally need to be complete (capture all important user needs) and independent; this is sometimes hard to accomplish at the beginning of a study, and the attribute list will sometimes evolve during the process, although in this example it did not.

Once a list of attributes is settled on, a formal multi-attribute utility (MAU) process[28,36,49] is used to determine the utility to the user of values of each attribute. These individual utilities are then integrated into an overall utility. In both cases, utility is a dimensionless metric of goodness that is customarily normalized to be between 0 (minimal user needs satisfied) and 1 (delighted user). In some cases, this metric can be given units, for example, cost per billable minute of a broadband telecommunications system, in others, for example, usefulness, to scientists, of scientific data, it can only be used as a relative metric. In the latter case, interpretation of these metrics is somewhat dangerous: A higher metric is better than a lower one, but a utility of 0.5 may not be half as good as a 1.0, nor a 0.99 only 1% off from a 1.0. Such interpretations usually require returning to the individual metrics, or the decision makers. The single utility chart on the left-hand side of Fig. 3 reflects (and quantifies) the fact that lower altitude data are more useful to the users, with an premium on very low altitudes.

The design vector is a list of variables that define the system architecture. To keep the analyses tractable, this vector must be limited to those variables that will have the largest effect on the attributes. Design variables are selected based on techniques such as quality function deployment (QFD).[51] In this application, QFD is used to select the design variables, not the design itself. The design vector may need to be revisited as the models mature.[52] Often, the exercise of picking the design vector is one of exclusion because variables of undoubted importance in the final design are excluded from the initial studies. In the example, the architecture is reduced to a set of choices of mission design, for example, how many vehicles and when they are flown, orbit elements, and some simple vehicle characteristics.

The system model has a well-defined and straightforward goal: Calculate the attributes given a set of specific values of the design vector. There is no one best way to do this modeling, but experience has indicated that a few commercial tools, for example, Analytical Graphics' Satellite Tool Kit® (STK) and simple analysis techniques, for example, the methods in Ref. 53 are of appropriate fidelity. Other models, such as operations, have proved more problematic. For example, as part of this work, an advanced operations model has been developed.[54] These models can be linked to automate, or at least partially automate, the analyses, allowing large design spaces to be analyzed efficiently with commonly available computer resources. In the example, both STK and student-written orbital calculations were carried out; spacecraft characteristics were calculated based on Ref. 53, and a launch module (selecting the best launcher for a given orbit and vehicle) was written based on an existing database of launch vehicles. These modules were used to build a database of the attributes of single vehicles in given orbits; for multivehicle mission designs these attributes were integrated over the lifetimes of the multiple vehicles. A design room with multiple personal computers considered powerful by the standards of the year 2001 was used to do the calculations. They took only hours and in fact were entirely repeated on short notice late in the project due to a shift in user preferences.

The results of the modeling are then reduced to utilities and costs. Utilities are calculated using the formalisms of MAU theory. Cost is estimated based on the best (and most appropriate) available cost model. The cost models are known to have low fidelity and also to disagree by large factors.[55,56] Interpreted correctly, the calculated cost should be viewed, like the utility metric, as a ranking rather than an absolute and correct value. If the cost models are used in this sense, the danger to watched for is incorrect sensitivities in the cost models, which would cause the relative costs of design options to be incorrectly ranked. To date, it has been found that this has not been a major problem at the level of fidelity of the analyses used. In general, for example, more complex designs have resulted in bigger and heavier vehicles requiring larger launch vehicles and, hence, more expense to build and launch; the current models capture this trend. In the example, a hybrid of the cost estimation model in Ref. 53 and NASA's space operations cost model** was used. The result of the analysis is a database of the tradespace, with thousands of potential architectures mapped to the resulting attributes, utilities, and costs. This database is the basis of the exploration phase, the learning of the lessons that the process has uncovered. At a minimum, the desire is to reduce the tradespace to designs worth considering (find the Pareto front), uncover the controlling physics or other constraints, and uncover the key design trades. Data visualization and manipulation techniques are usually needed, along with patience and curiosity, to understand the complex lessons of the design space. MDO methods may be very useful, and indeed necessary, for exploring very large design spaces.[47,48]

The bottom of Fig. 3 shows one possible slice of this database, the combined utility plotted against the total mission cost. In Fig. 3, each point represents a potential architecture. The Pareto front is clearly visible to the upper left, the few dozen architectures that give the maximum utility for a given cost. Figure 3 does not uncover the controlling physics; that took considerably more delving into the database. In the case studied, drag at the low altitude where the most valuable data could be collected limited mission life, becoming the key physical constraint, and also setting up the key trades: increased lifetime for either increased altitude (and, hence, reduced data utility) or increased vehicle weight (and, hence, cost) for added maneuver fuel. These trades are visible on the Pareto front: Short lifetime missions are somewhat cheaper at a penalty in utility.

The process is shown as being sequential, with each step following the previous one. In practice, as the process proceeds, circumstances can change, or knowledge can be gained that changes perceptions, causing earlier decisions to be called into question. For example, user needs can to shift late in the process, or the choice of attributes or design vector can change based on knowledge gained during analytical model development. The process is quite robust to iterations, however. The major time commitments are to getting up to speed on the proposed system and its related technologies and building the analytical models. If the user needs, utilities, attributes, or design vector change, the process can be repeated relatively quickly by modifying the analyses as necessary and rerunning them with new inputs. In our example, a change in user preferences at the conclusion of the process was quickly accommodated by changing the utilities and repeating the analysis.

Once the tradespace is explored, an architecture or architectures can be selected. This may be the optimum architecture as determined by the analysis, that is, the one delivering the most utility for the minimum cost. More likely, it will be selected from a reasonable subset of architectures (usually on the Pareto front) by the designers and users based on a deeper exploration of the attributes of the architectures and the characteristics of the surrounding tradespace. For example, architectures whose attributes are relatively insensitive to changes in assumptions or poorly controlled variables may be selected as being robust, or architectures that can be rapidly improved with additional resources or technology (even if they are not immediately available) may be selected as being versatile or upgradable.

MATE-CON

Once an architecture has been selected, rapid development of a design or set of vehicle designs is done using ICE. An interdisciplinary team with tools that communicate seamlessly through a common database does design sessions in physical or at least virtual colocation. Figure 4 shows the computer tools, referred to as sheets, linked to a server. Each tool is tended by a human operator who updates the tool as necessary, for example, updates a CAD model, makes major design decisions that are input to the tool, for example, changes the propulsion type, and provides common sense and wisdom unavailable to automated methods, for example, breaks nonconvergent behavior in the iterations. The combination

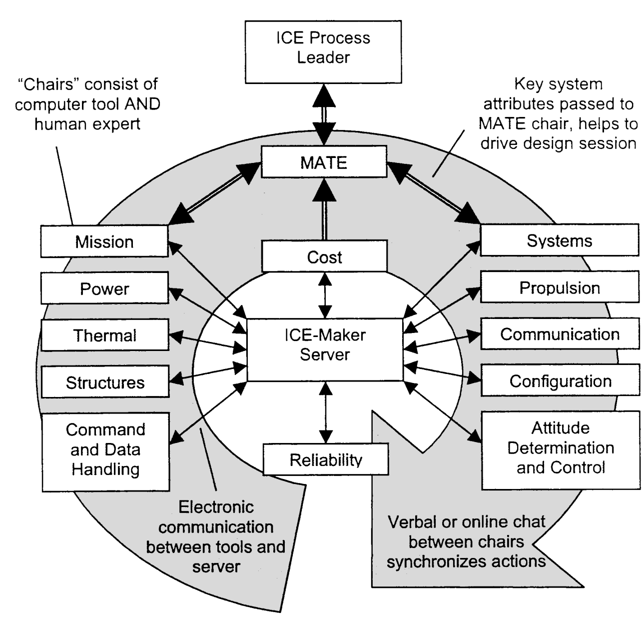

Fig. 4 Outline of ICE process with MATE chair.

**Data available online at http://www.jsc.nasa.gov/bu2/SOCM/SOCM.html.

of the human and the tended tool is referred to as a chair. The tools perform rote calculation, for example, rough sizing of solar panels, pass information, and sum up system characteristics, for example, mass and power budgets, automatically with each design change. A session consists of inputting design changes and iterating the calculations (by having each chair execute its sheet in turn, tended by the human engineer as required) until stable values are reached for all major system characteristics. Design changes are tried until a design is found that satisfies all major requirements.

The process is steered by a session leader based on a combination of traditional system requirements and user inputs. The latter are ideally provided by direct user/customer involvement in the ICE session. An innovation in the current work is the inclusion of a MATE chair that has the results, and often the models, of the preceding MATE effort at hand. The MATE chair can quantitatively assess the progress of the design not just toward meeting requirements, but toward maximizing the overall utility of the system containing the design. The chair can also help the user/customer translate needs into design changes and, thus, steer the design changes toward sweet spots in the tradespace. Finally, in the absence of a customer present throughout the session (or the absence of one of several decision making stakeholders, which is likely) the MATE chair can provide a surrogate presence, assuming the stakeholders will in the end desire the maximum utility.

This effort has also introduced more rigorous reliability methods into the ICE process, described in a companion paper.[40] The risk chair tracks the system reliability as the design evolves, allowing reliability requirements to be explicitly met. Just as the MATE chair allows an understanding of performance needs richer than simple requirements, the risk chair allows exploration of design alternatives for their risk or reliability impact and the steering of the design to achieve goals such as reliability at low cost, upgradeability, or design robustness. The risk chair also allows the identification of the key risk drivers, so that risk-reduction resources can be allocated to the correct subsystems when entering detailed design.

In our example, the X-TOS vehicle design trades reflected the MATE trades of orbit and reboost fuel capacity vs cost, lifetime, and the usefulness of the data collected. The designs illustrated the consequences to the vehicle of the trades that were discovered as abstractions in the MATE part of the process. A typical result is shown in Fig. 5. Note the large fuel tanks required by the need for sustained low-altitude flight.

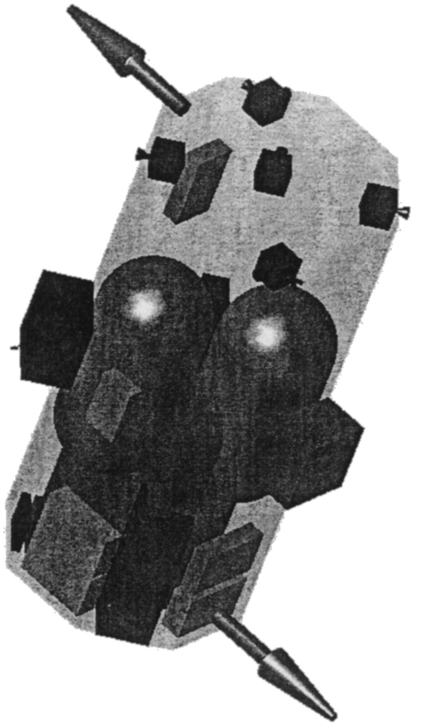

Fig. 5 ICE result: X-TOS vehicle CAD model.

Process Terminology

A note is in order on the terminology used to describe the method. In this paper and some of the companion papers, the architectural-level tradespace exploration is referred to as MATE, the rapid conceptual design process as ICE, and the integrated process as MATE-CON.[36,49] These methods are works in progress, and in some companion papers earlier or different versions of the processes were used. The MATE method is an expansion of the GINA method. GINA includes the system modeling and tradespace exploration aspects of MATE without the front end of a generalized MAU method and is specialized for systems that are primarily focused on information transfer. In some companion papers[37,38,52] one of several unnamed precursors to MATE are referred to as modified or advanced GINA methods. In one companion paper[48] reference is made to MMDOSA, which is a complement to MATE: It is a rigorous process for exploring extremely large tradespaces with MDO techniques. In another, the separate Stanford University SAM framework is used, which includes a quantitative risk analysis model of the not only the physical system, but also management decisions made during the design effort.[46]

Requirements

The methods described here take place at the beginning of the system design process. Traditional product development process descriptions often identify establish requirements as this first step, and so it is natural to ask how the current method interacts with the determination of system requirements.

The present method can be thought of as a powerful tool for coming up with the right requirements at the right time. It has been noted that current processes are not efficient at coming up with requirements, the resulting requirements do not necessarily provide a good statement of user needs, and the potential value of the system (and even its physical feasibility) are not well reflected by the requirements.[57] To this, we add the observation that most requirements are written with a solution to the design problem in mind and, hence, reinforce the premature narrowing of the design space that we attempt to avoid. For these reasons, requirement determination is replaced by the much more general collection of user utilities in the MATE process.

Requirements for the space vehicle to be designed in the ICE process can be generated at the conclusion of the MATE process. However, by including MATE and risk chairs in the ICE process, the richness of the knowledge of the user utilities, vehicle robustness, and the interaction between the vehicle and the rest of the system can be preserved into the conceptual design process, providing more flexible guidance than a set of fixed requirements.

At the conclusion of the MATE-CON process, on the other hand, sufficient information is available to write very good requirements for the detailed design of the vehicle. This capability is key to avoiding classic requirements traps. The utilities capture the needs of the key stakeholders, without which instability is likely. Tradespace knowledge allows avoidance of both physically unrealistic requirements and requirements that artificially preclude the best solutions. System interactions and program and technical risks can be estimated; they are very difficult to determine requirements for a priori. Finally, although flexibility and upgradability are clearly key to modern acquisition models, for example, spiral development, there is little experience in writing requirements for them. Most historic examples of flexible systems are serendipitous.[58] The present method can aid in understanding flexibility issues through understanding of the tradespace. Designs can be specified that can be improved to provide enhanced utility with reasonable expense, risk, and/or need for technology advancement.

Limits and Caveats

The MATE-CON method is a useful tool for architecture selection and conceptual design, but it must be used with a full understanding of the limits of the method and its component parts. The method requires careful selection of the attributes and design vector: These define the problem that is being addressed. Changes in these selections late in the process may require substantial rework. The definition of the tradespace requires models with the right fidelity. They must capture the factors that differentiate the architectures under consideration without being computationally intractable or excessively difficult to prepare and integrate. They must also have the correct precision given the uncertainties involved. Highly precise calculations based on sweeping assumptions will give misleading answers. If the problem is dominated by uncertainties, these uncertainties will have to be considered as part of the tradespace analysis. Particular care must be given to the use and interpretation of cost models, which are unlikely to give very accurate absolute results. The key is to assure that the cost models used provide the right relative answers, discriminating more expensive options from less expensive ones. The utility models must also be used with care. Ideally, real users, acquirers, and other stakeholders should be brought into the process as often as possible, to prevent the creation of utility functions based on poorly captured or shifting user needs.

Research in Early Design Issues

This section is a brief overview of SSPARC research in early design issues, covered more fully in the companion papers. Although the preceding section has concentrated on the MATE-CON process, the fundamental research reviewed in this section actually comprised the majority of the effort of the SSPARC program. The key thread in this research has been the handling of the risk and uncertainty inherent in early design stages.

The research has interacted with the development of the early design process in various ways. In some cases, MATE-CON models were rerun with minor modifications to study issues such as the effects of uncertainties or policy decisions on the tradespaces. In others, additional modules were added to or used with the MATE or ICE models to include automated capture of user utilities, MDO capabilities, reliability calculations, and knowledge capture. Other work covered fundamental questions relevant to the early stages of design, such as what design margins are appropriate at each stage of design, how to estimate the reliability of launch vehicles or other complex systems considered as a whole, how to understand the risks associated with geographically dispersed design teams, and the cost impact of U.S. government launch policies, using independent analysis and/or analytical frameworks.

Risk and Uncertainty

Uncertainty at the architectural level can be modeled through a variety of techniques once an analytical model is available. Simply visualizing the uncertainties is extremely valuable in conceptual design. Uncertainty may prevent discrimination between concepts (when the uncertainty is greater than the difference in calculated performance between them); it may also be a major discriminating factor (when some concepts have large amounts of uncertainty in their performance, whereas others do not). Often, there is a risk–reward relationship, which uncertainty analysis can quantify. The effects of these uncertainties can be managed using portfolio management techniques. A companion paper gives a framework for understanding and handling uncertainties early in the design process.[38]

Reliability is an important factor in analyzing the performance of systems at both the architecture and conceptual design levels. At the architecture level, the reliability of components that are themselves complex systems (such as launch vehicles) may have a major impact on performance. Estimating these reliabilities by methods such as PRA may be difficult, especially for new systems. A companion paper explores the use of Bayesian techniques for estimating launch vehicle reliabilities.[39]

A reliability chair was also developed and included in the ICE process. This creates a consistent framework for PRA-based reliability calculations to be moved upstream to conceptual design.[40] Design margins are a key tool for handling uncertainties and risks in preliminary and conceptual design, but the margins themselves are at best experience based and may be close to arbitrary. Probabilistic modeling has been used to understand risk and uncertainty in preliminary design rules and develop a new understanding of the use of (and values for) design margins.[42]

The coupling between the risk inherent in a design, the design process, and design management practices, for example, use of distributed teams introducing uncertainties or added risk in the design, was also explored, using the SAM framework.[44,46] This framework can be used to add management and design process issues to the architecture selection and conceptual design process.

Space Policy

Space policy issues are frequently determined asynchronously with the conceptual design. Policymakers make choices that impact the conceptual design, but that impact is not understood when the decisions are made. This leads to redesign and lost time. Potential policy choices that can be quantified can be incorporated in the tradespace exploration. A clear example is policy choices on budget and budget caps, which lead to stretch out or downgrading of systems, with predictable performance and life-cycle cost impacts. An analysis of this type is reported in a companion paper, along with a coping strategy for program managers based on real options methods.[37] Policy choices also have major impact on costs and constraints on space architectures through decisions concerning the availability of resources such as launch vehicles. Another companion paper addresses this issue with an analysis of policy impacts on launch costs and risks.[59]

Technology Assessment and Knowledge Capture

The rapid tradespace exploration allows for the easy inclusion of the impacts of advanced technology and design concepts. For example, swarm and cluster concepts and technologies can be modeled and their impact on the design tradespace studied. This allows rational apples vs oranges comparisons between different system architectures and can provide guidance on the new technologies worth investing in for maximum system performance impact. The performance impact of extended and/or separated structures for interferometry,[47,48] space-based radars,[38,60] swarm technologies,[32,37,38,40,52,61] and orbit transfer vehicles and their associated propulsion systems[62,63] have been analyzed under this effort.

One of the lessons learned in doing the tradespace analysis and in interviews with people in industry is the value of design capture and knowledge management. The semi-automated nature of the MATE-CON process allows for easy recording of the key parameters and choices. These can then be stored in a database, with annotations and notes added by the designers. This allows the sequence of decisions and the reasons for decisions to be recalled years after a design is finalized or a tradespace analysis has been done. This kind of knowledge management should facilitate learning from experience and expose forgotten assumptions. At the front end of the process, software can be used to capture the information necessary to construct utility functions; this both eases the process and formalizes its capture for later analysis and updating.[49]

The inclusion of these advanced topics in the conceptual design process will allow designs of greater realism to be constructed which incorporate such issues as life-cycle uncertainty, policy choices, choices on distributed design, and many others. These will help the design be right the first time.

Example Results

The new methods have been used to analyze eight original systems to date, along with several generic systems used to exercise advanced capabilities. Table 1 summarizes the systems considered, the types of analyses used on them, and the references to more complete descriptions of work on them or based on them. The versatility and general applicability of the method can be inferred from the variety of missions studied. The first eight missions, in roughly chronological order based on the start dates of the studies, show the evolution of the method from GINA to the full MATE-CON. Some of these mission analyses were also used to exercise advanced capabilities of the method such as uncertainty and policy analyses. The last three analyses were of generic systems, used to exercise or provide data for advanced studies. Two of these (the entire launch database to date and a notional world launch customer base) allowed

Table 1 Missions analyzed

Mission	Purpose	Configuration	Analyses used	References
Techsat 21	Moving ground target detection	Constellation of identical vehicles	GINA, MMDOSA, uncertainty analysis	38, 60
TPF	Search for Earthlike planets in other solar systems	One large, or four formation-flying vehicles	GINA, MMDOSA	47, 48
Broadband	High bandwidth communication	LEO, MEO, or GEO constellations	GINA, MMDOSA, uncertainty analysis	38, 60
A-TOS	Three in situ ionospheric measurements	Swarm of identical vehicles	Modified GINA with utilities, uncertainty analysis	38, 52, 61
B-TOS	Topside sounding of ionosphere and other missions	Swarm with central mother and small daughters	MATE with MAU, policy impact analysis	32, 37
C-TOS	Design vehicles for mission similar to B-TOS	Same as B-TOS	ICE with virtual collocation, risk chair	40
X-TOS	In situ ionospheric measurements	One or two independent vehicles	MATE-CON	36
Space Tug	Interorbit mass mover	Single or multiple vehicle	Simplified MATE-CON	62, 63
Generic launch customer base	Exercise launch policy model	Many vehicles and functions	Launch policy model	59
Actual launch vehicle histories	Provide data for Bayesian risk model	History of launch success/failure	Bayesian risk model	39
Generic satellite program	Exercise management risk model	One vehicle	SAM management risk model	46

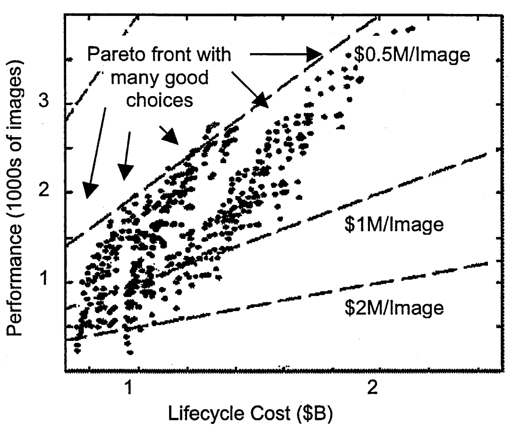

Fig. 6 TPF tradespace.

high-level analyses of risks[39] and policy impacts.[59] The generic satellite program allowed an analysis of management risks that was independent of the technical details of a specific vehicle.[46]

The first three missions were originally analyzed using the GINA process, and illustrate the uses and benefits of tradespace exploration. The terrestrial planet finder (TPF) study provided an easy-to-understand example. When the utility of the candidate systems, reduced to a metric of the number of scientifically useful images taken, was plotted against cost, a clear Pareto front of best designs appears to the upper right (Fig. 6). Along this front, there is a simple trade of performance for money, with the cost/image remaining relatively constant at $0.5 million/image. This is good news for the decision maker, who can decide how much to spend on the system (within a range) without worrying that the system will be a poor value. There is a twist not visible in Fig. 6, however. The Pareto front consists of a wide variety of types of systems, so moving along the front involves changing the architecture of the system, not just tweaking the design. Most smaller design changes drive the system away from the Pareto front. This means that although the decision makers can make a fairly free choice early in the program about what price/performance point they desire, once an architecture is chosen, perturbations in both design and budget will tend to result in a nonoptimal system.[60]

The broadband study provided an excellent example of the need to consider uncertainties when comparing widely disparate systems. The study recapitulated earlier work that showed that medium-Earth-orbit (MEO) or low-Earth-orbit (LEO) systems could provide much lower cost bandwidth than geosynchronous-Earth-orbit (GEO) systems. However, when the uncertainty analysis was included, this low cost was found to be accompanied by huge uncertainties in the results, driven primarily by market uncertainties.[38] This analysis effectively captured the reality of these systems; advanced LEO and MEO systems are currently floundering for lack of market.

The A-TOS study was carried out using a prototype version of the current process.[61] It provided a first experience in the emergent lessons possible with tradespace exploration.[52] Two of the three missions desired for the system proved to be at odds. The best systems as determined by the utility function simply ignored the last mission, doing it only nominally while optimizing for the other ones. Useful hybrid missions were possible, but only at fairly severe cost and performance penalties. This information would be very valuable to an up-front decision maker, who could (for example) drop one of the missions at great cost savings early in the program, rather than as a compromise later. Interestingly, it was precisely this tension between the needs of the missions that allowed the effective use of portfolio theory to minimize the risk of the overall program.[38]

The B-TOS study was the first carried out using formal MAU methods. The user needs involved four different measurements. The system architecture included a swarm of small daughter vehicles surrounding a central mother vehicle. Despite this complexity, the analyses ultimately revealed a simple dominant trade between the number of daughter vehicles and the accuracy of one of the desired measurements. Other factors proved either impractical, for example, a desire for global coverage was economically infeasible, or nondiscriminating, for example, other measurements could be performed well by many designs. The result, shown in Fig. 7, was a Pareto front with only five architectures (out of several thousand) on it. The stair stepping is due to the physics of the problem: Increased performance was only gained by adding complete rings of daughter vehicles around the mother ship. This result presents the decision makers with a straightforward set of choices, weeded out of many confounding considerations. It also provides a clear set of possible downstream choices, for example, dropping vehicles to save money, at a known performance penalty. This clarity made it particularly suitable for a study of mitigating possible policy changes, for example, funding cuts, using the real options method.[37] B-TOS work was done as part of a graduate space systems class. The MATE method was found to provide a good framework for educating students in system architecture issues.[64]

The C-TOS study was a follow on to B-TOS, in which ICE methods were used to design the vehicles for a B-TOS-like system. The requirements were altered by the user between the end of the B-TOS study and the start of the C-TOS effort, resulting in extreme difficulty in tying the performance of the vehicles being designed to the utility of the overall system. This motivated the creation of the MATE chair and the unified MATE-CON process. The C-TOS study was successful in advancing ICE methods through both virtual collocation techniques (CalTech/MIT/Stanford team at all three locations) and in incorporating a risk chair to bring formal reliability methods to the ICE environment.[40]

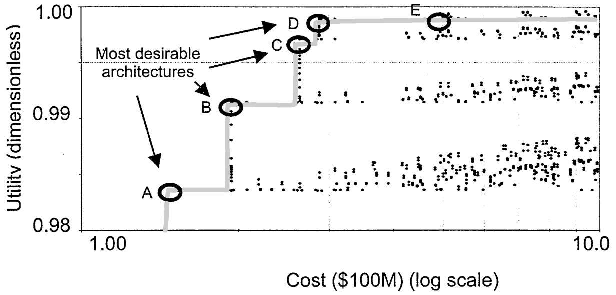

Fig. 7 B-TOS tradespace showing limited selection of Pareto architectures.

The X-TOS study used the full MATE-CON process to first architect, and then design, a small science vehicle, all in less than 15 weeks with parttime student labor. The unified process successfully drove the vehicle design using the utility of the overall system of which the vehicle was a part, in real time, rather than relying on static requirements. Also, the formal MAU interview process was set up and carried out successfully by a web-based software package.[49] This study also demonstrated the extreme robustness of the method because the user utilities were changed fairly drastically in response to the MATE results. The analyses were repeated in a matter of hours, and both sets of utilities were carried forward in case of mind change by the user.

The space tug study was the first use of the process at the request of an external customer. This study, which is currently ongoing, has used a somewhat simplified version of the MATE-CON process. Because the desire was to explore the design space of a basic service (moving mass in orbit) for a variety of possible customers, the utilities were considered parametrically rather than being collected by a formal MAU process. The tradespace exploration revealed fundamental physical limitations to the concept that have prevented past designs from reaching reality, as well as potential sweet spots in the tradespace where potentially useful systems may lie. These sweet spots have been studied lightly, if at all, to date. The tradespace knowledge was used to drive an ICE process to design a family of potentially optimal vehicles.[62,63]

An examination of the risk of failure of most current launch vehicle families was carried out using Bayesian analysis techniques. These techniques allow the launch risk to be quantified based on historical data, even in cases where that data are relatively sparse. The results, given in a companion paper,[39] give both the mean risk of failure for various launch vehicles and the uncertainty about that mean: key data for assessing the risks, redundancy costs, or reliabilities of any launched system.

An assessment of the total customer base for launch services was used to estimate the cost and risk impacts of restrictive government launch policies. Given cost and risk data, and the preferences (risk aversion level) of the decision maker, the effects of restrictive policies on the choice of launch vehicle were assessed. A wide range of satellite masses, orbits, and constellation arrangements was considered. It was found that restrictive launch policies often increase costs and risks. Knowledge of these restrictions ahead of time may allow architectural decisions to mitigate their impact.[59]

Finally, a generic satellite program was analyzed using the SAM framework, to understand the risk impacts of management decisions such as resource allocations and the geographic dispersion of the design team. The analysis showed reduced performance, under a variety of resource constraints, when a major spacecraft system (the payload) was designed remotely. The analysis could also be used to understand the sensitivities of the problem, for example, under what circumstances the decisions to disperse a design team would make sense.[46]

Conclusions

The new design methods and associated research summarized in this paper create the capability to find the best solution(s) to complex aerospace problems quickly and with limited resources. As important, the methods keep designers' visions open to the richness of the tradespace, avoiding premature concentration on a single architecture or design, and allow quantitative consideration of risk and uncertainty earlier in the design process. The methods can also be used to capture issues that are known to lead to poor up-front decisions, such as uncertainty in user needs, lack of information about the performance of new system architectures, technological and programmatic risks, and the impacts of policy changes. The results of the process create greatly enhanced information for go/no-go decisions, architecture and conceptual design selections, and specification of good requirements for further development. They also provide enhanced traceability of up-front decisions and understanding of sensitivities so that downstream processes remain adaptable.

Acknowledgments

This paper summarizes the work of many people, at three universities and several government agencies. The multi-attribute tradespace exploration and conceptual design process was developed and formalized by a large group of graduate students and researchers. Adam Ross and Nate Diller at Massachusetts Institute of Technology deserve special mention for formalizing this effort. The integrated concurrent engineering methods and tools are primarily the work of Joel Sercel and his group at the California Institute of Technology. The Stanford group led by Elisabeth Paté-Cornell contributed risk and uncertainty methods briefly reviewed here. All of these efforts were invaluably aided by the generous contribution of time and effort by personnel from all of the participating universities, several government agencies, and, through the Industrial Advisory Board, most of the major U.S. space contractors.

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