SSPARC

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"SSPARC BOOK" MATERIAL for Lecture 6

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TABLE OF CONTENTS

DEDICATION AND NOTE ON SOURCES

This document is an excerpt of a future book or hyper-book on the MATE-CON method. It is provided for class use as a draft. Suggestions for improvement are welcome, as are warnings of errors or omissions. The notes below apply to the entire work in progress; the work or excepts of it should not be reproduced in any form without these notes.

This document is dedicated to the memory of Joyce Warmkessel, a colleague, mentor, and friend to many in the SSPARC and LAI communities. Many of the core ideas behind this work were originally expressed and developed by her, and she was a key mentor and facilitator to the development of all of this work.

The content of this document was developed by the SSPARC consortium. The primary compilers and codifiers of the MATE-CON method were Lt. Nathan Dillar and Adam Ross, in Master's thesis entitled, respectively, "Utilizing Multiple Attribute Tradespace Exploration with Concurrent Design for Creating Aerospace Systems Requirement," [1] and "Multi-Attribute Tradespace Exploration with Concurrent Design as a Value-Centric Framework for Space System Architecture and Design." [2] Major contributors of the original concepts within the method, and/or complimentary methods and tools, include our SSPARC faculty and staff colleagues Elisabeth Paté-Cornell of Stanford University, Joel Sercel and Fred Cullick of Cal Tech, and Amar Gupta of MIT, post-doctoral researcher Bill Kaliardos, and graduate students Jimmy Benjamin, Jason Derleth, Bobak Ferdowsi, Dave Ferris, Russ Garber, Andre Girerd, Seth Guikema, Cyrus Jilla, Chris Roberts, Satwik Seshasai, Nirav Shah, Todd Shuman, Tim Spaulding, Dave Stagney, Dan Thunnissen, Myles Walton, Annalisa Wiegel, and Brandon Wood, along with their advisors and committees. Many other students, staff, and undergraduate researchers also contributed. Bill Borer, Kevin Ray, and John Ballenthin of the Air Force Research Laboratory, Steve Wall of NASA JPL, and Pete Hendrickson of the Department of Defense aided with the development of the method and the development of the case studies. SSPARC research work has been supported by an active group of industry practitioners, through both an Industrial Advisory Board (IAB) and on-site implementation activities.

The text of this manual is built on SSPARC research and member documents. Much of its contents are excerpts, modifications, or paraphrases of published or unpublished work done under SSPARC sponsorship. Every effort has been made to correctly attribute all contributions. Word-for-word excerpts are identified with quotes or indented, with citations. Many other excerpts have been edited to varying degrees and are integrated into the text for clarity. Their sources are cited in the text or in endnotes. Any omissions or errors of attribution should be brought to the authors' immediate attention for correction.

10.INTEGRATED CONCURRENT ENGINEERING (ICE)

Once the trade space is explored, an architecture or architectures can be selected. This selection may be the optimum architecture as determined by the analysis, i.e. 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 trade space. Once an architecture has been selected, rapid development of a design or set of vehicle designs may be done using modern rapid preliminary design methods.

Architecture vs. Design

The definition of what is "architecture" and what is "design" becomes important here. We have described MATE as a tool for selecting *architectures*, and ICE as a tool for rapidly developing *designs*. What is the difference? The formal definitions of the terms are not very helpful:[3]

> Design: (v) to conceive and plan out in the mind; to devise for a specific function or end; to make a drawing, pattern, or sketch of; draw the plans for; (n) the arrangement of elements or details in a product or work of art
>
> Architecture (n): formation or construction as or as if as the result of conscious act; a unifying or coherent form or structure; the manner in which the components of a computer or computer system are organized and integrated

Both are mental processes, or the results of such processes; both involve arranging parts. We will key on the differences. Architecture involves "unifying structure", while design involves the actual drawings and plans. The difference is one of level of detail; the definitions must therefore depend on the level of detail of the problem one is working on.

For the purposes of this work, architectural decisions can be characterized by:
- High "level", i.e. they are among the few most important decisions that will define the system
- High impact and interdependencies; they will have effects on many elements of the system
- Discrete and/or discontinuous choices
- Effects on user utility that must be considered at the global level (e.g .the MAU)
- Low initial knowledge of how choices will affect utilities, and whether solutions are feasible

while design decisions can be characterized by
- Lower level, i.e. there may be a great many of them
- Lower impact and interdependencies; they will mostly have local effects, and their global effects will be generic (e.g. by affecting system mass, but not the functional performance of many other system elements)
- Continuous or semi-continuous choices

- Effects that can be considered locally (e.g. by meeting constraint requirements and/or optimizing SAUs)
- Higher initial knowledge of sensitivities and feasibilities

These characterizations must be made in the context of the problem being studied. For a national transportation system, architectural decisions include how many airports to build and whether to subsidize high-speed rail; the body structures used on cars is a design detail. For the builders of automobiles, and even families of automobiles, the choice between uni-body and frame construction is a key architectural decision, affecting everything else about the vehicles. Likewise, for a distributed network of space vehicles, the number of vehicles, their orbits, and the distribution of functions among them are the likely architectural decisions; the design of the individual satellites is most likely a set of design details. If the system is a single vehicle, as is the case in our examples, then decisions that will affect the entire vehicle (e.g. what power source, propulsion type, or total fuel load to use) will likely be considered architectural, while the sizing and vendor selection for these systems become the design details of interest.

10.1. ICE Methods[4]

The most widespread advanced design method in the aerospace industry goes by several names. Here, it will be referred to as Integrated Concurrent Engineering (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. The 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.

In ICE, a rapid design is performed by an interdisciplinary team of human specialists and their computer tools. The tools communicate through a common database during design *sessions,* with the humans in physical or at least virtual co-location. Figure 10-1 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 (e.g. updates a CAD model), makes major design decisions that are input to the tool (e.g. changes the propulsion type), and provides common sense and wisdom unavailable to automated methods (e.g. breaks non-convergent behavior in the iterations). The combination of the human and the tended tool is referred to as a *chair*. The tools perform rote calculation (e.g. rough sizing of solar panels), pass information, and sum up system characteristics (e.g. 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.

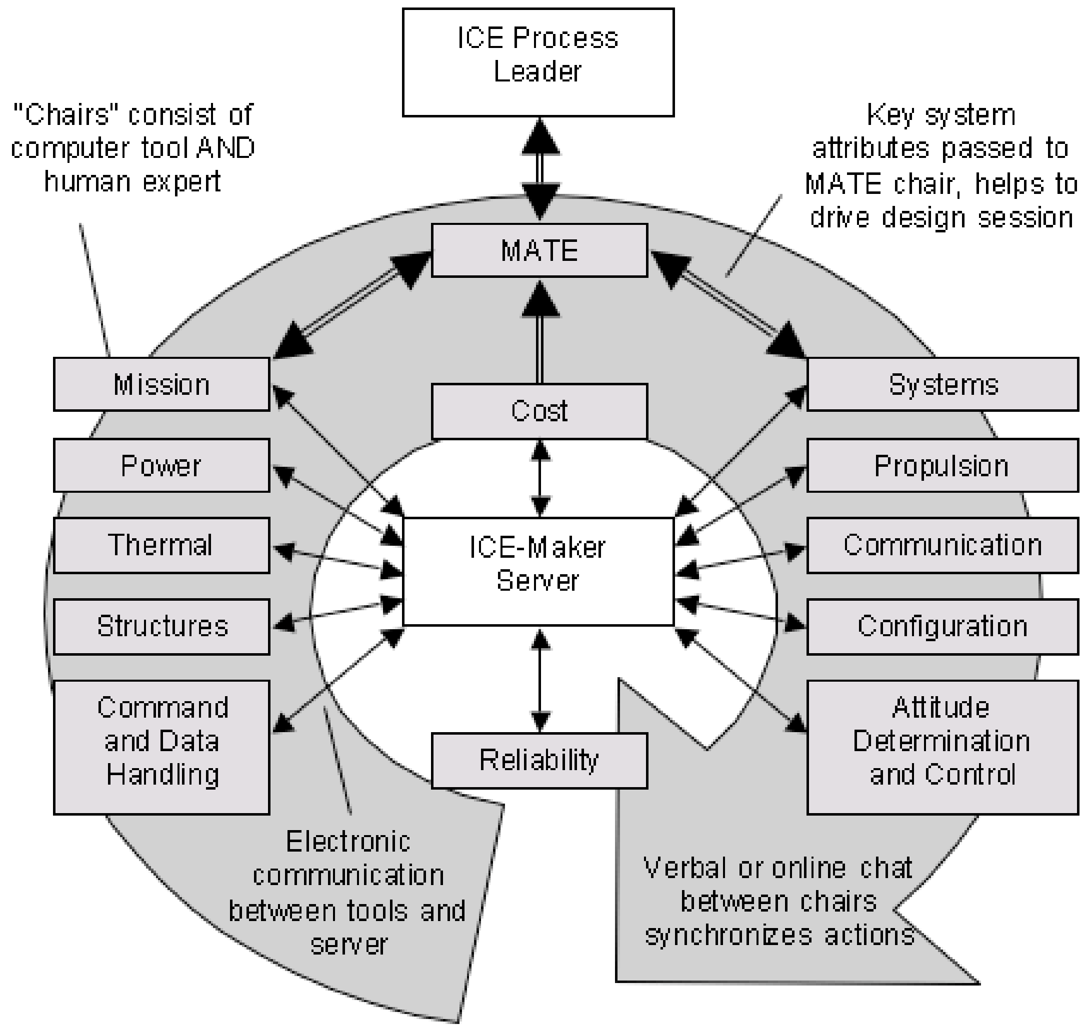

Figure 10-1. Overview of the ICE process.

ICE design sessions typically last several hours and usually address one major trade per design session. A senior team member, or "facilitator," leads the design sessions and helps to resolve disconnects between the clients. The design sessions are iterative, with each subsystem sending and receiving many times in order for the point design to converge. Although it has recently become possible to automate this iterative process, human operation of the client stations is almost always preferred. The human element is actually key to the method. The human expert can guide the iterations, catching bugs, nonsensical answers, divergence, and other pathologies that complex computational systems are prone to. More importantly, the experts make major discontinuous design decisions, or go "outside the box" by stretching parameter ranges or even adding new computational capabilities, making the ICE method a true design tool, not just a non-linear equation solver. The key role of the humans in the loop is developed in depth, in the context of the Aerospace Corp. implementation of an ICE-like process, in Neff and Presley.[5]

The session leader steers the iteration and convergence of the design session 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 his or her fingertips. The MATE chair can quantitatively assess the progress of the design not just towards meeting requirements, but also towards maximizing the overall utility of the system containing the design. He or she can also help the user/customer translate needs into design changes, and thus steer the design changes towards "sweet spots" in the trade space. 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.

Modeling

The sheets mentioned above are computational models of a subsystem of the system to be designed. These can take many forms. In one limit the sheet is simply an interface for the expertise of the human expert. In the opposite extreme, the sheet may contain complex modeling, analysis, and local optimization software. It is important to find the appropriate level of fidelity for these models, so that effort is not wasted on excessive detail, but conversely all important effects are modeled. To keep the modeling effort tractable, it is often necessary to trade detail for scope. An instrument or subcomponent could actually go through detailed design and analysis and be ready to build at the end of the session. A large system can only be analyzed at the conceptual design level. Aguilar and Dowdy[6] explore in depth the issue of appropriate fidelity, and its trade with scope, in their paper.

Typically, the models will include spreadsheets or routines written in general purpose computational engines such as MATLAB.®[7] Specialized Commercial off-the-shelf (COTS) software may also be used for some sheets; e.g. STK®[8] for orbital calculations, or computer aided design (CAD) software for layout and geometry. The breakdown of the models into individual sheets typically follows the functional breakdown of the system. Note in Figure 10-1 there are sheets for each of the functional subsystems of the satellite, as well as higher-level functions such as mission planning and systems integration. This is not the only way to break the problem down, but it is often the best. Current modeling techniques are oriented towards such breakdown, and many subsystem models are readily available. Chapters 10 and 11 of Space Mission Analysis and Design (SMAD) are the classic source for space vehicle subsystem models.[9]

Assuming the appropriate models are available, integrating the models into the data base becomes the hardest task in the preparation of the ICE capability. The basic idea is that any data used by more than one sheet be stored on the database, and that all data on the database have one and only one creator. The ICEMaker software from Caltech's Laboratory for Spacecraft and Mission Design (http://www.lsmd.caltech.edu/) is a useful tool for maintaining the database, providing communication between it and the sheets, and tracking the relationship between the sheets and the data elements. Parkin et al. have documented ICEMaker's capability.[10]

The process of determining the elements in the database and which sheet shall provide them, and establishing simple housekeeping such as variable naming conventions and units is very important. N-squared or Design Structure Matrix (DSM)[11] analysis can help sort out the relationships between the modules, although it is usually not possible to track individual variables as there are too many of them. An analysis of a typical ICE session using DSM techniques is contained in a presentation by McManus.[12]

The Design Room

Although the models communicate electronically and hence are location independent, the communication between the human experts is extremely important. Figure 10-1 shows the sheets communicating discretely to the ICEMaker server, but also shows a continuous flow of information between the humans in the loop. Experience has shown this is greatly accentuated by having all the participants in the same room, dedicating their time solely to the design at hand. Rooms suitable for such interactions, often dubbed "Design Rooms" are often built specially for this purpose. Nolet[13] documented his involvement in a project to design and build such a room at MIT, while Reynerson[14] recounts an industry application, and Mapar *et al.*[15] a government one.

It should be emphasized, however, that the design room itself is *not* the critical tool. If computational resources are tight, it can be an enabler of the computation and information sharing structure of ICE. More importantly, it is an enabler of the human dynamics of the ICE process, collecting all the participants in one place away from other work and distractions. However, with reasonable network capability, any conference or office environment can be used as a "design room." Virtual design rooms can also be created by links to remote sites, although experience indicates that this cuts substantially into the efficiency of the process, mostly because it impedes the human interactions necessary to make the ICE process work.

10.2. X-TOS ICE Modeling Example[16]

Through the use of a software tool that interacts with Microsoft Excel, called ICEMaker, the MATE-CON process is translated into a preliminary design tool. Each spacecraft subsystem specialist is responsible for an Excel workbook that interfaces with the other subsystem workbooks through the ICEMaker software. Each workbook has an Outputs worksheet and an Inputs worksheet. The subsystems are responsible for publishing their respective Outputs to the ICEMaker server. Publishing the Outputs to the server makes the variables available to all the subsystems, and in turn the subsystems request the published variables through their Inputs worksheet. Once an output on a single sheet is changed, it is an iterative process of publishing and requesting of all the subsystems to converge on a single design.

The arrangement of the specialists and their tools is shown in Figure 10-2. The computer sheets communicated through the ICEMaker software, while the human specialists communicated verbally and by projecting key results on the two video screens in the design room. The individual models are defined in detail in the X-TOS report. Each subsystem model is characterized in terms of its inputs, outputs, and assumptions. Each model, when coded, was subjected to some independent testing to assure appropriate fidelity and verify basic functionality; these are also described.

While all the subsystems seem to operate as direct feed-through models, the aggregate input/output dependencies of the ICE subsystems can create semi-implicit loops. As mentioned earlier, there is a strong interdependency among spacecraft subsystems and their Excel workbooks. Therefore, the publishing of a changed Output must propagate through all the subsystems several times before a design is said to have converged. The term convergence, in this context, refers to the stabilization of all propagating parameters to within five percent of the mean value in three consecutive updates.

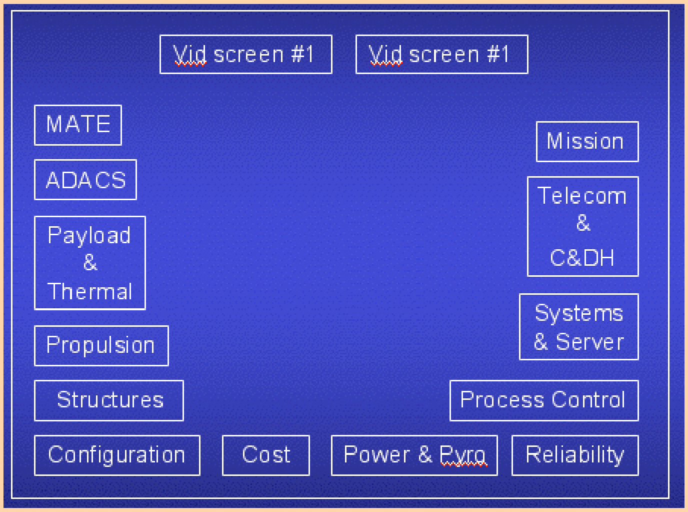

Figure 10-2 X-TOS ICE session set up.

10.3. *Spacetug Modeling Example*[17]

Ten ICEMaker modules were developed, with each module representing a different spacecraft subsystem or discipline. The six main modules were Mission, Systems, Propulsion, Link, Configuration, and Power. Each sheet performed all the calculations necessary to design its specific subsystem based on the inputs provided to it. The models were developed using first principles whenever possible, but rules-of-thumb based on current technology were also used to reduce complexity and coding time. These sheets were electronically linked through the ICEMaker server and interacted throughout a design session sharing information and updating each other of changes to the design made by the individual chairs. The ICEMaker server works primarily with Microsoft Excel® spreadsheets. This work also made innovative use of a new software tool (Oculus CO®) that was used to link routines written in Mathworks Matlab® and a parametric solid geometry model done in Solidworks® to the spreadsheets.

Several key simplifying assumptions were made. First, the sheets were only required to handle one vehicle per design session. The Mating and Payload subsystems were treated as “black boxes” with their specifications (mass, power, volume) fixed during the pre-processing segment by the Architecture chair. Software, control systems, and operations were not considered beyond a costing rule of thumb. Finally, a few aspects of the vehicle design were handled by “dummy chairs” at a low level of model complexity. Structures, Thermal, Attitude Control, and Command and Data Handling historically have a low impact on overall vehicle design at this level of analysis and can be handled adequately by rules of thumb. These dummy chairs can easily be expanded for future work without changing the overall architecture if desired.

A summary of the ICE model and the main module interactions are illustrated in Figure 10-3.

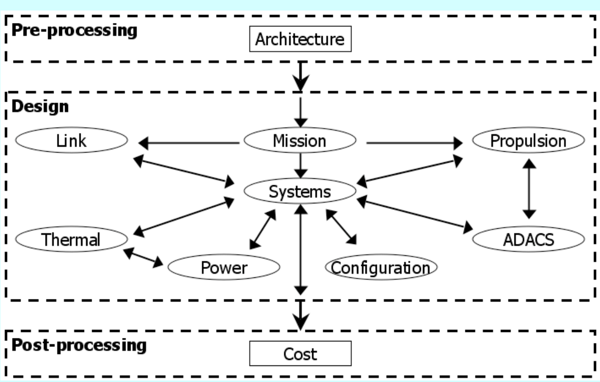

Figure 10-3 Spacetug ICE model components and interactions

The following is a summary of the six main ICEMaker modules including their major inputs and outputs:

- Mission: determines delta-V requirements and other high-level specifications
    - Inputs – target orbits, tasks, timeline
    - Outputs – orbital elements, mission sequence, delta-Vs, lifetime, mission duration
- Propulsion: sizes the propulsion subsystem, determines fuel requirements
    - Inputs – initial dry mass, delta Vs, thrust requirements, target satellite masses, refueling requirements
    - Outputs – fuel mass and volume, propulsion system type with mass and power requirements, wet mass of Space Tug
- Power: sizes the power subsystem
    - Inputs – power requirements (average and peak) from each subsystem by mode, orbit periods and eclipse length by phase
    - Outputs – solar array mass and area, battery and power management mass, temperature constraints
- Link: sizes the telecommunications subsystem, calculates mission link budget
    - Inputs – transmit station location, Space Tug orbit parameters, uplink and downlink margins, total data rate, mode durations
    - Outputs – antenna type and dimensions, power requirements by mode, telecomm subsystem mass
- Configuration: produces a visual representation of the vehicle
    - Inputs – system hardware dimensions and mass, fuel volume
    - Outputs – inertia tensor, surface areas, CAD model
- Systems: maintains summaries of all major specifications (mass, power, etc.)
    - Inputs – mass by subsystem, power consumption by mode, total delta V, overall dimensions
    - Outputs – total wet and dry mass by mode, link budget, cost estimate, contingencies, margins, mission summary

10.4. Uses of ICE and related methods[18]

New design methods are now frequently used in government and quasi-government settings (e.g. NASA, JPL, and the Aerospace Corp), and are also starting to make inroads into industry. (See, for example, http://NewDesignParadigms.jpl.nasa.gov/ and http://nsd2001.jpl.nasa.gov/). The Jet Propulsion Laboratory's Advanced Projects Design Team (Team X) uses this method for preliminary space system design.[19] The method as used by Team X is particularly suited to the exploration of novel missions using simple vehicles, as documented by Owens.[20] 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.[21,22] The Aerospace Corporation has also done extensive work of this type, referring to their efforts as the Concept Design Center (CDC).[23] The CDC has five teams, spanning a wide range of analysis types, from system architecture to electro-optical payload design. The teams trade scope for level of detail to keep the problems examined tractable.[6] The CDC experience has emphasized the role of human engineers and their efficient, tool-enabled interaction as the key to the ICE method.[5] ICE techniques are also in use at the European Space Agency (ESA) for preliminary assessment of space science missions.[24,25] These techniques have seen some use in industry, with SAAB, TRW, Boeing, Ball Aerospace, and probably others all using variants on the ICE environment.[13,14] 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.[26]

ICE methods require complex, multi-disciplinary models of the systems of interest. Multi-disciplinary modeling 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 centers at Langley,[27] Goddard[15] and Ames,[28] focusing on the analysis of advanced launch and reentry vehicles. These works have explored alternatives or complements to the ICE method for solving multi-disciplinary problems.

The exploration of architectures has been carried out using many of the above 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. As a general rule, MATE should be used for large tradespaces with large uncertainties, and ICE used when detail is desired for a small number of essentially "point" designs.

10.5. X-TOS Example Result

Figure 10-4 shows the converged X-TOS design. The body-mounted solar cells are shown transparent so internal details (sensors, fuel tanks, thrusters, etc.) are shown. The mass breakdown of the vehicle is shown in Figure 10-5. Most of these components are specified to the level of commercially available components.

The performance of the ICE designs was evaluated using the MATE MAU. The final design had a utility of 0.705, which was better than any of the designs considered in the MATE study. This was because the detailed design was iterated to stretch the tradespace constraints (see the previous section). The governing trade between orbit altitude, vehicle lifetime, and vehicle fuel mass was optimized in more detail by the detailed ICE models than by the simple, and coarsely explored, MATE models.

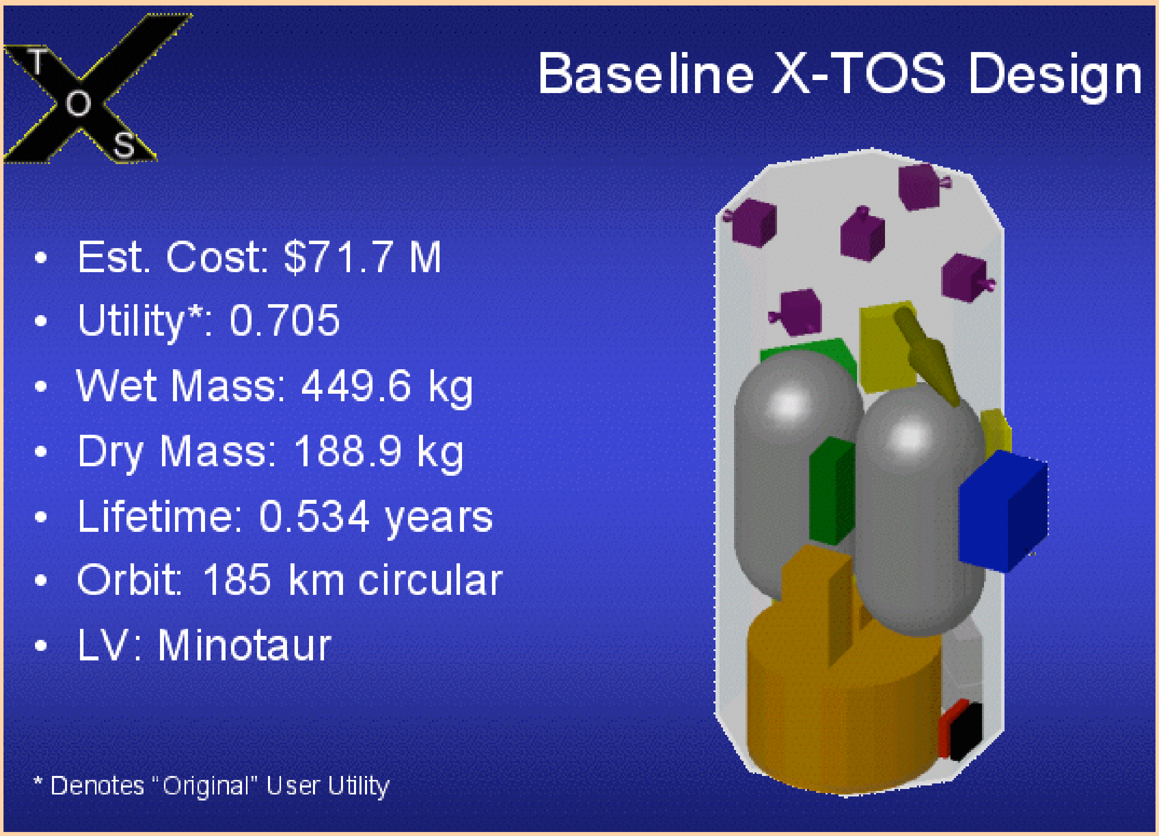

Figure 10-4 X-TOS ICE design

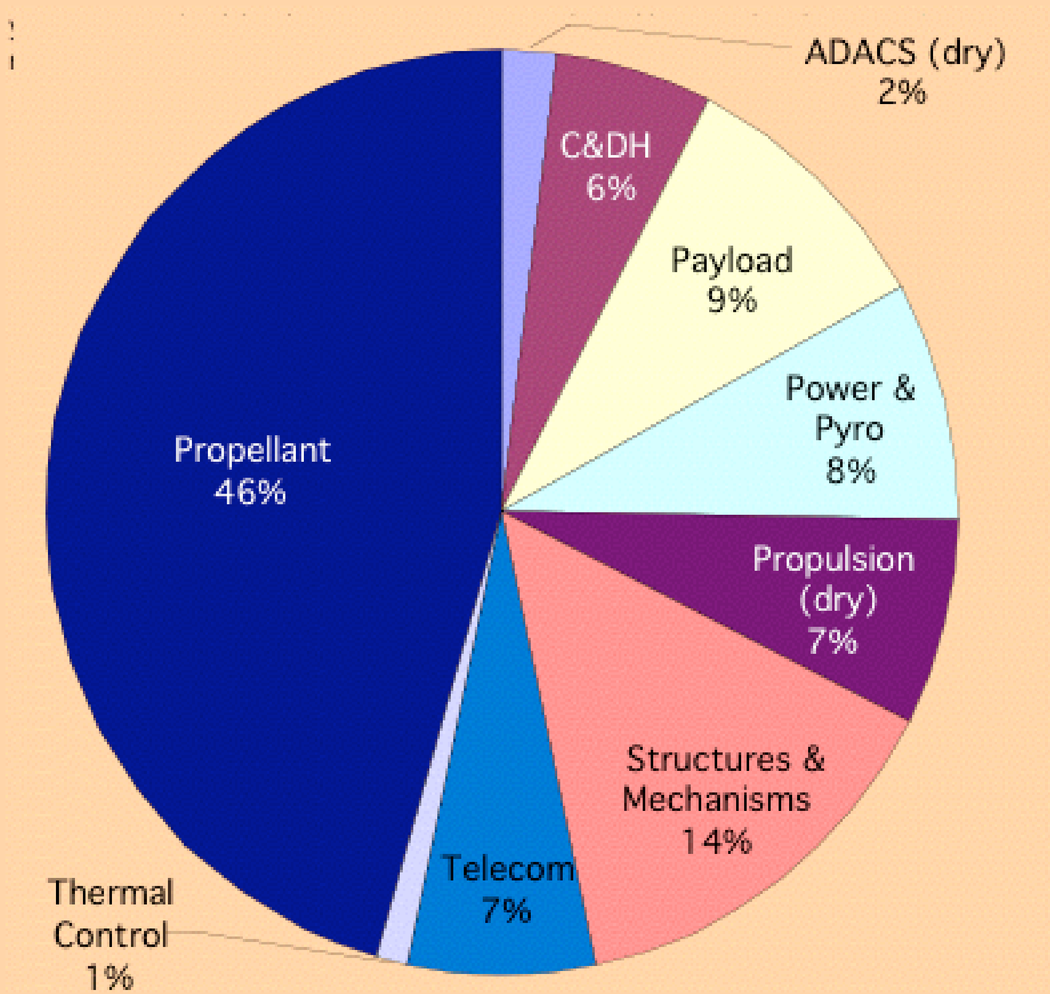

Figure 10-5 X-TOS ICE design mass breakdown

10.6. Space Tug Example Result[17]

Two main mission architectures were studied using the Space Tug ICE model: a GEO Tug and a GEO/LEO Tender. The GEO Tug is parked in LEO and waits for a single target mission, nominally a cooperative target of up to 2000 kg stranded in GEO transfer orbit. It then rendezvous with the target and inserts it into a GEO orbit, and if possible returns itself to LEO. The GEO/LEO Tender is parked in a populated, target-rich orbit and performs multiple missions during its lifetime. Possible missions include moving or disposing of targets near its original parking orbit. Both of these architectures assume a 300kg / 1kW mating device.

Tugs were designed for both one-way and round-trip missions using three different propulsion systems: bipropellant, cryogenic, and electric. The bipropellant and cryogenic round-trip missions could not close their delta-V budgets, leaving four feasible designs. Table 10-1 and Figure 10-6 through Figure 10-9 summarize the GEO Tug designs. The masses and power figures are taken from the ICE session results. The delta-V, utility, and cost numbers are taken from the MATE analyses to allow direct comparison to the tradespace results. The ICE system created considerably more design detail than shown in Table 10-1. Mass, power, and link budgets were created—see Figure 10-9 for a typical result. The physical sizes and layouts of major components were also determined and linked to a parametric solid model. The view in Figure 10-7 shows internal layout.

Table 10-1 GEO Tug Design Summary

Design	Dry Mass (kg)	Wet Mass (kg)	Power (w)	Delta-V (km/s)	Total Utility	Cost (M$)
Biprop one-way	300	11700	1200	5.5	0.65	510
Cryo one-way	1100	6200	1200	7.1	0.69	310
Electric one-way	700	1000	3600	9.8	0.65	130
Electric cruiser	700	1100	3600	12.6	0.69	140
GEO bi-prop tender	670	2100	1200	3.4	0.52	140
LEO 1 tender	680	1400	1500	2.1	0.40	130
LEO 2 tender	670	1200	1500	1.7	0.36	120
LEO 3 tender	630	1000	1500	1.4	0.32	110
LEO 4 tender	720	1800	1500	2.7	0.45	140
LEO 4a tender	970	4100	1500	4.2	0.60	230

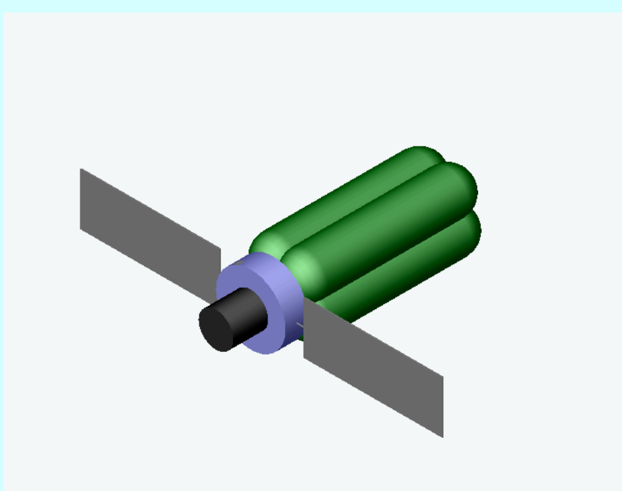

Figure 10-6 Cryo one-way tug, showing extremely large fuel tanks; Bi-prop tug appears similar

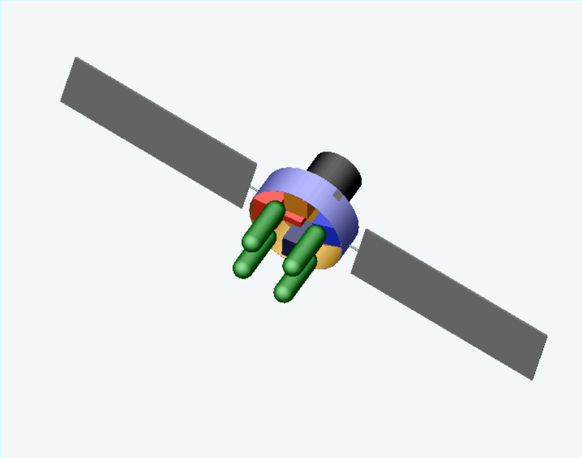

Figure 10-7 Electric Cruiser (GEO round-trip tug)

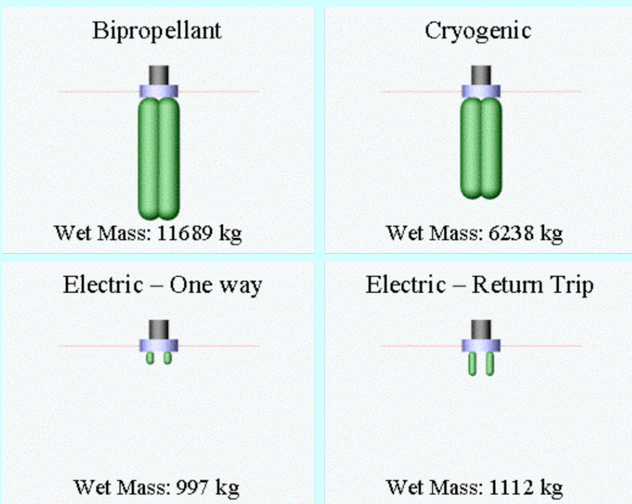

Figure 10-8 Comparison of all GEO Tug designs

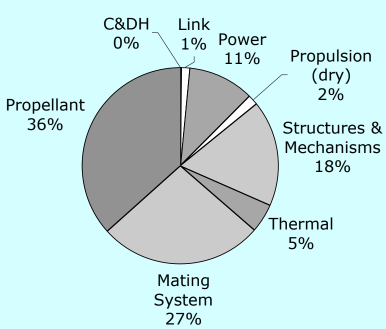

Figure 10-9 Mass breakdown of Electric Cruiser design

The bi-prop one-way tug is very large and therefore very expensive. It is also very sensitive to changes in any of the design assumptions; any increase in dry mass causes a very large increase in fuel required. There is some danger that such a design would not “close” (i.e. the required fuel mass would become infinite) if the dry mass fraction or delta-V requirements were greater than anticipated. The best that can be said is that such a vehicle could fill a niche for missions where a large payload must be moved quickly using existing technology. The cryo one-way tug is significantly lighter than the biprop tug, but is almost as large due to low fuel density. It would have a very limited life on-orbit due to the need to keep the fuel cold. It is less sensitive to mass fractions and other assumptions, but still cannot make a round trip to GEO.

The electric one-way and round-trip tugs seem to be practical, versatile designs with reasonable sizes and costs. The electric designs do have the drawback of slow transit time, but they appear to be well suited for missions where speed is not essential. The design impact of the large total power requirement can be minimized by managing power use. Not running the manipulator and the full thruster set all at once, and trading thruster power (and hence impulse) vs. solar panel size results in panels not much bigger than those required for the chemical propulsion designs.

A family of tender missions was developed based on research of target satellite population densities. All of the tender missions use storable bipropellant systems for reduced cost and complexity. Each tender lives in a heavily populated orbit and is capable of performing five or more missions involving moving or disposing of satellites near that orbit. The result of the tender study was a line of similar vehicles with different fuel loads depending on the delta V requirements of the desired orbit. These designs are discussed in a companion paper.[29]

It is interesting to compare the designs in Table 10-1, developed by a detailed ICE analysis, and the results in **Error! Reference source not found.**, developed using the much rougher MATE analysis. Power is not considered by the MATE analysis. All the other values are very close, with the only large disagreements being in the masses of the chemical-fueled GEO tugs. In these vehicles, the very large fuel tanks were outside the range of the design assumptions of the MATE model.

10.7. MATE-CON: Connecting the ICE Point Designs to the MATE Tradespace

The Multi-Attribute Tradespace Exploration (MATE) process generates a series of satellite architectures and their respective user utilities. In the Concurrent Engineering (ICE) portion of the design process, a point design of the chosen architecture is created using the ICEMaker software as a baseline design with a utility value known *a priori*. After the baseline design converges, design trades can be conducted in an effort to increase the user utility. The altered point design can be run back through the utility function to generate a utility value for the new design. Further design trades can then be carried out in an attempt to provide better utility, and hence provide the user with a better product.

In the X-TOS study, a MATE chair kept the utility function on call, so that every design iteration could be checked to assure that utility was increasing. The result, as noted, was a point design that had utility better than any of the points on the original tradespace.

In the SPACETUG study, there was no formal MATE chair connected to the ICEMaker server. Instead, as individual point designs converged, they were plotted onto the tradespace, and the results used to guide further iterations of ICE. Figure 10-10 shows the GEO tug designs plotted on the tradespace explored in the previous section. The comparison confirms the conclusions reached in the individual studies: the chemical propulsion tugs are up against a rocket-equation wall, while the electric propulsion tug is an optimum design (for the presumed user set).

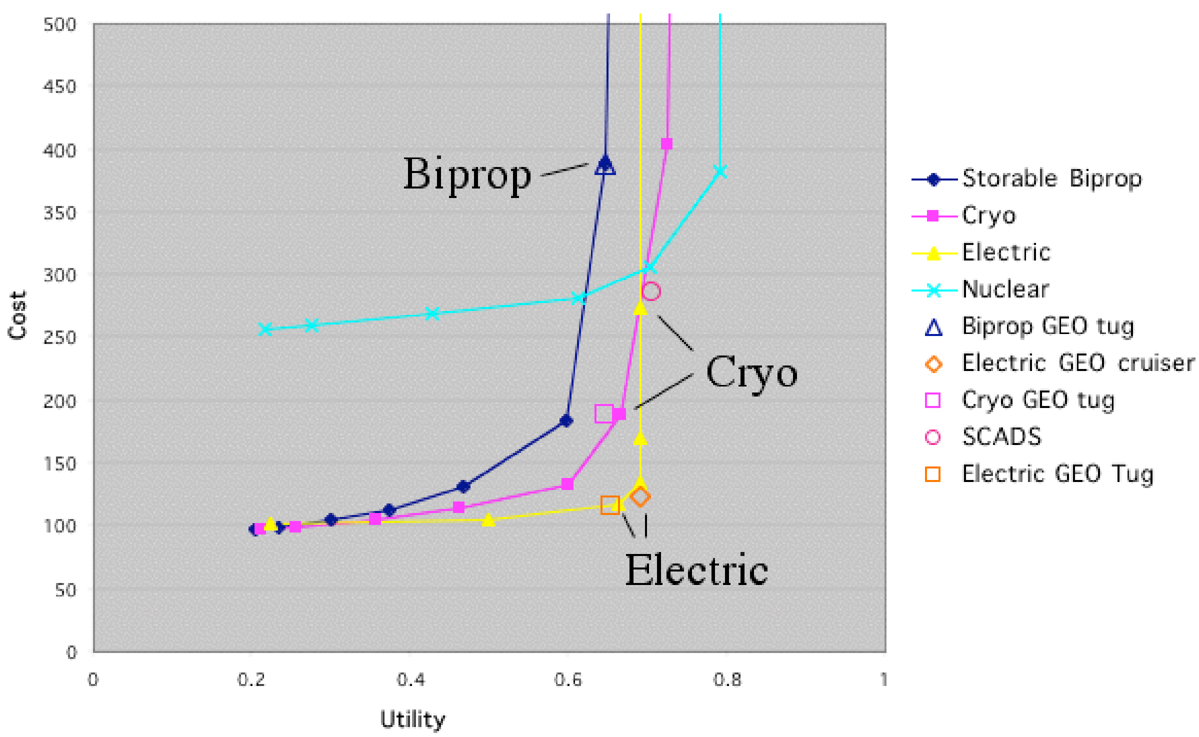

Figure 10-10 Spacetug GEO tug designs plotted on MATE tradespace

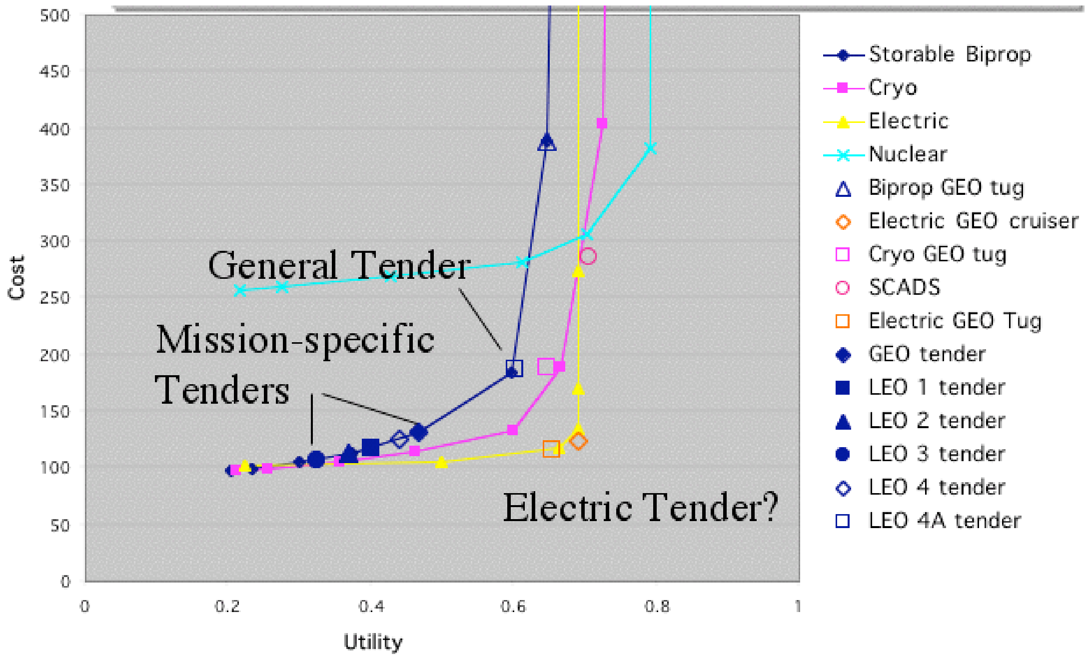

Figure 10-11 Spacetug tender designs plotted on MATE tradespace

Figure 10-11 shows the tender designs on the same tradespace. Note that many of them are not on the Pareto front, as the assumption of a bi-propellant chemical propulsion system takes them away from it. On the other hand, they are not very far from the front, and it could be argued that the advantage of having a family of similar vehicles could make up for any non-optimality of individual vehicles. Based on the mission specific designs plotted on the tradespace, a 'general tender", which could do any of the proposed tender missions, was proposed and designed. It sits on the knee of the bi-propellant tradespace curve—it is the largest practical bi-propellant vehicle. It represents the extreme that can be achieved within the proposed family; any greater capabilities would have to be achieved by, for example, switching propulsion systems, resulting in a hypothetical electric tender (conveniently, already designed during the tug studies).

These examples illustrate a general principle: the MATE and ICE analyses are highly synergistic. The MATE analyses can guide ICE sessions to achieve not only optimal point designs, but point designs that exceed requirements by achieving higher user utility (as happened in the X-TOS project). The MATE analysis can also capture trends in the development of multiple point designs, suggesting an architecture for a product family, and exploring its limits and what happens when these limits are reached.

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