Abstract for an Invited Paper in a session tentatively titled "Systems Engineering in the Real World" at the international Federation of Operations Research Societies to be held in 24-27 October, 1995 in Saint Louis, Missouri.

Reengineering the JPL Spacecraft Design Process

Clark Briggs, Member of Technical Staff, Jet Propulsion Laboratory

JPL has embarked on a reengineering journey that involves significant change. This is necessitated by a dramatic change in the business climate away from a period of stable growth based upon large space missions with 10 year development cycles. Now, missions must cost up to an order of magnitude less and have cycle times of only a few years. We are changing from a requirements driven design philosophy where getting the job done costs what it costs, to a cost-capped practice known as Design to Cost.

Over the last two years, JPL has constructed two new facilities that are central to implementing the newly reengineered spacecraft design process. The night System Testbed is a institutional capability to dramatically shorten development times through rapid prototyping of the mission end-to-end data system. This includes the spacecraft avionics, ground data system, and science processing. New projects find a working prototype spacecraft in the Testbed which can rapidly be modified to support critical design questions involving architecture, mission operations, or new technology. The Testbed can be useful in proposals, advanced studies, conceptual design, system integration, and mission operations.

The Project Design Center is the other institutional capability and focuses on rapid project design. The intention is to supplement the excellent subsystem and detailed design capabilities within the Technical Divisions with a systems-level design process. System design trades are evaluated in terms of life cycle cost in addition to traditional performance metrics such as mass, power, accuracy and science data return. The new, smaller projects are to be built by multidisciplinary teams who meet in the Project Design Center using new tools that support real time decision making and a broader exploration of the design space.

At JPL, concurrent engineering is replacing sequential design. In the past, the mission trajectory and science opportunity were first identified. Then the spacecraft was designed and built to achieve the best possible performance and reliability. Finally, the flight operations and science data system were devised to fly the mission. This frequently resulted in spacecraft that were difficult to operate or required cumbersome and labor intensive sequence preparation. Today, we are concurrently designing all three elements of the mission. This enables trades that have the potential to dramatically reduce total project costs. For example, on board capabilities in the avionics system can be traded against light weight operations plans.

We have been unable to find the appropriate tools to support this new process of system-level trade space exploration and have an ongoing prototyping activity involving several new tools. These are individually appropriate for different design phases and mission types, but all support multidisciplinary design and analysis. The nature of these tools, their approach to solving complex system engineering problems, and our difficulty in implementing them in a working environment will be discussed.

The new design process specifically emphasizes optimization of multiple performance objectives. Traditional objectives, such as minimizing mass and power, have been augmented with measures of science performance and cost. To emphasize our seriousness about living within cost constraints, cost has been elevated to the number one objective. In practice, this means every trial design has a cost, every subsystem produces cost along with performance estimates, and every trade looks first to reduce costs.

The most successful system-level tool currently in use is the Project Trades Model (PTM). The PTM supports a very manual form of optimization where the design team proposes design changes and the model predicts the cost, mass and technical performance. These are displayed as deltas along with the current baseline design and the team decides to accept them or evaluate a different alternative. Sometimes proposed trades require modification to the existing models. In preparation for these trade meetings, members of the design team must extend the model as homework.

Another system-level tool in development is the Multidisciplinary Integrated Design Assistant for Spacecraft (MIDAS). MIDAS build upon the distributed computing technology that has come from the High Performance Computing initiative and analyzes proposed designs by stringing together tool executions on distributed machines. The analysis process is captured in a flow graph where tools are nodes and data flows down arcs. MIDAS can collect input data for a tool, launch the tool on the appropriate system, and collect the results. The graph of tools and data flows that represent the design process is automatically traversed and executed by MIDAS.

More complex performance objectives are being formulated as the tools come up to speed. For example, probability distributions associated with subsystem costs can be used to identify ranges of outcomes and can play a key part in constructing a project's approach to risk management. Another area is the quantification of potential science return. One project has used simply the accumulated amount of data collected. This might be extended to account for quality or captured opportunities. Interest has been expressed in reflecting customer and sponsor values in the trade process, but this has not yet been implemented in the tools.

More fundamental problems lie in other issues. Reengineering is a traumatic undertaking. JPL is experiencing many of the typical problems associated with change, from denial of urgency, to protection of traditional interests, to resistance from middle management. Issues to be discussed include:

Changing Behaviors. Our new process is about getting people to behave differently. Teams must take responsibility for their own project. Decisions are to be made by consensus. Optimizing the mission is higher priority than optimizing the subsystem. Openness, discussion, trades and understanding replace resource allocations, interface control documents, and requirements tracking. Each team member must accurately cost each design option.

Keeping the Designer in the Loop. A great emphasis has been placed on using computer aided design tools to improve the efficiency of the design process. We very much need to move analysis farther forward in time toward the proposal effort. Yet the engineers are needed to provide the knowledge and participate in designing. We arc really struggling with what role, using which tool, in what time phase should the human be in the loop and what can be left to automation. What acti vities constitute "capturing the design"? Automated tools need to have design rules embedded in them so that, when valid ranges of operation are exceeded, they issue messages such as "GO get a human."

Leadership styles. System engineering is very much an art. Leading multidisciplinary teams through complex problems with tight mission constraints, tight cost caps and short timelines in a high pressure environment is very much a matter of individual style. I believe the four prototype system design tools in the JPL PDC reflect the different leadership and problem solving styles of their principle authors. Other style issues arc present. JPL has traditionally depended on a strong project leader who can make the tough decision and reap the rewards of potential success. Teams require a different style leader, one that facilitates, builds consensus and seeks to maintain ownership with the team. Such leaders must resist the urge to dictate, make choices, or break tics and instead, coerce the team into deciding for themselves.

Optimization. Certain branches of systems engineering and a good portion of operations research rests upon mathematical modeling and solution of optimization problems. At onc extreme, machines can spend large numbers of CPU cycles and find the optimum design. At the other end of the spectrum, it is difficult to pose a solvable problem and a great deal to intuition, experience and luck arc needed. In our early stage of development, most of our population believes that numerical optimization is many years away, if it is even possible. Our problems are believed to be sufficiently complex as to be unmodelable for optimization purposes.

These issues, and others, absorb a lot of our energy. Sharing them with the community can be good for us, and good for others struggling with similar real world issues. In the paper, I will try to elaborate on what seems to work and what doesn't.

Acknowledgment

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Spat.c Administration.