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ABSTRACT

In June of 1994, the Jet Propulsion Laboratory (JPL) opened the Project Design Center (PDC) to develop and implement new tools and processes for engineering of space systems. This paper reports the status of two concurrent engineering teams resident in the PDC (team-X for space mission design and team-I for space instrument design). It discusses the nature of the process changes needed to implement *real time* concurrent engineering of systems and the resulting improvements in cost, schedule and quality. The PDC has demonstrated that real time concurrent design, enabled by new information technology, promotes very efficient production and exchange of information within design teams.

INTRODUCTION

The purposes of this paper are to present the techniques employed at the Jet Propulsion Laboratory (JPL) for concurrent engineering of aerospace systems and to discuss lessons learned from implementation of concurrent engineering teams in the JPL Project Design Center (PDC). As implemented in the PDC, concurrent engineering is defined as the examination of design issues by teams that include all relevant disciplines in *real time* design sessions. The use of real-time design sessions, in which design teams examine design alternatives employing an interconnected, distributed suite of tools constructed to support those design sessions, is unique to JPL's Project Design Center.

JPL opened the Project Design Center (PDC) in June of 1994. The PDC has implemented and supports as customers two resident, standing design teams, or Integrated Product Development Teams (IPTs), one each for the conceptual design of unmanned space missions and space instruments (e.g., space cameras, telescopes and spectrometers). These teams have demonstrated dramatic savings in time and money relative to the traditional process for space systems conceptual design. The principal lesson learned is that improving the productivity of design teams requires improvements to the processes those teams employ and the processes that support those teams, not simply or primarily the introduction and use of 'better' software tools or models.

By reviewing the implementations of team-X and team-I, the paper illustrates how the emergence of modern information systems enables fundamental improvements to the systems engineering process through the use of real time concurrent engineering.

A discussion of tool selection and development for concurrent engineering teams concludes that tools must be tailored to support both the design problems or issues that each team faces and the engineering talent that is resident on the team. This is illustrated by the dissimilarity between the toolsets that have been developed for team-X and team-I. Team-I is similar in most respects to team-X, except that team-I designs space instruments while team-X designs space missions/spacecraft. The differences between these two jobs are sufficient to require quite different tools, including different approaches to tool integration. These differences are further reflected in team processes.

The paper reviews five major process changes that have been successfully implemented in the PDC to improve the productivity of JPL design teams. These process changes are:

1. Use integrated product development teams, as pioneered by Boeing and others
2. Establish 'permanent' design teams, or equivalently, keep teams together through multiple designs or for a sufficient length of time to benefit from learning-on-the-job
3. Investigate design issues/trades in *real-time* design sessions that include all relevant disciplines and their tools and databases
4. Include life-cycle cost as a primary metric, equivalent to mission performance, in the design trade and selection process (referred to as Design-to-Cost) and
5. Organize and fund institutional support for design teams that provides a rich menu of services, including process improvements, software tools, computer support, costing, scheduling and budgeting support. Make these services relevant by adopting a strong

customer service focus. At JPL these services are provided by the Project Design Center.

Given that process change is key to productivity change, the motivation of design teams to adopt different modes of operation must be addressed. The mere existence of integrated design models is not sufficient motivation for a design team to fundamentally alter its mode of operation (process). Simply making integrated models available will not cause teams to function concurrently—they must make this choice explicitly. *If* a team decides to operate concurrently in real time, then it has a need for integrated design models to support that concurrent operation. *Until* it makes this decision integrated design models are an unnecessary, although interesting and potential useful, curiosity to a design team.

THE PROJECT DESIGN CENTER

The Project Design Center was formed by JPL to develop, promote and support the use of concurrent engineering techniques by JPL design teams. Its initial focus has been at the earliest phases of new space missions—mission conceptual designs and proposals for new mission starts although the intent is to infuse concurrent engineering techniques through at least Phase B (preliminary design) of JPL project development.

The PDC provides a facility, with multiple rooms, for design teams to use to conduct concurrent engineering sessions. It provides all the equipment needed by teams for these design sessions, including computers, projectors, audio/video conferencing, network connections, etc. It also provides the software needed by the design teams—both COTS and custom developed. It operates the facilities including scheduling, system administration, audio/video conferencing, and maintenance.

The experience of the PDC is that concurrent design teams prefer dedicated design areas configured to their specific needs. For teams with similar jobs, facilities and equipment can be shared as long as their scheduling requirements don't seriously overlap.

The PDC views design teams as its customers and the PDC is judged primarily on the basis of customer satisfaction. Metrics are kept on the usage of the PDC and the feedback from PDC customers. The design teams view the PDC as a supplier of custom-designed environments that enable the teams to function concurrently and in real time.

Thus, to be successful the PDC must be responsive to the real needs of JPL design teams.

TEAM-X FORMATION

Team-X, formally called the Advanced Products Development Team, was created by the JPL Advanced Planetary Missions program office in 1995. This office is responsible for formulating new unmanned planetary exploration missions.

The environment for proposing, developing, and flying new space missions has changed dramatically in the 90's, as the result of initiatives by the NASA Administrator, Dan Goldin, as well as other forces for change. These changes include the now famous *faster, better, cheaper* paradigm invented by Goldin. This new paradigm results in a large increase in the number of space missions. And it leads to an even larger increase in the number of space missions that are studied and proposed.

Another profound change for JPL has arisen due to the decision by NASA to compete a significant portion of new space missions among NASA centers and other space development organizations (e.g., Johns Hopkins' Applied Physics Laboratory). Previously, missions were awarded non-competitively among the NASA centers, according to predetermined *Center Roles and Missions* statements. Now, not only have portions of the planetary exploration business been opened to competition (previously a JPL monopoly), but portions of space exploration previously reserved for other centers are now open to JPL proposals (e.g., Earth observation missions). Thus, JPL is forced to compete to retain its previous business, but also has the opportunity to expand into other lines of space exploration.

Another important change has been the emphasis placed by NASA on cost control, including the threat of cancellation when costs overrun.

Clearly, in this new environment JPL needed to study many more missions and do a better job of formulating winning proposals. The old process did not require a large number of JPL proposals (5-10 per year). Competition and the *faster, better, cheaper* paradigm have led to an order of magnitude increase in this number (JPL now submits more that 50 mission and instrument proposals every year). JPL's old proposal process could not support this rate of proposal submittal, nor did it consistently produce proposals of high quality, especially in the areas of cost estimation and cost risk mitigation and control. Thus, it was a change in the external business environment that forced JPL to adapt its internal processes.

Team-X was the response of the Advanced Planetary Missions program office to these new challenges.

The PDC provided a natural home for team-X. The fortuitous marriage of team-X and the PDC has resulted in fundamental changes to the JPL product development process. Before describing those changes and their implementation in the PDC, it is useful to discuss the traditional JPL product development process, which is ubiquitous throughout JPL and the aerospace industry.

THE TRADITIONAL DESIGN PROCESS

The development of aerospace systems has a number of salient characteristics that have impacted the process employed to achieve successful developments. Among these characteristics are (1) the large size and complexity of aerospace systems, including large uncertainties in performance and cost; (2) the long time from beginning to end of an aerospace project; and (3) the wide diversity of expert disciplines that must be coordinated and managed toward a common goal.

Aerospace projects proceed over many years and through at least several distinct phases. These phases are often dictated by the project sponsor, which in JPL's case is NASA. NASA requires that JPL projects pass through several important gates, at which the project is reviewed. If the project has a successful review it is a candidate for funding in the next project phase. Thus, noncompetitive JPL missions pass through the proposal phase (internally funded), a study phase, a preliminary design phase, a detailed design and build phase, launch and operations. These phases have been modified by NASA for competitive proposals.

Each phase has as its primary objective to advance successfully into the next project phase, which means successfully completing the products (or functions) required to pass the review and obtaining approval and funding to proceed into the next phase.

The nature of work and the number of people involved changes dramatically as the project progresses. In later phases design teams can include hundreds or even thousands of people, each of whom brings skills or expertise to bear on the project. Coordination of the activities of these experts is extremely complex. As the project advances through the phases, the organizational structure changes, and the processes necessary to manage the organization and its product become more formalized.

Another important characteristic of the traditional process is the techniques employed for exchange of information. The universally favored methods are staff meetings, usually weekly, combined with periodic reviews and supplemented by phone calls, documents, memos, additional meetings and, more recently, by e-mail and shared file spaces. Staff meetings and reviews are the only times in the process at which key members of the project assemble. The purposes of these meetings are to exchange information and to assign action items (give direction). No design work is conducted in these meetings, in the sense that design issues are rarely explored. The 'real work' is done after the meeting ends and everyone goes back to her/his office, where each proceeds to carryout action items or other previously assigned work. This continues until the next opportunity (meeting) for communicating progress and assessing the status of the rest of the project.

Thus, the work of the project (programming software, setting up tests, computing various parameters and metrics or figures of merit, etc.) proceeds throughout the week in labs and offices around JPL. Periodically, usually weekly, the staff convenes to exchange status and redirect the work. This process proceeds until the design converges and the products are produced that are necessary to support the next review. Often it is the prospect of an upcoming review that forces this process to converge to a consistent design.

It is useful to consider why the aerospace development process has evolved staff meetings combined with periodic reviews as the dominant methods for coordinating design and development team activities. As mentioned, the primary functions of the weekly staff meeting are to review status and assign or modify action (work) items. This occurs because the time necessary to carryout these action items and other project work items is often quite substantial.

For example, to compute the radiation environment for a particular trajectory around Jupiter has typically taken the group at JPL who does that calculation about a week. Thus, an action item for any mission going to Jupiter could be to compute the radiation dose expected for a newly proposed orbit. Another example might be to determine the effects on costs and annual budget requirements from a contractor change order. Such actions take time to fulfill. Staff meetings serve to coordinate and reset the project, allowing enough time between meetings for various actions to be taken and figures of merit produced.

THE NEW PROCESS

The advent of modern computers and information systems has greatly reduced the amount of time necessary to fulfill many action items. For example, with its newly developed Jupiter Environments Tool, JPL can now compute radiation doses for Jupiter orbits in about five minutes. Likewise, properly designed costing tools can allow a costing expert to make assessments of the effects of contractor change orders in a few minutes. Thus, sometimes design teams no longer need to wait weeks for information to be produced. This offers an opportunity to employ a new process for aerospace design that takes advantage of real-time computations to explore the design space with all relevant disciplines present.

While it is modern information systems that enable this change, the benefits arise primarily from the changes in team process, not directly from the use of new tools. If JPL simply employed new tools in the traditional process, the institution could derive some cost savings, but would miss the big payoff.

This payoff comes from five sources:

1. By employing IPTs the concerns of downstream disciplines are introduced early in the conceptual design

2. By convening real-time design sessions with all necessary tools available for immediate use, the team is able to rapidly search the design space by looking at many point designs, thereby increasing the number of choices and, by extension, the quality of the final choice
3. By employing standing (permanent) concurrent design teams, or at least long-lived teams, important benefits can be derived from learning on the job
4. By including cost experts on the design team lifecycle cost becomes a primary metric by which the team judges its own design output
5. By providing teams with adequate institutional support, they are able to devote their attention to designing exciting space missions, instead of figuring out how to do their job and arranging necessary support as they go.

This institutional support can also provide important benefits to the institution by increasing the quality of project/task management, and capturing, promulgating and encouraging the use of best practices.

The next section returns to the implementation of team-X and team-I in the PDC to illustrate these process changes.

TEAM-X IMPLEMENTATION

Team-X began operating in the PDC in April of 1995. The primary motivation for team-X was the need for JPL to respond to the new environment NASA had created. In particular, team-X was formed to enable JPL to produce the large number of space mission proposals and associated conceptual designs demanded by the new external environment. In so doing it was necessary to greatly reduce the average cost of a proposal, since the resources available to produce proposals had not risen nearly enough to cover the large increase in number required.

Before team-X, proposals were prepared using the same process as employed on all other JPL tasks. A proposal manager was appointed for each proposal, s/he formed a team in the normal fashion and proceeded to produce the proposal, with all (or almost all) relevant functions being performed by the team.

One of the most important jobs or functions of a proposal team is the formulation of a proposed conceptual design and an analysis of its implications for cost, schedule and risk. In the traditional process this activity typically occupied the bulk of the time of the team and consumed a majority of its resources. Completing a space mission conceptual design requires contributions from a number of diverse engineering disciplines. With the traditional process each proposal team would separately hire these services from the JPL technical divisions.

Team-X is structured to significantly alter this process. Team-X is a permanent design team whose primary purpose is to develop conceptual designs for space missions. Proposal teams are customers of team-X, and contract for (pay) for the services of team-X. Proposal teams no longer must hire from the divisions all of the expertise necessary to produce and analyze a design—they can simply employ the services of team-X. Each proposal is still produced by a dedicated team, but that team is significantly smaller and can devote more of its time to other issues associated with winning the competition (e.g., outreach), since less effort need be devoted to producing the conceptual design. Proposal teams still employ key technical skills to augment the products of team-X.

The process changes implied by team-X's formation were quite radical and controversial at the time. Teams thought there would be a loss of autonomy, or that the output of team-X would be inferior or not worth the cost. Initially, some teams refused to use team-X and continued to use the traditional process. The opinion was expressed that the institution should require teams to use team-X due to this resistance. It turned out that this was not necessary.

Use of team-X has remained voluntary. Teams quickly learned that the benefits of employing team-X outweighed the costs by a large margin, so the demand for team-X services has been high. Proposal teams are able to quickly produce and assess mission conceptual designs by using the services and co-located experts of team-X, and the supporting tools and databases provided by the PDC. Use of team-X lends credibility to a conceptual design based on the reputation that team-X has developed for providing competent technical support. Twice JPL has cloned team-X (team-XX) to meet peaks in demand. Now, almost all JPL mission proposals and other space mission conceptual designs pass through team-X, often with several revisits during the early life of a proposal or project.

Team-X conducts its business in an area of the PDC designed for its use. Team-X has a leader that is responsible for conducting the business of team-X, including hiring and replacing team-X members, interfacing with team-X customers and prospective customers, and leading team-X design sessions with customers present.

Each of the disciplines necessary to produce a conceptual design and assess a space mission and associated spacecraft is represented by a qualified expert on team-X. There are currently 18 design stations on team-X, including the normal spacecraft subsystem disciplines—mechanical, thermal, propulsion, power, trajectory design, systems, telecommunications, etc.—and the downstream disciplines found on the operations station (spacecraft operations, ground system operations), the mission design station (launch operations) and the systems station (risk management). Each of these stations consists of a discipline expert and her/his computer tools and databases. The configuration of team-X continues to evolve. Working in conjunction with the PDC, new stations, tools and databases are added to the current capability.

Team-X members are recruited from the technical divisions. Engineers with at least 10 years of experience in their fields of expertise are preferred. All team-X positions are staffed with both a primary and a backup expert, in case the primary is unavailable. Often, backups assume the primary roles when there are staff changes. Team-X members are expected to serve for at least a year, but the intention is to rotate membership at about two year intervals.

A customer reserves design sessions with team-X—either morning or afternoon sessions of three hour duration (9:00-12:00 or 1:00-4:00). A customer can book more or fewer sessions depending on the complexity of the task. A minimum of two sessions separated by several days is required even for the simplest design tasks. Complex missions such as Mars sample returns can require up to 10 sessions over three months.

The team-X process is well-defined. The first step is for the prospective customer to contact the team-X leader and to have one or more preliminary discussions about her/his task and how team-X might help. If an agreement is reached the customer reserves time on the team-X schedule. At the first team-X design session, the customer (e.g., proposal manager or scientist) briefs the team on the mission and the job that team-X is requested to perform. The team is given an opportunity to ask questions and seek clarification on issues of importance to them.

At this point the team-X leader assumes control of the session and begins a systematic investigation of potential design points. Usually the first attempt to construct a conceptual design occupies all of the first design session. The team has developed a procedure, called a 'script', for arriving at this first conceptual design. This script leads the team through a sequence of design choices beginning with the science to be accomplished, the design of the science instrument, the data that are to be sensed, stored, and sent back to Earth, the design of the telecom system to accomplish this communication, and proceeding to computer processor choice, power system design, guidance and control, mechanical, thermal, etc.

Much of this design activity can proceed in parallel, with each discipline working her/his specialty in real time. All of the tools necessary for each specialist to proceed are made available in the PDC. The tools are integrated to allow easy and automatic transfer of data among the various stations.

During the team-X sessions various subsystem technical performance requirements, figures of merit, and other relevant information must be produced in a timely fashion (i.e., during the session). If any discipline asserts a need to compute off line or to confirm data with outside experts or with management (e.g., cost estimates), the entire team is forced to cease work. If any discipline is absent the team does not proceed. The team has not attempted to capture the 'decision rules' of any of its members in software.

The real time nature of the work demands that information be processed rapidly. In general, it is this limitation that most inhibits the development of real time concurrent engineering processes. Unless information can be processed rapidly into figures of merit upon which design decisions can be based, real-time concurrent design is not possible.

Once an initial conceptual design is completed (each member of the team is satisfied that her/his 'requirements' have been met), the design is examined by the team. Cost is one of the first items of interest. Usually, the outputs of the cost analysis station, completed by the cost expert on the team, are displayed for all to see on the overhead projector. Mass and power consumption estimates are also often a major focus in evaluating the design, as are data rate, lifetime, reliability, technology assumptions, etc.

Design modifications are proposed by team members, the customer and the team leader, and investigated by the team in real-time, until a design is found that meets all mission requirements at acceptable costs and risks. Since the customer is present, the 'requirements' imposed by science on the mission are part of the design space—they are not immutable. If the initial science requirements cannot be met within cost constraints imposed by the customer, they can be rescoped as part of the team-X effort.

Team-X does not search for an "optimal" design and does not use formal optimization techniques. Team-X searches for 'good' or 'attractive' designs, and is always open to suggested design improvements.

Team-X produces a report for each of its customers that documents the results of the selected design. This document is drafted in real-time during the design session, with each station drafting its section of the report. These sections are sent to the documentation station, where the team-X documentarian prepares the introductory material and assembles the final document, which is ready for distribution about a week after the final design session. In addition, team-X can produce a 3-D color, shaded picture of the spacecraft.

Team-X has completed more than 100 conceptual space mission designs. Figure 1 shows metrics of the improvements in efficiency resulting from team-X and the PDC. Note the dramatic reduction in average time to prepare proposals, and very significant decrease in cost per proposal.

In addition, it is generally believed (although no objective metric exists to confirm the belief) that the quality of JPL proposals has improved as a result of team-X and the PDC. While JPL often produced high quality proposals in the past, the new process has made major contributions to the ability of JPL proposal teams to estimate and control costs. Cost estimates are now a primary focus of all JPL proposal teams, and the dependence of system performance on costs is much more thoroughly assessed in the team-X process. Probability distributions of projected costs are produced and used to establish cost reserves. Descope options are designed, costed and included in JPL proposals as a primary method of cost control. The ability to investigate multiple design options provides a fundamental improvement in the quality of JPL proposals since the menu of design choices is significantly expanded.

The motivation for increased attention to costs and cost control has come primarily from NASA. The *faster, better, cheaper* paradigm forces strict cost control. Team-X has explicitly changed the JPL development process in response to this pressure. In the traditional process, conceptual design and costing are sequential activities—costs are estimated after the design is completed. And the costing process is often not understood by the engineers who design the system, so they do not easily accept estimates that are higher than they had assumed should be the case. This often results in conflict between design teams and the costing group.

Team-X includes the costing expert on the design team, equivalent to other design team experts. The cost ‘station’ computes project costs employing cost models or other costing techniques. The cost models and methods are available for all team members to investigate simply by asking for information from the cost expert. Costs are computed in parallel with other figures-of-merit, and the costs estimates for the project and its components are subject to challenge, explanation, and change by the entire design team. In this way the cost estimates become the team’s estimates, and costs are treated equivalently to other important mission performance measures. In fact, costs are usually the first set of summary information about a new point design that is projected for the entire team to peruse.

In response to the needs of team-X, the PDC has developed and implemented the team-X toolset as shown in Figure 2:

1. The Concurrent Engineering Methodology, which is a set of Excel spreadsheets that are distributed across all team-X stations and are used for subsystem conceptual design and for communicating among the stations. The Excel worksheets are linked cell-to-cell across the network using the Macintosh utility Publish and Subscribe. The CEM was developed under contract for JPL by the Aerospace Corporation
2. Databases of spacecraft components, spacecraft buses, launch vehicles, etc., in electronic formats for use by each team-X expert
3. Distributed documentation software
4. Configuration graphics software for producing 3-D images
5. Subsystem conceptual design tools for each team-X station.

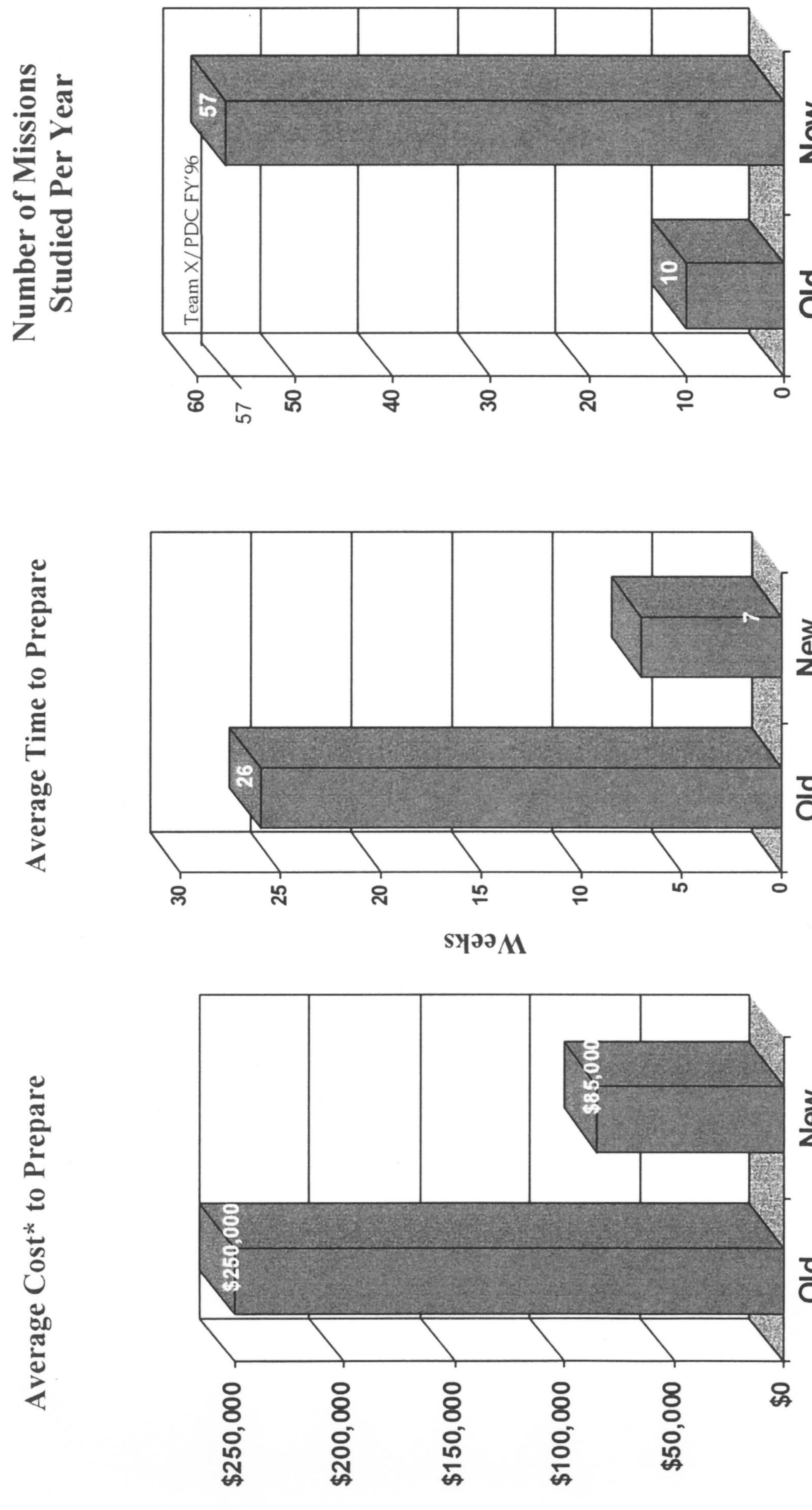
TEAM-I IMPLEMENTATION

In the spring of 1997 the PDC began hosting its second concurrent design team, called team-I. This team is patterned after team-X, except that it designs space instrument concepts instead of concepts for space missions and spacecraft. Team-I occupies a separate area of the PDC that has been designed for its use.

Unlike space missions, space instrument proposals require that an optical analysis and associated structural and thermal analyses be completed. This requirement occurs because in order to demonstrate in a proposal that a space camera, spectrometer, telescope, etc., can do its job, it is necessary to show through analysis that structural and thermal distortions or deflections will not adversely effect the resulting image or data.

Completion of structural and thermal analyses requires the use of high-end design tools—computer-aided drawing, engineering and manufacturing tools (CAD/CAE/CAM) and thermal analysis tools—that require significant time to use. In particular, it takes a long time for a designer to develop, assemble and enter all of the information needed by these tools. Since the time required to interact with these tools far exceeds the time constraints of real-time design, the concurrent design process must be modified. Naturally, the required modification is to allow the CAD/CAE/CAM designer(s) and the thermal engineer(s) to work off-line prior to and in between concurrent sessions. For example, models of all major parts are completed in the CAD tool off-line. And the CAD model is parameterized off-line so that primary design variables (e.g., focal length, mirror diameter) can be changed parametrically. Thermal meshing and structural meshing can also occur off-line. Once the basic design is captured and parameterized in these high-end models, they can be employed in real time concurrent design sessions. Thus, the team-I process includes more design sessions with sufficient intervening time for designers to work with the high-end design tools.

Another important result of the need to employ high-end tools is the mix of computer platforms and integrating software employed by team-I. As mentioned, team-X tools are integrated through Excel spreadsheets. These spreadsheets are running on Macintoshes, since most members of team-X prefer Macs. Clearly, such a system is not suited to the team-I need for high-end tools that run on UNIX.



* Includes cost to prepare and submit formal mission proposals

Figure 1. JPL Mission Design Metrics (Conceptual Mission/Spacecraft Designs)

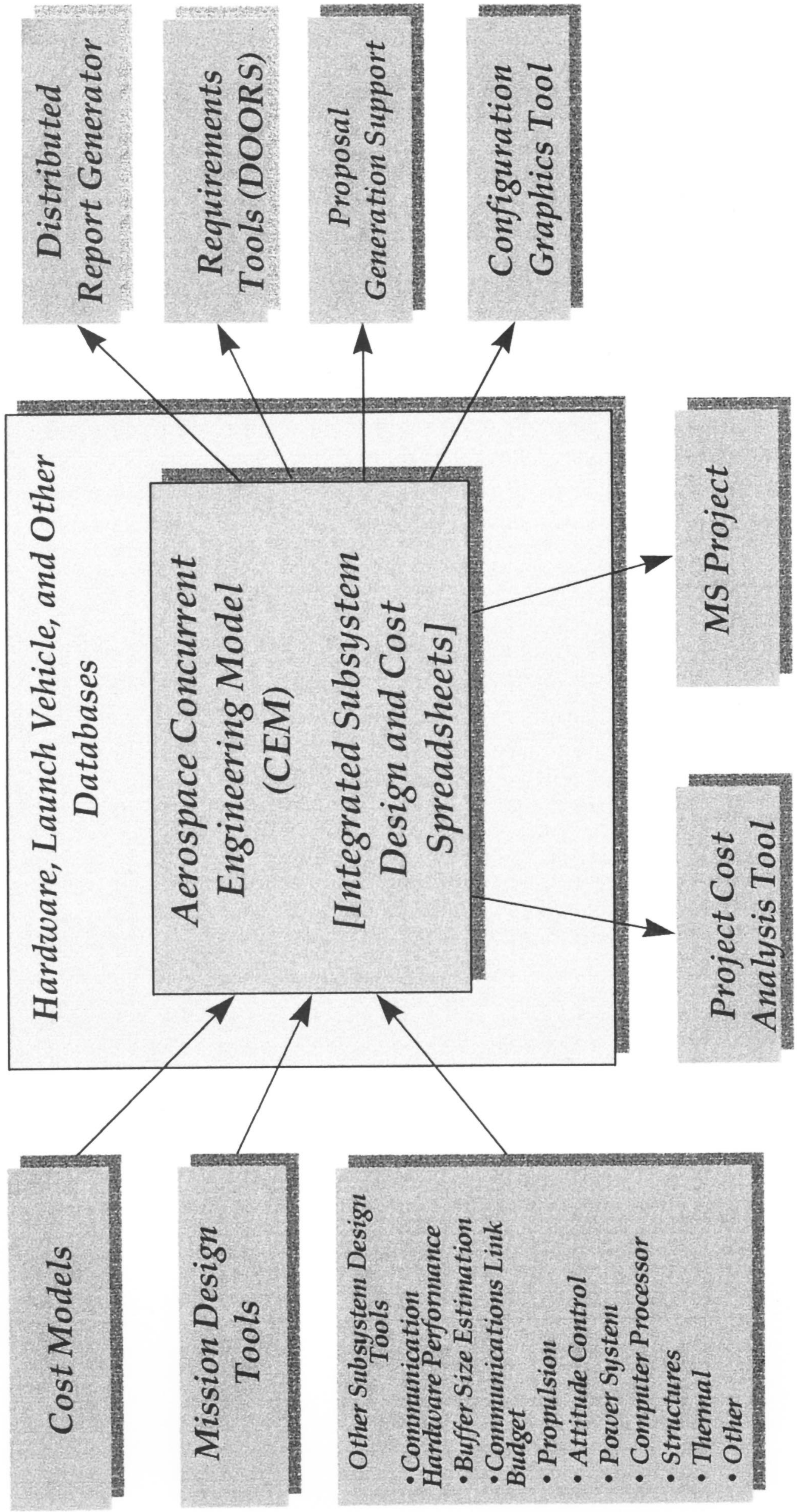


Figure 2. Team X Tools Integration in the PDC

Thus, the PDC implemented an entirely different hardware configuration and tool integration technology for team-I. Team-I tools run on a combination of UNIX, personal computers (PCs) and dual-processor pentiums. The integrating technology is Labview. 'Executives' were developed for each team-I station using the programming language (G) developed by National Instruments for Labview. These executives are used for implementing graphical user interfaces on each station, for manipulating and running applications and for transporting data between applications. The present team-I toolset is illustrated in Figures 3 and 4. Since team-I just recently started, the toolset is far from complete.

PDC PROCESS CHANGES

The PDC has implemented five fundamental changes to the traditional JPL product development process. These changes are:

1. The teams include all disciplines necessary to introduce downstream considerations in the conceptual design (IPTs)
2. The teams are permanent design teams—they will continue to develop new space mission and instrument conceptual designs indefinitely
3. The teams function real-time with the customer present
4. The teams include project life-cycle cost as a primary metric, equivalent to mission performance, in the design trade and selection process (referred to as Design-to-Cost)
5. JPL provides adequate, effective institutional support through the PDC, allowing team-X and team-I to take advantage of modern information systems.

The benefits derived from IPTs are well-known. Some of the most persistent deficiencies of the traditional process arise because the conceptual design does not always adequately consider downstream implications, such as manufacturing and operational issues. Also, the traditional process is criticized for the inflexibility of the resulting requirements. By including experts from all relevant technical disciplines and the customer in the concurrent design sessions, both of these issues are significantly ameliorated. Manufacturing, tooling, operations, reliability, quality assurance, and other downstream concerns are directly raised in the design team, and the design is modified until those concerns are addressed satisfactorily. Similarly, science (customer) requirements become variable once their implications are made clear to the scientist as part of the concurrent design sessions. The quality of the design is improved by including all relevant disciplines and the customer in the design process. These were the primary benefits realized by Boeing from their invention and use of IPTs for the 777 development program [1].

Team-X is the first permanent design team established by JPL. Most JPL teams are created to complete a specific design or mission, and then disbanded.

Increasing the life of design teams has several important benefits. Since team members do the same kind of work many times, they get better at it—they learn on the job. Not only does each individual learn to do his own part of the task more efficiently and effectively, but the team as a whole refines its process and internal communications.

Furthermore, the team is motivated to discover and adopt tools and processes that increase the efficiency with which they function. Traditional JPL design teams are motivated to invest in tools only if necessary to produce an answer—investments to improve the efficiency with which answers are produced will, in general, be too large and too late to provide them with any benefit. However, if a team must generate a similar answer 50 times a year, large incentives exist to define and invest in tools that improve the efficiency of the process that generates that answer.

Finally, permanent teams, in conjunction with the PDC, provide a method for the institution to help preserve and promulgate the best practices of all JPL design teams.

Thus, the benefits from establishing permanent or long-lived design teams are clear and substantial.

The third process change was the adoption of concurrent, real-time engineering design sessions. The traditional process does not include such sessions. With the traditional process the design activities of each engineer proceed in isolation or in small isolated groups, contingent upon the review and reaction of the rest of the project.

The essence of design is making choices (decisions). When these choices are made off-line in offices and labs around JPL, they are contingent upon acceptance by the rest of the project. Since every element of the project is proceeding in this fashion, a great deal of time is spent waiting for reactions from other affected project elements, working on tentative solutions that are ultimately rejected, waiting for crucial inputs from other elements, etc. Just keeping the entire project working on the same baseline can be a major difficulty.

The benefits of examining a concept in real-time with every relevant design discipline present are very large. If the team is able to convene sessions in which relevant information is quickly made available to all project elements, the inefficiencies just discussed disappear.

The fourth process change was the inclusion of the costing expert on the design team and the elevation of cost metrics to equivalent importance with mission performance. Unlike commercial product development, government funded aerospace product development has not always elevated cost to a position of primary importance. Cost estimation and control are now a primary focus of the new space mission development process. New costing techniques have been introduced (e.g., computation of cost probability distributions), and project life-cycle costs are computed in real-time along with other important mission figures of merit.

The final process change was the provision through the PDC of adequate institutional resources to develop and support the capabilities necessary for real-time concurrent design. The computer, software, and facility needs of team-X and team-I are quite substantial. The PDC has spent over $1.5M developing team-X capabilities, and spends about $500K/year to support team operations and upgrade its capabilities. The requirements for investment in team-I capabilities are comparable, although considerably less has been invested in team-I to date.

MODEL-BASED DESIGN OR TEAM-BASED DESIGN?

This paper has argued that aerospace design and development are complex problems of coordinating the activities of many expert disciplines. Each discipline makes critical contributions to the system. It takes experts many years of concentrated effort to become experts—they devote their careers to developing and maintaining that expertise. All of these experts are essential to the systems engineering process—the system cannot be engineered without their contributions.

No engineer has all the expertise necessary to design an entire aerospace system. However, some system engineers exhibit a desire to develop systems models that ‘capture’ in software the relevant expertise of subsystem experts. If models can be built that parametrically define the ‘design space’, those models could be executed by system engineers to do the job implied by their title—engineer the system to satisfy customer requirements.

But the ability to ‘capture’ the knowledge of design experts is lacking. The history of expert systems is a history of unfulfilled expectations. It simply is not presently possible to produce computer programs that fully duplicate the skills of spacecraft propulsion engineers, structural designers, electrical engineers or any of the other expert skills necessary to design aerospace systems. Specification of ‘design rules’ is wholly inadequate to introduce true disciplinary skill. While computers can make ‘routine’ decisions, they cannot come close to duplicating the judgments and associated decisions of experts.

An implication of this fact is that system design models cannot, given present technology, duplicate or substitute for a design team. Or equivalently, whenever a new system design issue is broached, it must be addressed by a complete team of experts, not just by a computer program or by models and their operators.

System level models can be built that allow quick excursions through a design space that has already been defined by a team (including definition of limits or boundaries of applicability). But building this kind of model requires that a design team do the real design work first. For this reason, system engineering design models have never progressed much beyond demonstrations—they can demonstrate a design space that is pre-canned, but they cannot easily support the exploration of a new or different design space.

Nevertheless, the development of advanced system models is an appropriate research topic. Indeed, concurrent engineering teams such as team-X could benefit greatly from the development of expert system ‘agents’, that are capable of duplicating the *routine* decisions of discipline experts (design rules).

While discipline experts are, in general, necessary to deal with true design unknowns, for most missions many of the design decisions are routine. For example, many JPL missions fly with well-understood propulsion systems or computer processors that have flown many times before. Thus, most JPL missions have areas of high challenge and uncertainty where experts are truly required, as well as areas of routine design where they may not be required. Present tools do not allow teams to pick and choose expertise—all disciplines must be represented even when some disciplines are making routine decisions. The ability to reduce team size through the use of expert system agents would significantly reduce costs.

Expert agent models attempt to emulate the decisions of experts through decision rules, neural networks, or other expert system techniques. Presently such agents do not exist, nor is there much effort directed at developing them.

The simulation models typically incorporated in present system-level models are not designed to make decisions. These simulations predict aspects of the performance of the system design and variations on that design. It is presumed that the system engineer will use the outputs of these simulations as the basis for her/his design decisions. Such models could prove useful for systems engineers to make preliminary assessments of potential design options for consideration by a design team.

Furthermore, with sufficient investment any of the systems modeling and simulation approaches under development could serve as a basis for implementation of concurrent engineering toolsets in support of specific design teams. These systems models often contain sophisticated approaches for integrating tools and models that can serve quite well as integration and communication systems for design teams’ toolsets.

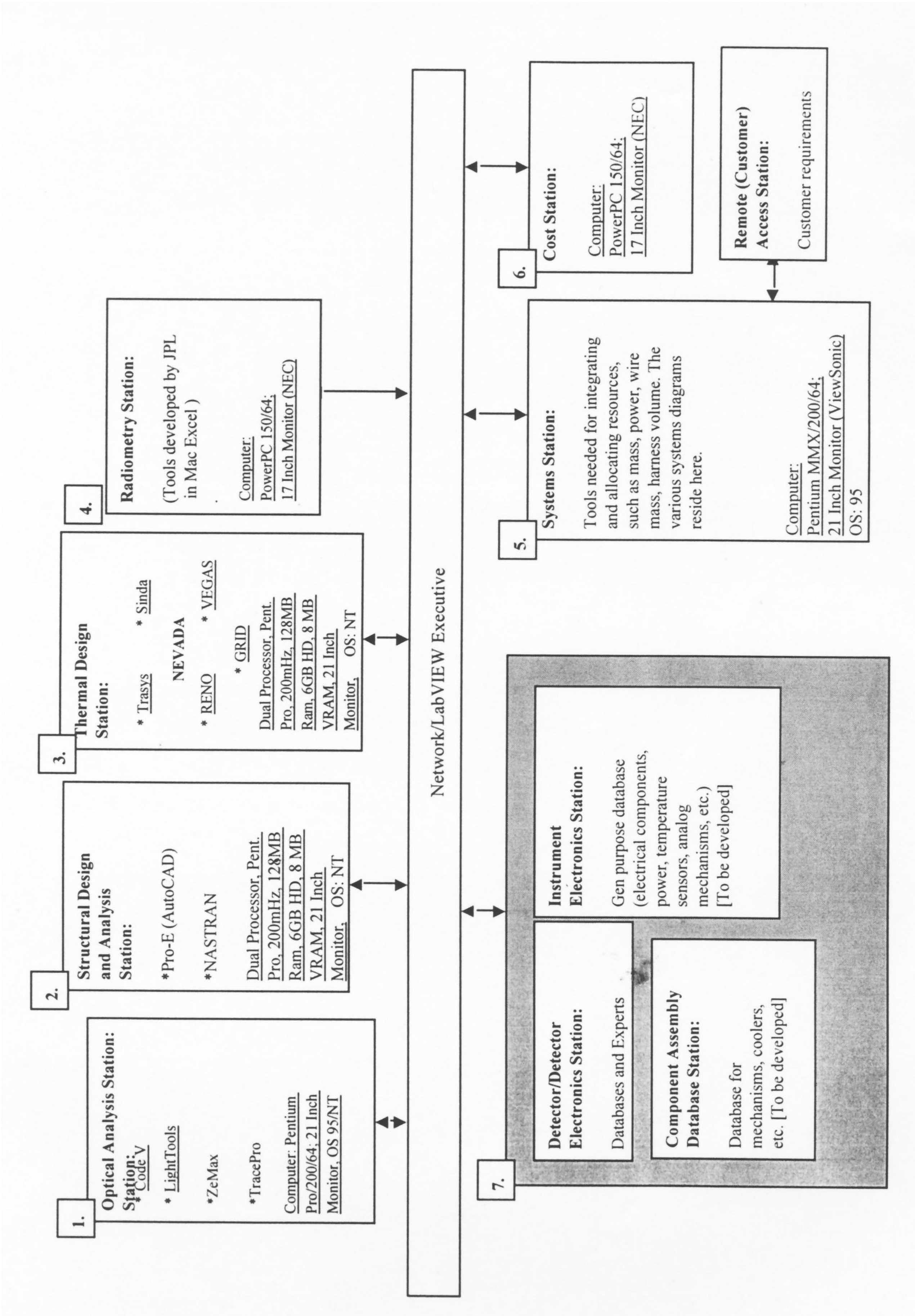


Figure 3. Team I, Phase 1 Toolset Configuration

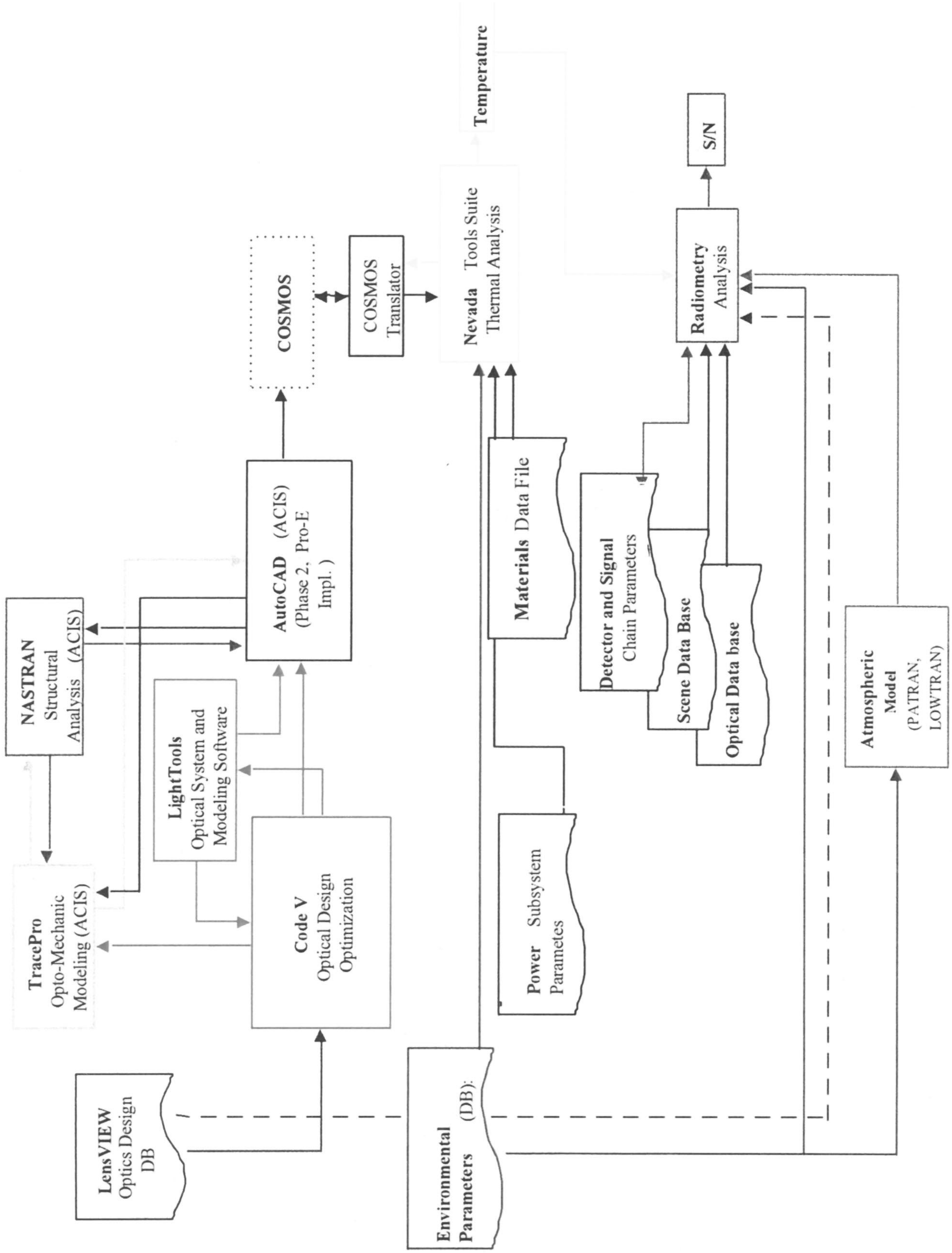


Figure 4. Team I, Phase 1 Optical Analysis Toolset

This exposes the question posed in the title of this section—model-based design or team-based design?—as disingenuous. Design teams need their tools to be integrated to support real time concurrent engineering, so the correct answer is: design teams *and their* design models. The key is that the models and information technology be selected to serve the needs of the team. The issues each team faces as well as the skills resident on the team must be considered when selecting an appropriate integrating system or technology. Furthermore, to prove useful in real-time design sessions, the tools need to be distributed across a set of interconnected design stations—at least one for each discipline on the design team.

MOTIVATING DESIGN TEAM PROCESS CHANGE

The traditional aerospace design process has evolved over the past 50 years to produce very complex and technically challenging systems in the face of large uncertainties. Meanwhile, information technology has changed radically over that time span, offering opportunities to improve and speedup the traditional process.

However, aerospace engineers understand how to use the traditional process and are often resistant to changing it, especially if the change involves significant investments of time and money.

Adoption of real-time concurrent engineering processes requires that a design team make a substantial commitment to the new process. Even if the investment is not funded by the design team, the team must commit to working with tool developers for 3-4 months just to establish an initial or pilot concurrent design capability. Then working from this initial capability, the team must work with its customers and the tool developers to complete the concurrent design environment over the next year or two. A substantial commitment of time and money is required to establish a fully functioning real-time design environment.

On the other hand, most engineers find the real time design environment to be stimulating and challenging. The ability to quickly examine designs as a team is very attractive to design teams. Most JPL teams like the PDC design environment, and would like to function similarly if the institution funds the required investment.

Nevertheless, the design team must make a conscious and substantial commitment to real time concurrent design. It cannot be ‘tried-out’ in an afternoon—at least several months of effort are required before any benefits can be proven.

Finally, the key to successful implementation of integrated toolsets to support concurrent engineering is customer-focused tool development. The tools must be customized to match the design issues each team faces, and the design team must provide guidance on tool choices and development priorities. Tool developers must be responsive to design team tool requirements, and should be judged on the basis of overall customer (design team) satisfaction.

SUMMARY AND CONCLUSION

This paper has reviewed the status of concurrent engineering in the JPL Project Design Center, with a focus on lessons learned. It reviewed in detail the formation of team-X and the concurrent engineering processes employed by both team-X and team-I. The paper argued that process improvement is key to productivity improvement—just adopting new or standardized tools is insufficient. It included discussions of the traditional JPL process for product development and of the changes to this process implemented by the PDC and its resident concurrent engineering teams.

Five fundamental process changes were discussed. Each of these changes has been successfully implemented in the PDC with resulting large improvements to team performance, costs and schedule.

Such process changes, enabled by modern information technology, offer an opportunity for teams designing complicated products to make major improvements in their productivity.

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