INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN

ICED'93

THE HAGUE, AUGUST 17-19, 1993

AN ANALYSIS OF COORDINATION PROBLEMS IN DESIGN ENGINEERING

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ABSTRACT

The design and engineering of large, complex electro-mechanical artifacts for use in space requires the integration of many engineering groups, spread across the components of the artifact and across the customer and suppliers. And within each engineering group there is a need to integrate the many diverse skills required, such as electrical, mechanical, thermal, materials, etc. This paper describes the results of a study conducted during the summer and fall of 1992 at a medium sized aerospace company. The goal of the study was to identify project delays that were due to poor coordination/integration. During the study, 25 cases were compiled and classified into six problem categories: Information Acqusition (24%), Information Access (32%), Knowledge Access (4%), Decision Interdependence (8%), Activity Management (12%), and Agent Access (16%).The delay associated with information acqusition, information access and knowledge access range between 1 day to a year, and between 1 day to a week for the remaining categories.

INHALTSANGABE

Das Design und die Entwicklung von, komplexen, elektromechanischen Spezialanfertigungen für den Gebrauch in der Raumfahrt erfordert die Integration vieler spezialisierter Expertenteams, welche sich mit den verschiedenen Komponenten der Spezialanfertigung befassen und sowohl firmenintern als auch auf Kunden und Zulieferer verteilt sind. In den individüllen Expertenteams ist es wiederum erforderlich, daß die unterschiedlichen Fähigkeiten in Bereichen wie Elektrizität, Mechanik, Thermodynamik, Materialkunde, etc., integriert werden. Die vorliegende Veröffentlichnug beschreibt die Ergebnisse einer Studie, die im Sommer und Herbst 1992 an einer mittelgrossen Firma in der Raumfahrtindustrie durchgeführt wurden. Das Ziel der Studie war die Identifikation von Projektverzögerungen, welche auf mangelhafte Koordination/Integration zurückgeführt werden konnten. Im Zuge der Studie wurden 25 Fälle analysiert und die Ursachen für die Verzögerungen konnten in sechs Kategorien unterteilt werden: Informationsbeschaffung (24%), Unzugänglichkeit von Information (32%), Unzugänglichkeit von Wissen (4%), Unabhängigkeit von Entscheidungen (8%), Management von Aktivitäten (12%) und Unzugänglichkeit von Vertretern (16%). Die Verzögerungen, welche mit Informationsbeschaffung, Informationßugänglichkeit und Wissenßugänglichkeit verbunden werden konnten daürten zwischen einem Tag une einem Jahr. In den restlichen Kategorien lagen die Verzögerungen zwischen einem Tag und einer Woche.

1. INTRODUCTION

Information Systems (IS) have penetrated the engineering workplace in many forms and have had a great impact on the efficiency with which work is done. Within the field of design, IS has centred mainly around design graphics aids such as AutoCAD, CADKEY and Unigraphix. Within engineering, a large host of software packages now exist and consist mainly of analysis tools for establishing requirements, parameters and other inputs for a design, or for verifying the feasibility of designs. More recently, much work has been done in the area of Design Automation. Studies of the design process, and the use of Artificial Intelligence (AI) have resulted in systems that design artifacts with reduced human involvement; This has occurred primarily in configuration-based design, e.g., of computers and motors. However, the design problems themselves have changed, and those being tackled today are of ever-increasing difficulty.

Many artifacts are so complex that their design requires the efforts of many engineers. To accomplish this the artifact must be functionally and/or physically decomposed, and responsibility for engineering the components is divided among members of the engineering team. Consequently, a coordination problem arises. That is, how can each engineer's design task be managed so that it integrates well with the results of others. Coordination of design teams is difficult because each part of a design constrains the others. A change in one part has a "domino effect" on other portions of the design. Unfortunately, changes occur frequently during the course of design, so that each engineer must continually revise their work. Lack of coordination leads to sub-optimal decisions, which in turn lead to high cost, low quality, and delays in completion. Kitzmiller and Jagannathan described the current trend as follows:

> "Design problems...are often of such size and complexity that no single individual, organization, or design environment is capable of effectively addressing all aspects of the design. In such situations, the design problem must be addressed by a team of specialists or experts ... Although many computer-aided design and engineering environments have been developed, few are capable of supporting the type of distributed, multidisciplinary, team-oriented approach such problems require" [1]

In order to provide the right kind of design support, given these conditions, a thorough understanding of design as a social process must be obtained. While there may often be a straightforward solution to a design decision, the way in which designs ultimately evolve can be as much influenced by human factors, both individual and group, as by requirements, cost, schedule. This social aspect of design has significant impact on its other aspects; problems in coordination invariably result in schedule delay and therefore cost increase.

Pennell and Winner stated, in their paper on concurrent design, that future research "... needs to be done to improve understanding of ... the psychological and sociological phenomena in the execution of a team design process" [2]. Comparatively little research, however, has come forward. The impact of social aspects on design continues to be largely ignored, although there has been a significant increase in the study of Computer Systems for Cooperative Work.

The question of how groups of over 50 people interact on major design efforts, and the coordination problems they encounter are examined in this paper. The analysis is based on 25 case studies of coordination problems that occur in a large design project. Identification and classification of these problems and their impact on the design process are presented [3].

2. DESIGN OF THE STUDY

The study focuses on everyday activities in a division of an aerospace company. A series of 25 problem cases was compiled, all of which are real-life situations encountered in a multi-billion dollar international space program which has been underway for some five years at the time of the study. The particular program is contractually structured with a prime contractor performing design work of its own and supervising the activities of several subcontractors. The cases are from the point of view of employees working for the prime contractor, some regarding dealings within the prime contractor organization, and some regarding interaction with subcontractor.

All 25 cases were provided by one employee/source person who worked for the prime contractor. The cases are based on the personal experiences of a small group of employees which includes the source person. The cases cover a period of time during the design and development phase of the program. The approximate time period is from 05/92 to 12/92.

This is an exploratory study, but it is not definitive. The study is not, and should not be interpreted as, a complete study and evaluation of the problems of interaction that will be encountered in large scale design situations. This study does provide insight into problem types and tendencies in large scale design situations, and it is hoped that it will contribute to the overall understanding of design coordination problems.

3. CASE STUDY ANALYSIS

Our analysis of the cases identified six broad categories based on the cause of the coordination problem [3]. In the following we define each category and analyse its impact.

*1. **Information Acquisition:*** Six of the cases, 24%, focused on information unavailability due to difficulties in acquiring it. In many of the cases, an engineer inherits a partial or complete design for which there is little information as to why it was designed that way. There are two sources of the difficulty. First, design rationale, i.e., why a decision was made and upon what data or analyse, is seldom recorded. Engineers loathe recording their thought processes, even if they are introspective; all that ever gets recorded is the outcome. Second, if design rationale is recorded, it tends to be informal, in an engineering notebook, scrap books, envelopes, etc. and hence lie outside of any formal systems. Delays associated with this category ranges from days to weeks. Sometimes, the information is never located and the design process has to be reinitiated.

*2. **Information Access Problem:*** Eight of the cases, 32%, focused on the difficulty of accessing information that is either physically or electronically available. This information could include: standards, specifications, requirements etc., that are available through catalogues and other documents. Design versions is an example that occurs often. Whether available in physical or electronic form, three problems recurred: learning of the existence of information, finding where it is located, and then actually retrieving it. Delayed access to information in a physical form but located elsewhere is understandable, but just as pervasive is the lack of integration of information systems resulting in similar problems. Another side of this problem is that there may be too much information available, burying what is needed among the rest, thereby making it inaccessible. this is especially problematic when the information is physically recorded making it difficult to search. The delays associated with this category were in the range of 1 hour to 1 week.

3. Knowledge Access Problem: Expertise among more senior people is always in demand. Many of the older employees are veterans of many years with the company, and have stores of knowledge, the importance of which even they do not fully appreciate. When more junior members need to ask these senior people a question related to their work, they often are inaccessible, due to the amount that they are in demand. Conversely, the senior engineers are left little time to do engineering because they are constantly being asked questions. As well, the moment such an employee walks out the door on retirement, most of their knowledge walks out the door with them. Their knowledge therefore does not benefit others as much as it could. Since the junior people cannot benefit from their knowledge, they often must research their solutions and spend additional time. This problem arose in only one case, 4%, but in follow up interviews has been cited as a major problem. In fact, it is just this problem that led to the wide spread investigation of Expert Systems by industry. This category had only long term effects which are not easily quantifiable. However, the delays could be anywhere from 3 days to 1 year.

4. Decision Interdependence Problem: Two of the cases, 8%, focused on how individual decisions can cause severe coordination problems and introduce delays to the program. This problem occurs when large numbers of designers work on components of the same artifact, and a decision made by one designer constrains decisions to be made by others. If the decisions are made in isolation, a coordination problem can arise. A designer may make changes in the design without considering their overall effect and/or might delay the design task without knowing the impact the delay has on the overall program schedule. Though only 8% of the cases exhibited this problem, follow on interviews highlighted this as a major problem facing large system engineering projects. The resulting delay time was in the range of 1 day to 1 week.

5.Activity Management Problem: Three of the cases, 12%, focus on the non-adherence to schedules for non-technical reasons. Of particular concern was the inability to perform review activities on time. Given the vast amount of information to be reviewed, and the other, more "important" activities and engineer/manager has to perform, reviewing other peoples work was not high on their list. Another source of the problem is the shifting players in the project. Engineers are reassigned or go on vacation and as a result deadlines are missed simply because they "fall through the cracks." Though engineering organizations spend significant amounts of time creating schedules, they are not very good at enforcing them. Part of the problem is individual time management but also there is a lack of procedures and systems to support project management. And in cases where there are systems, each level of personnel uses different systems that are not integrated. The delay time associated with these problems was in the range of 3 days to 1 week.

6. Agent Access Problem: This problem arises when key individuals are inaccessible because they are busy or because of their location. In some cases, key decision makers are unavailable when an important decision has to be made, leaving many engineers idle or unproductive until the decision is made. In other cases, it is simply difficult trying to find where a person is located when the project is large and dispersed geographically. Four of the cases, 16% of the total cases fell into this category. Problems in this category caused delays which could range from 1 day to 1 week.

The histogram in figure-1 shows the break-up of all the 25 problem cases by category. Note that one case did not fit into any category due to its vagueness. Overall it was felt that the combined

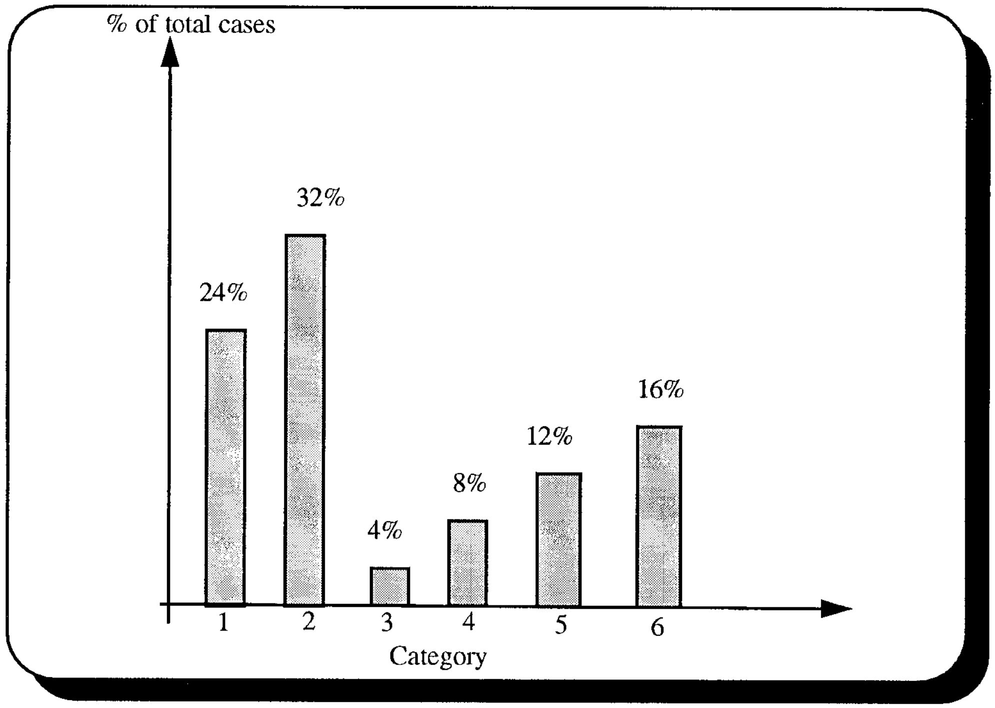

Figure-1: Percent of cases in each category

effect of all the problem categories produced an increase in the time taken for engineering and design of large projects in the order of 20-30%.

4. RELATED STUDIES

Several papers which study and analyze design have pointed out problem areas in coordination of design which are of relevance to, and which support the findings of this paper.

In a study of information requests of mechanical designers Kuffner and Ullman commented on the drawbacks of engineering notebooks: "Sketches are made on cocktail napkins and the backs of envelopes, groups work out ideas on chalkboards...This work seldom makes it into even the most meticulous of design notebooks". Kuffner and Ullman also pointed out that "the other forms of design documentation available (i.e. drawings and specifications) are unsatisfactory in answering purpose oriented questions" [4].

On the use of CAD/CAM in concurrent engineering, Brazier and Leonard maintain that they "must serve as an 'information pump', a central data base in which all design data and management controls reside"[5]. The lack of a central authority on design information could be countered by applying this philosophy.

The many problems encountered by different versions of designs available within an organization at a given time is treated by Biliris and Zhao, who postulate that:

"...since teams of designers are needed to design components of a large product, and the design activity produces many versions in parallel, the following requirements should be met: designers in the same team should be able to 1. synchronize their designs by being aware of the new versions as they are being produced, and 2. prevent premature disclosure of a version, produced by one of them and shared among them, to other designers"[6].

Inconsistencies in design versions could be more tightly controlled by meeting these requirements.

Sprague, Singh and Wood make recommendations to "Team Enhancement" [7] which are based on problems comparable to those encountered in this study. To enhance communication between team members they recommend "Networked collocation...multimedia communications among experts, applications, services and information repositories...". Better access to information is achieved with the "organization...unified with mechanisms for storage, control, and retrieval of all information and data relevant to the product". Better team coordination includes "...cooperative-work, activity and task-management services and decision tools fed by knowledge from the shared- information model". Finally, to combat re-invention of artifacts, "Corporate memory. This would involve electronic documentation of the evolving and final product or system configuration. The data...includes the history and intent of decisions and transactions made"[7].

Olson and Bly outline 3 goals for development of new tools to enhance the effectiveness of work groups. Goal 1 is to make "...separate physical environments more like a single environment". Goal 2 is to "...improve the efficiency of reciprocal interdependence" because where reciprocal interdependence is required, "...generally a great deal of time is spent informing the other members of the work group. Tools that focus on improving the efficiency of this process might reduce the amount of information required to be shared, by increasing specificity or standardization". Finally, Goal 3 is to "increase the capacity of reciprocal interdependence by improving the accessibility of shared information. Tools of this type increase the amount of information sharing among work group members, either in order to overcome the barriers of space and time, or to make face-to-face interaction more effective"[8].

And finally, Sinclair et al. [9] commented on problems in the management of design information, particularly with respect to design histories in the following excerpts:

"The maintenance of design histories is critical to the success of future design; typically, these are accessed by human-to-human communication, with experienced designers acting as repositories of the organization's design knowledge, even when documentation is adequate. Loss of these experienced designers can be critical.".

"...there is a further source of complexity...changes to the design brief due to external events, that shift the design problem as a whole, and render obsolete some of the knowledge structures already created. A consequence of this phenomenon is that there must be very careful control of design information, and careful management of design history, to avoid confusion and errors in the final design...".

5. CONCLUSION

Today, the complexity of systems and the variety of knowledge required in their design, move the design/engineering process away from the single engineer model, to a group problem-solving model. The goal of this study was to identify the categories of problems that arise due to the engineering process being performed by a group. That is, our focus was on the process of coordination in design and engineering. Though our study was narrow in the sense that it is the experience of a single engineer, it is interesting in that the group numbered between 50 to 100 designers and engineers.

At the level of evaluation of this study, the problems of coordination are many and diverse, and cause significant delay in schedule. Six categories of problems were identified: Information Acquisition, Information Access, Knowledge Access, Decision Interdependence, Activity Management, and Agent Access. They result, according to the findings of this paper, in increases of 20-30% of the time taken to complete a program. This represents not only profit lost to a company once a program is underway, but a decreased competitiveness when estimating costs for bidding on future contracts.

In order to solve these problems, some fundamental research issues have to be addressed. First and foremost is the information acquisition problem. Capturing design rationale is a particularly difficult task. Though enabling technologies, such as pen-based computers exist, it remains to be discovered how the procedures and technology can be engineered so that engineers will willing record such information. Second, access to information is impeded by engineering's continuing desire to maintain paper-based documentation systems, and the lack of integration among the various programs and systems that the organizations use. Third, capturing and distributing expertise is possible using Expert System technologies, but the cost of acquisition and its continued maintenance is still too great to be of much use to all but the most important tasks. Fourth, decision interdependence requires a method of modelling and managing the inter-dependencies. Luckily there appears to be solution: constraint networks. Fifth, activity management technologies abound, e.g., project management systems, but the engineering of usable system that adds value to the process still remains beyond our grasp. And sixth, access to people and systems remains a problem, but is being reduced with current communication technologies such as faxes and cellular phones.

The biggest problem we face is our inability to recognize that collaborative design/engineering is a social process. All of our information system technologies, are simply enabling technologies and not a solution in of themselves. Solutions will arise when we realize that they have to be system solutions, where the system is redesigned as an integration of people, procedures and technologies.

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