Appeared In: Proceedings of Joint JSME/ASME Workshop on Design, Tokyo, Japan, June 1993

Design Engineering: Problems in Coordination

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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. 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 in the summer and winter of 1992 at a medium sized aerospace company. The study had two goals. The first was to identify the activities which occupy engineers at the company and to rank the activities by the level of frustration and wasted effort encountered in them. The second goal was to identify project delays that were due to poor coordination/integration. The first goal was accomplished with a survey in which 30 questionnaires were circulated to engineers in 5 different departments, and the time spent in 7 activities was tracked by the participants over an actual week, and estimated over a typical week on a percentage basis: Information Gathering (13.9% - actual; 12.4% - typical), Problem Solving/Thinking (28.4% - actual; 31.6% - typical), Documentation (23.1% - actual; 18.2% - typical), Planning (7.6% - actual; 8.6% - typical), Negotiating (7.5% - actual; 9.2% typical), Support and Consulting (17.4% - actual; 18.3% - typical) and Others (2.1% - actual; 1.8% typical). Based on the survey results, the activities were scored from 1 (most frustrating) to 7 (least frustrating). The overall scores were: 4.0 - Information Gathering, 4.4 - Documentation, 4.5 - Planning, 4.6 - Negotiation, 4.8 - Support and Consulting, 5.3 - Problem Solving/Thinking and 6.6 - Other. The second goal was accomplished by studying 25 cases of coorindation problems, 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 problems range between 1 day to a year, and between 1 day to a week for the remaining categories.

1. INTRODUCTION

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.

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" [1]. 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, the activities they perform, the frustrations and coordination problems they encounter are examined in this paper. The analysis is based firstly on a survey of 30 engineers, in which the time they spent in 7 activities was tracked and estimated over a one week period, and secondly on 25 case studies of coordination problems that occur in a large design project. Analysis of the survey results, and identification and classification of the problem cases and their impact on the design process are presented [2].

2. DESIGN OF THE STUDY

The study focuses on the everyday activities in a division of an aerospace company. In the survey portion of the study, 30

surveys were distributed (5 each) to the Mechanical, Electrical, Systems, Controls & Analysis, and Software departments from 02/93 to 04/93. The engineers who received the surveys recorded, for one week, the hours they spent working in 7 activities: Information Gathering, Problem Solving/Thinking, Documentation, Planning, Negotiation, Support and Consulting, and Other (specified by the participant). For the same activities, the participants estimated what they thought the percentage split of their time would be in an typical week. The participants rated the frustration levels they encountered in the activities, along with their reasons. Finally, the participants were asked to provide examples of questions, essential to the performance of their work, for which they found it difficult to obtain answers.

In the case portion of the study, a series of 25 coordination 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 activities and problems that will be encountered in large scale design situations. This study does provide insight into activities performed and 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. SURVEY RESULTS ANALYSIS

The survey presented 6 activities, plus an additional category of their choosing (other), which the participant engineers could use to categorize the time spent at work. The engineers rated the same categories based on frustration levels encountered in each, and indicated the types of questions in each that they found difficult to answer. 30 surveys were distributed; at the time of writing of this paper, 25 had been returned. The following section presents the survey result, grouped by category.

Information Acquisition: Includes such activities as reading, attending seminars and getting answers to questions. The average percent of time spent doing this activity was calculated as 13.9% for the actual hours tracked and estimated as 12.4% for a typical week. Information Acquisition scored as the highest source of frustration and wasted effort. It's score was 4.0 on a scale of 1 to 7, with 1 as the highest level of frustration and wasted effort. The reasons given for the level of frustration were:

- The length of time to obtain information,
- The length of time taken by resource groups within the company in supplying, reviewing and approving information,
- The lack of standard technical information, and
- The lack of documentation available on-line.

Common questions the participants found difficult or impossible to answer were:

- Who has the information needed? Where (in what document) is the information?
- Is this the latest revision of the information? Is change coming?
- Is this my responsibility? Who is responsible for this item/task?
- What is the history of this design? Why does it have the form it have?

Problem Solving/Thinking: Includes simulations, analysis, experiments and what-if studies. The average percent of time spent doing this activity was calculated as 28.4% for the actual hours tracked and estimated as 31.6% for a typical week. Problem Solving/Thinking scored as the 6th highest (5.3) source of frustration and wasted. The reasons given for the level of frustration were:

- Analysis tools are inadequate in some cases, and a standard set of tools should be chosen.
- Computer hardware is insufficient for analysis, or access to it is insufficient.
- Better training is required, and better support between resource groups is required.
- Too little time is allocated for this activity, too many interruptions take place, and decisions are too slow.

Common questions the participants found difficult or impossible to answer were:

- What analysis is required? What model is appropriate? What methods should be used?
- How much analysis is required? Is analysis adequate?
- What testing is required? What are the user's requirements?
- What is the impact of a design change on the analysis?
- What previous trade-offs or analyses have been done?

Documentation: Includes preparation of reports, memos, flow-charts and diagrams. The average percent of time spent doing this activity was calculated as 23.1% for the actual hours tracked and estimated as 18.2% for a typical week. Documentation scored as the 2nd highest (4.3) source of frustration and wasted effort. The reasons given for the level of frustration were:

- Too few document standards, inadequate document preparation procedures (i.e. boilerplates), too much time spent on document sign-off.
- Too few up-to-date document hierarchies.
- Too few documents on-line, no way of showing figures on-line.

Common questions the participants found difficult or impossible to answer were:

- What document is required? What format? How much detail? Who establishes the criteria?
- Who should sign the document? To whom should it be sent?
- How can I get more information than document shows? What is the document hierarchy?

Planning: Includes activity planning and scheduling. The average percent of time spent doing this activity was calculated as 7.6% for the actual hours tracked and estimated as 8.6% for a typical week. Planning scored as the 3rd highest (4.5) source of frustration and wasted effort. The reasons given for the level of frustration were:

- Schedules are sometimes completely unrealistic. This can negatively impact designs.
- No standard way of doing schedules. No knowledge of deadlines and no overall strategy.
- Updating of schedules is time consuming, plans are always changing.

Common questions the participants found difficult or impossible to answer were:

- What is the schedule for this activity? What is the priority? Is the schedule realistic?
- What is the need date for this item? Do I have time to do this task?
- How did we plan this the last time? How do I allow for change? Are there standard measures for activities?
- What resources are there available for this task? Who is in charge of this item?

Negotiation: Includes establishing requirements and changing requirements. The average percent of time spent doing this activity was calculated as 7.5% for the actual hours tracked and estimated as 9.2% for a typical week. Negotiation scored as the 3rd highest (4.6) source of frustration and wasted effort. The reasons given for the level of frustration were:

- We're stifled by earlier designs - new ideas don't make it. Requirements are too vague and are hardware driven.
- People are too conservative in establishing requirements - they need guidance especially regarding cost impacts.
- Requirements are unclear, sometimes misleading due to too much documentation.

Common questions the participants found difficult or impossible to answer were:

- How do we maintain continuity of requirements? How do agree on minimum requirements?
- What is the background/justification of the requirement?
- Are these good test requirements? Are specs in line with baselined design?
- How much safety factor is there in the figure? What do we really want?

Support/Consulting: Includes meetings and answering questions posed by others. The average percent of time spent doing

this activity was calculated as 17.4% for the actual hours tracked and estimated as 18.3% for a typical week. Support/Consulting scored as the 5th highest (5.8) source of frustration and wasted effort. The reasons given for the level of frustration were:

- Meetings are unproductive and frustrating. We deviate, there are too many interruptions, and too much arguing.
- Support causes delay. There is too much consulting.

Common questions the participants found difficult or impossible to answer were:

- Where is the expertise I need to consult?
- What information do you need from me and why? What will you use it for?

Other: Includes computer downtime, administrative, expediting and demonstrations. The average percent of time spent doing this activity was calculated as 2.1% for the actual hours tracked and estimated as 1.8% for a typical week. 'Other' scored as the lowest (6.6) source of frustration and wasted effort. The reasons given for the level of frustration were:

- Expediting is frustrating and time consuming. It would not be required if we had better organisation.

4. CASE STUDY ANALYSIS

Our analysis of the cases identified six broad categories based on the cause of the coordination problem [2]. In the following we define each category and analyse its impact.

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.

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.

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.

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.

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.

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.

Overall it was felt that the combined 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%.

5. OBSERVATIONS

The two parts of the study are different from one another. The survey is aimed at establishing what engineers do: the time spent by engineers in six different activities, the level of frustration that these activities present to the engineers surveyed, and the questions which the participants find difficult to answer adequately. The problem case study, on the other hand, focuses on problems in information and knowledge access and acquisition, and general coordination problems in design-in-the- large.

The two parts of the study were conducted independently of one another, but trends from the survey results add an extra dimension to some of the problem case results, as would be expected.

In the survey, information gathering was chosen overall as the most frustrating of the activities. Participants raised a variety of issues around the length of time to obtain information, the lack of information in standard form, pending changes to information, outdated information and the lack of detailed information. Fortunately, given the high level of frustration indicated, the time spent gathering information was found to occupy only 12 to 14% of the participants' time. It is also important to note that the participants rated the task of documentation as the second most frustrating of the activities, but that this activity occupied substantially more of the participants' time, 18 to 23%. Issues raised around documentation included poor document standards, poor document hierarchies, too few documents on line and inadequate document preparation standards.

Based on the above observation, a point which should made is that better documentation is an important part of the solution to the problems experienced in information gathering. But since the participants have indicated that they find the level of frustration of documentation second only to that of information gathering, it can be anticipated that people will do as little documentation as they can. Also, one of the complaints raised on documentation was that information on how and what to document was difficult to obtain - which is itself an information gathering problem.

The case study analysis shows that 24% of the problem cases were due to information acquisition difficulties, and 32% of the problems cases were due to information access difficulties. When this result is considered alongside the survey findings, it suggests that the results of the information gathering are very important to the work of the participants, being responsible for over half of the problems encountered in the case studies. Thus the 12 to 14% of time spent gathering information has a huge impact on the level of difficulties experienced overall.

A positive aspect of the findings is that the activity which occupies the most of the participants time, problem solving and thinking, is the one in which they experienced the least frustration. This would seem consistent with the generally held notion that technical problem solving tools supplied to engineers in today's offices are an adequate support to their users.

Finally, a hypothesis based on anecdotal observations. Could it be that the difficulties and frustrations experienced in information gathering lead the participants to do more problem solving and thinking instead? This would suggest that where there might be an acceptable solution to an engineering problem already in existence, the difficulty in ever finding the solution within the organization's information structure makes it more likely that the engineer in question would "re-invent the wheel" rather than use the organization's knowledge resource. If this hypothesis is true, the potential for enhancing the efficiency of the design process using information tools is great indeed.

6. 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 establish what activities occupy engineer's time, what frustrations they encounter and what questions they find difficult to obtain satisfactory answers to. The goal was also to identify the categories of problems which arise due to the engineering process being performed by a group. Though this part of 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.

The survey indicated that engineers spend about 13% of their time in information gathering, 30% problem solving and thinking, 21% documenting their work, 8% planning their work, 8% negotiating requirements, 18% supporting and consulting and 2% doing other thing such as downtime, administrative functions and expediting.

The frustrations they encounter are many, and they rank their activities from highest to lowest level of frustration as follows: 1-Information Gathering, 2-Documentation, 3-Planning, 4-Negotiation, 5-Support and Consulting, 6-Problem Solving & Thinking, and 7-any other activities.

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.

The survey results show that the organization can exhibit the symptom of difficulties in information gathering coupled with poor documentation practices, which can act as a damaging cycle since good documentation is very helpful in remedying information gathering problems.

When the survey results are considered alongside the problem case analysis, the fact that information gathering and documentation are most frustrating to the participants is reflected in the result that almost 60% of the coordination problems are due to information access and acquisition. In other words, more of the right information needs to circulate, and this circulation needs to be facilitated.

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.

7. REFERENCES

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8. ACKNOWLEDGEMENTS

We gratefully acknowledge the support provided by Dr. Graham Norgate.

This research was supported, in part, by the Natural Science and Engineering Research Council, Digital Equipment Corporation, Micro Electronics and Computer Research Corporation, Spar Aerospace Ltd., Carnegie Group Inc., and Quintus Corporation.