Research in Engineering Design (1997) 9: 70–84

Research in
Engineering
Design

Case Studies of Coordination Activities and Problems in Collaborative Design

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Abstract. *The design and engineering of large, complex electromechanical 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, software and materials. This paper describes the results of a study conducted from the Summer of 1992 through the Fall of 1993 at a medium sized aerospace company. The study had two goals. The first goal was to identify project delays that were due to poor coordination and integration. The second goal 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 performing them. The first goal was accomplished by studying 25 problem cases, compiled and classified into six problem categories: information acquisition (24% of cases), information access (32% of cases), knowledge access (4% of cases), decision interdependence (8% of cases), activity management (12% of cases) and agent access (16% of cases). The delays associated with information acquisition, information access and knowledge access range from 1 day to as much as a year; they range from 1 day to a week for the other categories. The second goal, to identify the activities which occupy engineers and to rank the activities by the frustration and wasted effort encountered, was accomplished by conducting a survey, circulated to 30 engineers across five different departments. The participants were required to track the time spent in seven different activities over an actual 5 day week. They also estimated the time they would spend on these activities in a typical week on a percentage basis. The percentages of time spent were: information gathering (13.7%—actual; 12.2%—typical), problem, solving/thinking (28.0%—actual; 29.8%—typical), documentation (23.5%—actual; 19.5%—typical), planning (7.8%—actual; 8.5%—typical), negotiating (7.6%—actual; 9.8%—typical), support and consulting (17.1%—actual; 18.1%—typical) and other (2.3%—actual; 2.1%—typical). The participants also rated the activities from 1 (most frustrating) to 7 (least frustrating). The average scores, beginning with the most frustrating, were: 3.33-information gathering, 3.48-negotiation, 3.56-documentation, 3.67-support/consulting, 3.9-planning, 4.52-problem solving/thinking and 6.67-other.*

Keywords. Collaborative design; Collaborative engineering; Concurrent engineering; Design coordination

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 Unigraphics. Within engineering, a 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 physical behaviour of designs by simulation and analysis. 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 support the design of artifacts with reduced human involvement; this latter trend has occurred primarily in configuration-based design, e.g. design of computers or motors. Accompanying these major changes in technology, have been changes in the design problems themselves, and those being tackled today are of ever-increasing size and difficulty. The size of the teams required to undertake these projects usually introduces confounding social aspects to design which are the focus of this paper.

Complex artifacts, requiring the efforts of many engineers, must be functionally and/or physically decomposed, and responsibility for engineering the resulting components must be divided among members of the engineering team. Consequently, a coordination challenge arises: how can each engineer's design task be managed so that it interacts and

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their possible values. The grey fields illustrate the situation of this project.

Referring to education, the experience of the two different workprocesses A and B, as well as the analysis of the video recordings, was seen as a vital learning process by all students. To work on problems first without and then with supervision—and the comparison between the two approaches by the team members themselves—was an essential element of learning. This technique should be used more often in design education. Video recordings have proved to be very helpful in that context.

The project described in this article required more time and effort of students and supervisors involved than is usually available or required in design education. However, the motivation of the students and the quality of the results in design and production support further such projects in design education. Prospective engineers should be given the possibility to learn the systematic approach in design teams on concrete tasks and thus to prepare themselves for the practical requirements of industry.

Acknowledgements

The authors would like to thank the students who participated in the project, BMW, Munich for the disposal of the workshop and Prof. D. Ullman for his comments on a draft of this paper. We thank Wolf Meier-Ewert for his support in translation and Maximilian Hiebl for his work on the final layout of the paper. We are grateful to the reviewers of this paper and their constructive comments.

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integrates well with the efforts and results of other engineers and designers? Coordination of design teams is difficult mainly because each part of a design constrains the others. That is, a change in one part has a down-stream effect on other portions of the design. Furthermore, changes occur frequently during the course of design, so that each engineer must continually revise his work. Lack of coordination leads to schedule delay, rework and therefore cost increase. Kitzmiller and Jagannathan described problems supporting large scale design:

> 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].

Furthermore, in order to provide the right kind of design support, given these conditions, a thorough understanding of design as a social process must be developed. 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 and schedule. Sub-optimal decisions ultimately lead to higher cost, lower quality and delays.

Pennell and Winner [2] 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'. 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 [3].

In order to examine these coordination and social aspects, this paper focuses on how groups of over 50 people interact on major design efforts, the activities they perform, and the frustrations and coordination problems they encounter. Initially, the study was to be confined to a case study of coordination problems which occur in a large design project. The goals of the case study analysis were to:

1. Establish that collaboration problems exist;
2. Identify problem categories, if any; and
3. Determine if the problems have an impact on the organization.

Based on initial results, it became clear that further investigation was needed to answer the following question: do these collaborative problems occupy a significant amount of an engineer's time within the organization? To address this question, a survey was designed which focused on what activities engineers spend their time. In the survey, engineers recorded the actual time they spent in seven activities over a 1 week period. They also estimated what the breakdown would be for them over a 'typical' week. The analysis of the survey results, and the identification and classification of the problem cases and their impact on the design process are presented below.

2. Design of the Study

The source of information for both parts of the study was the everyday design activities in a division of an aerospace company.

In the case study, 25 problem cases were compiled, all of which are real-life coordination problems, mostly involving several members of the design team. Some of the problem cases are based on an individual team member's interactions with the organization as a whole. The problems are encountered in a multi-million dollar international space program which has been underway for some 5 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, mostly regarding dealings within the prime contractor organization, and some regarding interaction with subcontractors.

All the cases were provided by one employee/source person who worked for the prime contractor. The cases (including the delay time estimates) are based on the personal experiences of a group of employees which includes the source person, and cover a period of time during the design and development phase of the program. The approximate time period is from May until December, 1992.

The case set was analysed by the authors to determine whether classes of problems could be detected. This analysis revealed the six different problem categories discussed later, and the percentages of the problem cases which fell within these categories.

In the survey portion of the study, 30 surveys were distributed, five apiece, to the mechanical, electrical, systems, controls and analysis and software departments from February to April, 1993.[1] The criteria for selection of the survey participants were that they had to be engineers (as opposed to managers), and assigned to a design program at the time they filled out the survey. This represented a group of approximately 300 people at the company.

The researchers felt that the method would provide representative data on the activities of design engineers at the company for the following reasons:

1. The company was structured as a matrix organization at the time, therefore most engineers had worked on several different programs.
2. The engineers surveyed represented approximately 10% of the engineers who met the survey participant criteria at the company.
3. Any large differences between the actual surveyed week's activities and those of a 'typical' week were accounted for in the survey.

The engineers who received the surveys recorded, for 1 week, the hours they spent working in seven activities (to within 1/4 h). The activity categories were selected by a group made up of employees from the aerospace company, and members of the research group from the University of Toronto. The employee group included four engineers with differing levels of experience in design, from 1.5 years to over 15. The activities chosen, which best captured the areas in which engineers spent their time were:

1. Information gathering: locating and reading documents, and getting questions answered.
2. Problem solving/thinking: performing simulations, analysis, experiments, and studies.
3. Documentation: producing reports, memos, and diagrams.
4. Planning: planning and scheduling activities.
5. Negotiation: establishing and changing requirements.
6. Support and consulting: attending meetings and answering questions posed by others.
7. Other: (specified by the participant).

For the above activities, the participants estimated what they thought the percentage split of their time would be in a typical week. The participants then rated the frustration and wasted effort they encountered in the activities, along with their reasons. Frustration levels were scored by the participants on a scale of 1 to 7, with 1 as the highest level of frustration. 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.

It should be stressed that the two parts of the study were conducted independently of one another. While the activity selection group included the source person for the problem cases, the results of the case study had not been compiled at the time of the selection of the survey activities, and the approximately 5–7 problem cases then compiled were not shown to the group. In fact, it was not foreseen at the time that the survey and the case study were to be analysed jointly in future work.

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 encountered in large scale design situations. This study does provide insight into activities performed, frustrations encountered 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.

1. The quantity of surveys completed was based on how many were willing to cooperate!

3. Case Study Analysis

The analysis of the cases identified six broad problem categories based on the cause of the coordination problem [4]. In the following section, each category is defined, its impact is analysed and a sample case is given.

3.1. Information Acquisition Problem

This category focuses on information created or used by one part of the team that is not accessible by other team members—it is neither physically nor electronically available—hence lies outside any documentation and cannot be traced directly, and is therefore not available to employees needing it. Six of the cases, 24%, focused on information acquisition problems. In the problem cases, this can result from an engineer being assigned a partial or complete project with little or no information as to why it is designed the way it is. An example from this category is given in the following excerpt from the problem case set:

> An engineer inherits a design in its preliminary stages because the engineer who was previously working the design has been moved off the design onto some other project. The design has evolved a certain way due to requirements and constraints, but the drawings only show the results of these influences. Specs only document so many of the requirements; many are the result of telephone conversations, meetings, memos and other more informal modes of communication. Therefore, an

inherited design is quite overwhelming to the inheritee, who, confused by the particular form the design has taken, may not know how to proceed with it. When the inheritee begins to make her design changes, she might unknowingly violate one of these less formal requirements, forcing redesign at a later time, that would not have been necessary had the original engineer remained on the job [4].

The excerpt refers to constraints which emerge from the design process itself, which are not normally captured in a specification. In this particular case, the specification contained approximately 250 requirements for the item related to its performance, quality and workmanship, environments in which it must operate, qualifications for certain components, etc. The specification would not contain constraints dictated by the availability of certain stock materials, locations of certain features as constrained by other features within the item, sizes of certain features, etc.

There are two sources of the difficulty. First, design rationale, i.e. why a decision was made and upon what data or analysis, is seldom recorded. Most engineers dislike recording their thought processes, even if they are introspective; usually all that is 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 it lies outside of any formal systems.

Typically, delays associated with this category range from days to weeks, or long enough for the engineers in question to 'acquire' the desired information. It is possible that design rationale information can never be located and the design process has to be re-initiated in a situation where identical rationale could be applied. In this instance, delays associated with this problem category can ultimately range from 1 week to as much as a year.

3.2. 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 contracts, specs, catalogues and other documents. Different (i.e. more up-to-date) design versions are another form of this problem category which occurs often. Whether desired information is available in physical or electronic form, three time consuming and sometimes exasperating steps recur: (1) learning of the existence of information, (2) finding where it is located, and (3) retrieving it. An example from this category is given in the following excerpt from the problem case set:

> An engineering resource group places a design requirement in a specification. The requirement goes unnoticed until a question comes up on the fact that the requirement is not being met in a particular design. During a discussion on the issue, a request to see the requirement in a spec is made by project engineering. When the most likely specification is searched, the requirement cannot be found, having been either deleted, or omitted accidentally from the most recent issue of the document, or perhaps moved to another location in the document structure. No one with knowledge in this area is available to help answer the question, hours are wasted in a fruitless search through documents, and the requirement is still not found. Project engineering may or may not agree to accommodate the requirement, potentially forcing redesign of some components, or redefinition of requirements [4].

This particular problem case relates to the familiarization of users with the latest format of a specification. One might wonder if the problem could be solved with strict adherence to document standards. In fact, all the proper document control steps had been followed at the company (compliant with MIL standards); the designers in question were unaware of a change in the location of a requirement which had been migrated to a higher level specification two or more document generations ago. Adherence to ISO9001 would mean that only the latest revisions of documents are in use, and obsolete documents retained 'for legal and/or knowledge preservation purposes are suitably identified', but would not mandate that they be accessible to designers.

In general, difficult and delayed access to information available in a physical form but not located nearby is understandable if not unavoidable at times. However the lack of integration of information systems is as pervasive, and results in similar problems and delays. Another aspect of this problem is that there may be too much information available, burying what is essential among the rest, thereby making it inaccessible. This is especially problematic when the information is physically recorded making it tedious to search. The delays associated with this category are in the range of 1 h to one week.

3.3. Knowledge Access Problem

This problem category appeared in only one case, 4%, but its impact is very far-reaching. The problem type is illustrated in the following excerpt from the problem case set:

> 'Expertise among more senior people is always in demand at a company. Many of the older employees are veterans of many years with a company and with other companies that they may have worked for in their careers, and have stores of knowledge the importance of which even they do not appreciate. When more junior members need to find out something from these senior people, they very often are inaccessible, due to the amount that they are in demand, and their knowledge therefore does not benefit others the way it could.
>
> In addition to this, the moment that such an employee walks out the door on retirement, most of their knowledge walks out the door with them. The results of this knowledge may be present at the company in the form of designs, reports, drawings, etc., but the process that generated the work is not recorded, therefore not retrievable. This information is a tremendous asset of the company's, but the company can no longer benefit from it after the retirement of the employee within whom the knowledge resides [4].

Many senior people at companies have knowledge that is in demand among less experienced employees. These senior people have their own deadlines and responsibilities to meet, and therefore cannot always provide the level of support required by their colleagues. In fact, it is this type of problem that led to the widespread investigation and implementation of expert systems in industry.

Although it might seem that the problem would be more relevant to less experienced engineers, the problem can affect engineers anywhere in their careers. The problem category usually is characterized by the wasting of time and money in the investigation of sub-optimal designs and blind alleys which could have been avoided through knowledge and experience present in the expert. Consequently, this problem category produces long term effects on the design process which are not easily quantifiable. The delays can range anywhere from several days to a year, perhaps even more.

3.4. Decision Interdependence Problem

Two of the cases, 8%, focused on how individual decisions can cause severe coordination problems and introduce delays to a program. An example from this category is given in the following excerpt from the problem case set:

> A design incorporates a standard fitting as a requirement agreed on by the company and their client. The pattern for the standard fitting is taken from a catalogue.
>
> Several months later, the design has matured to the critical design audit (CDA) stage, but no one has remarked that the pattern from the catalogue is an antiquated design which is not base-lined for the program in question. A new pattern for the standard fitting has come from the client, but no one at the company is aware of it, and it is only by chance that a company engineer, who has heard about the new pattern, notices the discrepancy in drawings he is reviewing for sign-off.
>
> The drawings must now be reworked, at a cost of many man-hours. As well, the mistake can propagate to other parts of the product which are also using the standard fitting, causing more rework [4].

This particular case is unusual since the supplier of the component was the client, a very large organization. Strictly speaking, the contract stipulated that changes of this nature were to be well publicized, but in this case, they were not. Also, due to the relatively small impact, the additional cost and responsibility for the mistake was borne by the company.

This problem type 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 such decisions are made in isolation, a coordination problem often arises. 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.

Although only 8% of the cases exhibited this problem, it is felt that the problem type is probably much more pervasive than this figure indicates. The resulting delay time is in the range of 1 day to 1 month.

3.5. Activity Management Problem

Three of the cases, 12%, focus on the non-adherence to schedules for various reasons. Of particular concern was the inability to perform review activities on time. Given the vast amount of information which is routinely reviewed, and other, perhaps more pressing activities an engineer has to perform, reviewing other peoples' work can slip in the priority list. An example from this category is given in the following excerpt from the problem case set:

> An engineer tries to get qualified people to review a document and to supply their comments prior to

its release date in accordance with a company schedule. The people he is dealing with are very busy, perhaps more highly placed, so he decides to use an unobtrusive method to impose the deadline, namely by stating it in a cover letter on the document. Along with the statement of the deadline, the engineer requests that if any of the reviewers are unable to meet the deadline, they are to call the engineer to let him know when they can have their comments on the document available.

When the deadline arrives, the engineer approaches the people whose comments had been requested, but not yet forwarded. He finds that of these people, some had not yet completed the task, and no one had bothered to call, although they realized that the engineer had specifically asked them to do so [4].

Another source of the problem is the shifting of players that takes place in a project. Engineers are reassigned or go on vacation and as a result deadlines are missed simply because no one is aware of them. Though engineering organizations spend significant amounts of time creating schedules, these can be very difficult to adhere to.

Part of the problem is individual time management but there is also a lack of procedures and systems to support project management. And in cases where there are systems, different levels of personnel use different systems which are not always well integrated. The delay time associated with these problems ranges from 3 days to 1 week.

3.6. 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 makers are available. In other cases, it is simply difficult to find where a person is located when the project is large and dispersed geographically.

An example from this category is given in the following excerpt from the problem case set:

> An engineering team leader was having a busy day such that he was hardly at his desk, but spent the day running around between meetings, and talking with people. That day, several design issues which required the leader's attention came up, and several other engineers, all on the team, were trying to get hold of the team leader, to no avail. The result of the leader's inaccessibility was that these other engineers, who needed the leader's input, were forced to wait until the leader was available for consultation [4].

Four of the cases, 16% of the total, fell into this

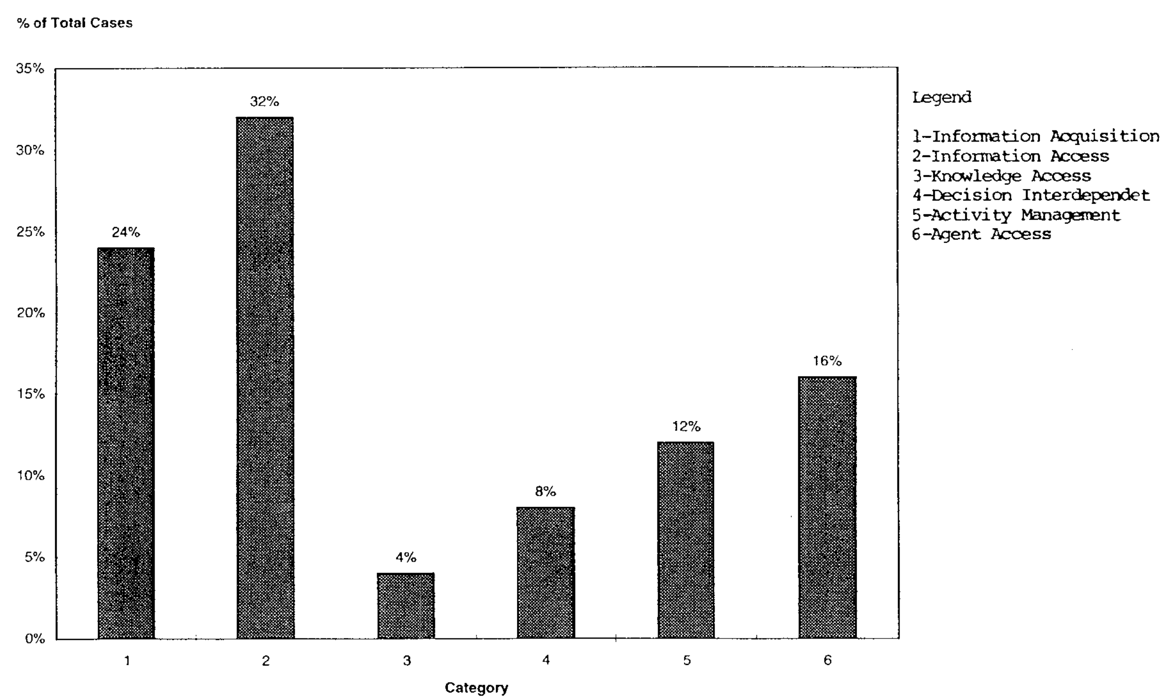

Fig. 1. Histogram of problem cases versus categories.

category. Problems in this category cause delays which range from 1 day to 1 week.

The histogram in Fig. 1 shows the distribution of the 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 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%. This is strictly a subjective view of the researchers not backed by any survey data but neither was it challenged by company management.

4. Survey Analysis

The survey presented six activities, plus an additional category if desired (called 'other'), which the participant engineers could use to categorize their time spent at work [4]. The engineers scored the same activities 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, and 27 were returned. The following section presents the survey results, grouped by activity category.

4.1. Information Gathering

Includes such activities as reading, attending seminars and getting answers to questions. The average percentage of time spent doing this activity was calculated as 13.7% for the actual hours tracked and estimated as 12.2% for a typical week. Information acquisition scored as the highest source of frustration and wasted effort. Its score was 3.33 on a scale of 1–7, 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 has?

4.2. Problem Solving/Thinking

Includes simulations, analysis, experiments and what-if studies. The average percentage of time spent doing this activity was calculated as 28.0% for the actual hours tracked and estimated as 29.8% for a typical week. Problem solving/thinking scored as the second lowest source of frustration and wasted effort. Its score was 4.52 on a scale of 1–7, with 1 as the highest level of frustration and wasted effort. 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 and too many interruptions take place.

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 my 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?

4.3. Documentation

Includes preparation of reports, memos, graphs and diagrams. The average percentage of time spent doing this activity was calculated as 23.5% for the actual hours tracked and estimated as 19.5% for a typical week. Documentation scored as the third highest source of frustration and wasted effort. Its score was 3.56 on a scale of 1–7, with 1 as the highest level of frustration and wasted effort. The reasons given for the level of frustration were:

- Too few document standards, inadequate document preparation procedures (i.e. no 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 the document shows? What is the document hierarchy?

4.4. Planning

Includes activity planning and scheduling. The average percentage of time spent doing this activity was calculated as 7.8% for the actual hours tracked and estimated as 8.5% for a typical week. Planning scored as the third lowest source of frustration and wasted effort. Its score was 3.89 on a scale of 1–7, with 1 as the highest level 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?

4.5. Negotiation

Includes establishing requirements and changing requirements. The average percentage of time spent doing this activity was calculated as 7.6% for the actual hours tracked and estimated as 9.8% for a typical week. Negotiation scored as the second highest source of frustration and wasted effort. Its score was 3.48 on a scale of 1–7, with 1 as the highest level 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 should we agree on minimum requirements?
- What is the background or justification for 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?

4.6. Support/Consulting

Includes meetings and answering questions posed by others. The average percentage of time spent doing this activity was calculated as 17.1% for the actual hours tracked and estimated as 18.1% for a typical week. Support/consulting scored as the fourth highest source of frustration and wasted effort. Its score was 3.67 on a scale of 1–7, with 1 as the highest level 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?

4.7. Other

Includes computer downtime, administrative, expediting, travelling and demonstrations. The average percentage of time spent doing this activity was calculated as 2.3% for the actual hours tracked and estimated as 2.1% for a typical week. 'Other' scored as the lowest source of frustration and wasted effort. Its score was 6.67 on a scale of 1–7, with 1 as the highest level 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 organization.

4.8. Summary

Table 1 shows the results of the survey analysis at a glance.

5. Observations

The two parts of the study differ. The problem case study focuses on determining the type and frequency of coordination problems that arise in large engineering projects. The survey, on the other hand, is aimed at establishing what engineers do: the time spent by engineers in six different activities, the level of frustration the engineers surveyed experienced in these activities, and the questions to which the participants find difficult to obtain adequate answers; the ultimate objective being to determine whether coordination activities occupy a significant portion of an engineer's time.

The two parts of the study were conducted independently of one another. The case study quickly revealed that there were indeed coordination problems in collaborative design. It was clear that an unbiased survey of where engineers spend their time was needed in order to see if coordination made up a significant component. The significance of coordination in the study is developed below.

Table 1. Survey results at a glance.

	Activity						
	Information gathering	*Problem-solving*	*Documentation*	*Planning*	*Negotiation*	*Support/ consulting*	*Other*
% Time actual	13.7 (sd = 9.0)	28.0 (sd = 21.0)	23.5 (sd = 18.4)	7.8 (sd = 7.4)	7.7 (sd = 8.4)	17.1 (sd = 13.5)	2.3 (sd = 5.6)
% Time estimated	12.2 (sd = 8.9)	29.8 (sd = 17.4)	19.5 (sd = 17.6)	8.5 (sd = 4.1)	9.8 (sd = 8.4)	18.1 (sd = 12.4)	2.1 (sd = 6.5)
Frustration score	3.3 (sd = 2.1)	4.5 (sd = 2.1)	3.6 (sd = 2.1)	3.9 (sd = 2.1)	3.5 (sd = 2.2)	3.7 (sd = 2.1)	6.7 (sd = 1.2)

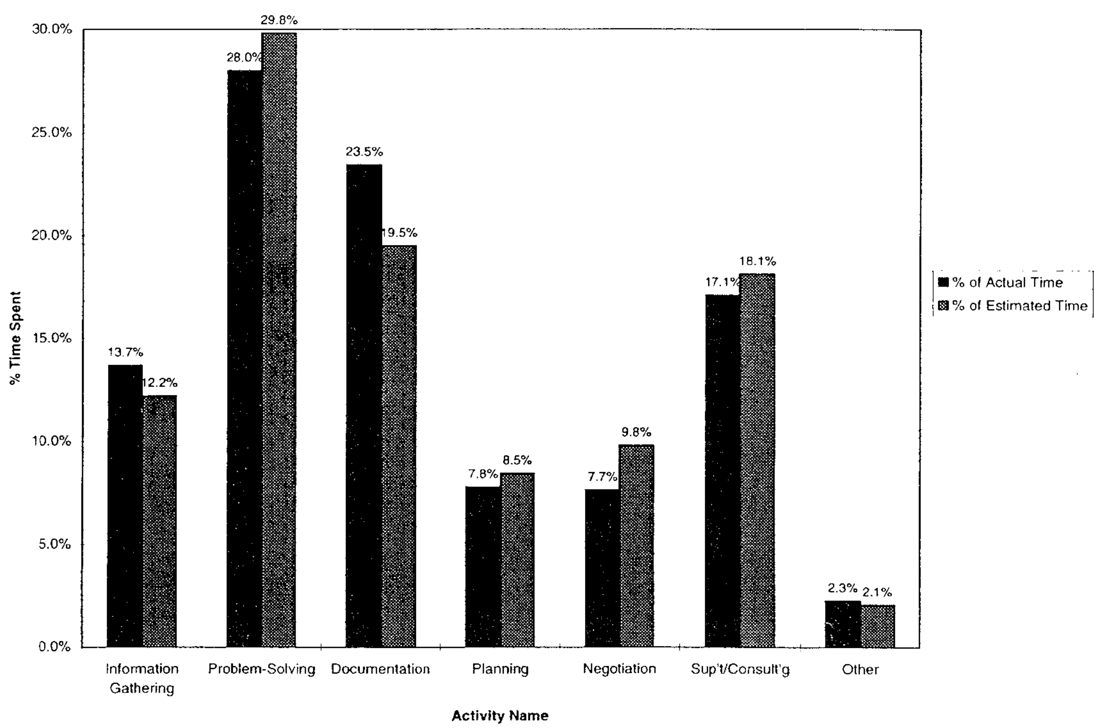

Fig. 2. Histogram of activity type vs % time.

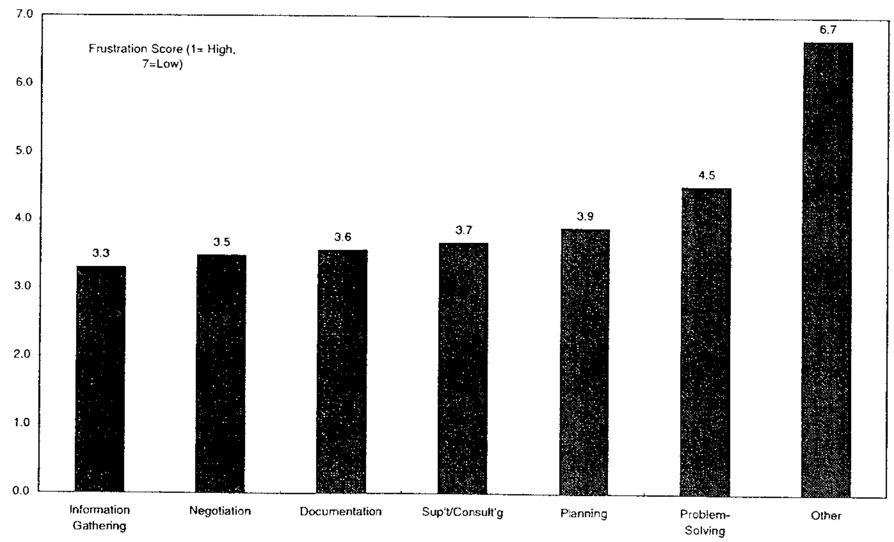

Fig. 3. History of activity type vs frustration score.

5.1. Observation 1

Examination of the survey results alongside the coordination problem categories shows signs of correlation:

1. The activities 'information gathering' and 'documentation' appear to relate to problem categories 'information acquisition' and 'information access'. The activities involve setting out within the knowledge resource of the organization to seek and obtain information consisting of basic inputs to design work, or recording the same information to make it available to all members of the team. And the problems encountered when gathering this type of information, or created when insufficient documentation takes place are mainly that the documentation is available but engineers cannot reach it—an information access problem, or that the information is available, but lies outside the available documentation forms—an information acquisition problem.
2. The activity 'support and consulting' appears to relate to problem categories 'knowledge access' and 'agent access'. The survey activity refers to answering questions posed by others and supporting meetings, or in general, interaction with others to give or obtain support or knowledge. And when one encounters a coordination problem in this activity, the best descriptions from the problem categories are that either the knowledge source is inaccessible— a knowledge access problem—or the source of support is inaccessible—an agent access problem.
3. The activity 'planning' relates to the problem category 'activity management'. In the survey, planning refers to activity planning and scheduling. Problems encountered in this area stem from non-adherence to schedules, or, from the problem categories, activity management problems.
4. The activity 'negotiation' relates most closely to the problem category 'decision interdependence'. Negotiation is the establishment and changing of requirements between members of the design team, and when requirements are changed in collaborative design, the problems which arise are the impact to one area of the design from a decision made in another. In the problem case study, this is known as decision interdependence.

Based on these relationships, it is clear that all the activities surveyed, except for problem solving and thinking, can be viewed as coordination activities. When the percentage of time spent performing the survey activities listed above (namely all activities except 'problem solving and thinking') is compared to the percentage of problem cases falling into the problem categories listed above, a strong relationship emerges, as shown in Table 2. Note that the survey activity percentages are given as a raw percentage and as a normalized percentage leaving out the activity 'problem solving and thinking'.

The results from the table suggest that: based on the relationships established above, the activities which involve coordination take up, on average, approximately 69% of an engineer's time in collaborative design. They also show that the percentages of time spent in survey activities correspond closely to the frequency of coordination problem types.

Table 2. Survey vs case study results.

	Survey			*Case Study*	
Rank	*Activity*	*% Time raw*	*% Time normalized**	*Category*	*% Cases***
1, 3	Information gathering and documentation	34.5	50.00	Information access and information acquisition	58.0
2	Support and consulting	17.6	25.6	Knowledge access and agent access	21.0
5	Planning	8.2	11.8	Activity management	12.5
2	Negotiation	8.7	12.6	Decision interdependence	8.5
	Total	**69**	**100**	**Total**	**100**

* 'normalized' refers to the hours spent in the listed activity divided by the total hours minus time spent on problem solving and thinking
** percentages differ slightly in this table as they have been adjusted to offset unclassifiable case mentioned in section 3.6

The case study analysis shows that 56% of the problem cases were due to information acquisition and information access difficulties alone. When this result is considered alongside the survey findings, it suggests that the results of information gathering and documentation are very important to the work of the participants, being the source of over half of the problems encountered in the case studies. The relationship between information gathering and documentation is explored next based on the frustration scores from the survey.

5.2. Observation 2

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. The time spent gathering information was found to occupy 12–14% of the participants' time.

The participants rated the task of documentation as the third most frustrating of the activities. Documentation did occupy more of the participants' time, at 19.51–23.45%. Issues raised around documentation included poor document standards, poor document hierarchies, too few documents on-line and inadequate document preparation standards.

With respect to the above, it would appear that more and better documentation is needed to relieve the frustration and problems experienced in information gathering. One might think that engineers would try to alleviate this frustration by doing more and better documentation. But because engineers experience a substantial level of frustration in documentation, they do less than they should. Also, one of the complaints raised about documentation was that information on how and what to document was difficult to obtain—which is itself an information gathering problem.

Another factor affecting the desire to create documentation, is that management and engineers believe that they are 'swimming in a sea of documents'. There is too much paper, too many versions, many of which are outdated but not known. It is difficult to find the 'one piece' of information in the mountain of paper. Simply making everyone document more is not the solution.

5.3. Observation 3

Negotiation was rated as the second most frustrating activity, and the reasons given are mostly that other people in the organization do not always appear to be 'up-front' enough when establishing requirements, resulting in too much conservatism, lack of justification and lack of agreement on the negotiated result. The participants also pointed out that new ideas tend to get stifled due to confidence being placed only in previous designs—an impediment to innovation. People spent between 7.65% and 9.8% of their time in negotiation.

It is also possible that better documentation, and perhaps better communication in general, can help alleviate the issues raised around negotiation, for example the lack of requirement justification, and the presence of too much conservatism in the establishment of requirements.

5.4. Observation 4

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, and which produced no problem cases directly. This is consistent with the theory that technical problem solving tools supplied to engineers today are comparatively well suited to their users' needs. It also suggests that engineers would prefer to be left alone to solve their technical problems without getting disrupted by goings-on in the outside world.

5.5. Observation 5

Finally, a hypothesis was developed based on anecdotal observations: could the difficulties and frustrations experienced in information gathering lead the participants to do more problem solving and thinking instead? If this were the case, it 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.

6. Related Research

A review of the literature has revealed that there are few studies which have investigated the question of how large groups of people collaborate in design from the perspective that the preceding study has taken. However, many papers have observed problems and activities of collaborative design similar to what this study has extracted. In the following section, literature related to the problem case study is discussed first, then a paper with a section related to the survey activities is presented, and lastly, two papers which address the collaborative design environment are cited.

A useful general outlook on the problem issues of team design work is given in a paper by Prasad *et al.* [5]. They describe the issues of developing tools to support concurrent engineering (CE) as how to '... capture, manage, coordinate and utilize the CE environment's constantly evolving data, knowledge, and processes', which resembles information access and acquisition issues raised in earlier sections. Product data and knowledge is developing in parallel, which requires designers to 'proceed with partial information, incomplete knowledge, and subjective interpretations'. The issue of proceeding with incomplete knowledge can be seen as a potential decision interdependence problem, however, the issue of subjective interpretations is not considered directly in this paper.

Although McNeese *et al.* [6], address the information access problems now familiar to readers of this paper, they also emphasize the issue of interpretation, communication skills of individuals, and mental models in the following quote: '... Groups often experience difficulty in collaboration because members: (1) have access to different information which has not been effectively distributed ... (2) may have access to the same information but interpret it differently, (3) may lack a common conceptual framework, and (4) fail to communicate their own perspective to other team members'.

Kleinman's [7] characterization of design information as possibly 'incomplete and inaccurate due to lax updating, missed detection of events, information whose quality changes with time, errors in data taking, etc.,' is consistent with problem cases discussed, namely information access and acquisition and to some extent decision interdependence. Kleinman stresses that the team must coordinate their information to develop a unified common assessment of the design situation for decision making and action taking to control interdependence problems.

In a paper based on experiences from industry, Lindeman and Wijaya [8] describe a system called 'Concurrent Engineering Data Structure' (CEDS) implemented at Texas Instruments in Plano, Texas. Some problems prior to implementation of CEDS were: (1) multiple versions of the design existed, (2) engineers wanted to work free from the worry of design changes by other team member's alterations, but could not, and (3) the team did not have an effective mechanism to share data, resulting in much wasted time and duplication of effort and data.

These problems fit the descriptions of information access and decision interdependence from the problem case set. CEDS brought the following benefits to TI: (1) single point of access eliminated confusion and data duplication: entire team works from same structure, and shares data, (2) data became 'up-to-the-minute', (3) the system helps monitor program progress, ensures completeness of design input, and (4) design analysis history is naturally captured at the point of release. These features would reduce frustration experienced by the survey participants in information gathering (benefits 1, 3 and 4), and planning (benefit 2).

Information acquisition and access are mentioned in several other papers. The many problems encountered by different versions of designs available within an organization at a given time is treated by Biliris and Zhao [9]:

'... 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'.

Sinclair *et al.* [10] commented on problems in the management of design information, particularly with respect to design histories (information acquisition) and knowledge access:

'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 ....'

Thomas and Drury [11], highlight the difficulty of keeping a complete, shared view of the current design. Problems in acquiring and using system knowledge include 'limited policies for recording experience' within companies. They also mention 'a disinclination to search for solutions' due to scarcity of experts and support staff for documentation retrieval, etc., which relates to the knowledge access problem category, and which supports the hypothesis at the end of Section 5 of this paper.

Information acquisition is the focus for Garcia and Howard [12] in 'Acquiring Design Knowledge Through Design Decision Justification'. They state that 'very little, if any, of the design decisions and rationale for those decisions is captured in current documents'. They propose a system which, like an engineering apprentice, extracts design rationale information from designers, including hypotheses proposed, assumptions made, changes in previous parameter values and decision history.

The 'specific requirements of the CE environment', given by Prasad *et al.* [5] are listed below. There are strong similarities to the activities of engineers which involve coordination as shown in Section 5 of this paper:

- 'information modelling' resembles documentation,
- 'teaming and sharing' and 'collaborative decision making' resemble support and consulting,
- 'planning and scheduling' resembles planning,
- 'networking and distribution' resembles information gathering,
- 'reasoning and negotiation' resembles negotiation,
- 'organization and management' had no direct counterpart with the survey activities, but could be considered a form of planning.

Much analysis of engineering design has focused on the steps and stages of group design itself, often in order to propose a prescriptive model for design, which does not relate to this paper. However, an analysis by Wallace and Hales [13] observed that approximately half of the work effort they observed in a 2-year, 37 person design project consisted of 'steps of the design process'. The other half consisted of:

- personal day-by-day work planning
- reviewing and reporting project progress
- cost estimation
- information retrieval and processing
- social contact and interactions
- informally helping on other projects.

This result compares with the present study's finding which showed that problem solving and thinking and documentation accounted for 52% of the actual and 49% of a typical work week.

7. 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 approach, to a group problem-solving approach. The first goal of this study was to identify the categories of problems that arise due to the engineering process being performed by a group. Though this part of the study was narrow in the sense that it was the experience of a single engineer, it is interesting in that the designer operated within a group numbering over 100 designers and engineers. Once the categories of coordination problems were established, understanding whether coordination-related activities occupied a significant portion of an engineer's time, and the degree to which they feel frustrated by them, was the next goal.

At the level of evaluation of this study, the problems of coordination are many and diverse, and cause significant delays in schedule. In all, 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 increased costs to a company once a program is underway, as well as decreased competitiveness when bidding on contracts.

The survey indicated that engineers spend about 13% of their time in information gathering, 29% problem solving and thinking, 21.5% documenting their work, 8% planning their work, 9% negotiating requirements, 18% supporting and consulting and 2% doing other things such as downtime, administrative functions, travelling and expediting. The study finds that *activities which involve coordination occupy approximately 69% of an engineer's time in collaborative design*, and include all but problem solving and thinking. The percentages of time spent in these survey activities corresponded closely to the frequency of coordination problem types. Given the percentage of time an engineer spends in coordination-related activities, the increase of project time due to coordination problems, i.e. 20–30%, is probably a conservative estimate.

Many frustrations are encountered by the participants, and they rank their activities from highest to lowest level of frustration as follows: 1-Information gathering, 2-Negotiating, 3-Documentation, 4-Support and consulting, 5-Planning, 6-Problem solving and Thinking and 7-Other activities.

Where do standards such as ISO9001 fit in? In theory, ISO9001 solves many interdependency problems through documentation and communication procedures. But in practice, when designing large complex artifacts, whose specification is provided by the customer, where the specification is incomplete and even ambiguous, and where concurrency in design is a goal (hence engineers begin work with only a partial specification), conformance to standards is quite difficult unless buttressed with a better support infrastructure.

In order to solve the problems of collaborative design presented in this paper, 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 willingly record such information [14, 15]. 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 maintenance are still too great to be considered for 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 [16, 17]. Fifth, activity management technologies abound, e.g. project management systems, but the engineering of a usable system that adds value to the process still remains beyond reach. And sixth, access to people and systems remains a problem, but is being reduced with current communication technologies such as facsimiles and cellular phones.

Nevertheless, industry cannot wait for these problems to be solved. The building of an infrastructure to support collaborative design must begin today. Two technologies have begun to make this possible. First, the development of engineering reference data models that provide an integrated representation of engineering data and knowledge. These reference models provide a repository which existing applications can upload/download information to/from. Second, the World Wide Web provides a client/server standard for browsing information and accessing to applications. With Web standards, organizations can create an Enterprise Wide Web that provides engineers with access to the repository and other applications from everyone's PC.

The biggest challenge is to recognize that collaborative design engineering is a social process. To date, information system technologies have been simply enabling technologies and not solutions in of themselves. Real solutions will arise when it is recognized that solutions must be system solutions, where the system is redesigned as an integration of people, procedures and technologies.

Acknowledgements

This research was supported, in part, by Industry Canada and the Natural Science and Engineering Research Council of Canada, and by Carnegie Group Inc., Digital Equipment Canada Ltd, Micro Electronics and Computer Research Corporation, Quintus Corp., and Spar Aerospace Ltd. We would like to thank C. Butlin, D. Cooper, P. Cross, J. Gabriel, G. Norgate, S. Sachdev and T. Tucker for their support in conducting this study.

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