Where design engineers spend/waste their time

R. A. Crabtree, N. K. Baid, M. S. Fox
Department of Industrial Engineering
University of Toronto
4 Taddle Creek Road
Toronto Ontarioa M5S 1A4 Canada

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

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, 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 [3].

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.

1. 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?

2. 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?

3. 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 (ie. 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?

4. 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?

5. 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?

6. 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?

7. 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 [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 dif cult 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 signi cant 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 dif cult trying to nd 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

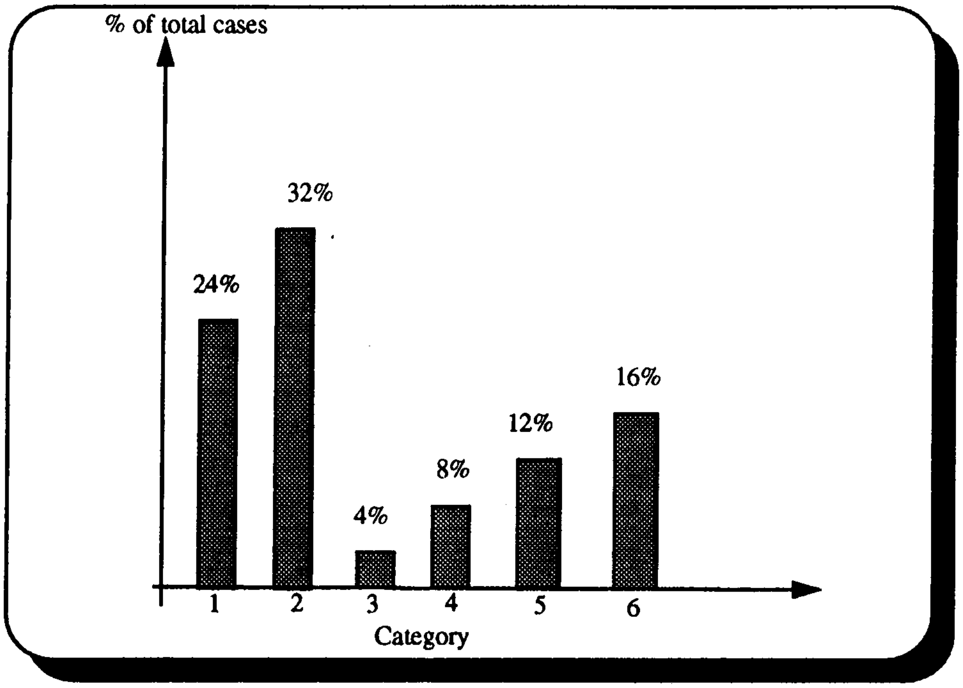

Figure-1: Percent of cases in each category

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%.

5. 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 ndings 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 speci cations) 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...uni fied 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 con figuration. 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 ef ficiency of this process might reduce the amount of information required to be shared, by increasing speci ficity 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... .

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 pro fit lost to a company once a program is underway, but a decreased competitiveness when estimating costs for bidding on future contracts.

The dominant problem arising out of both studies is consistent. ***Information access*** is both the most fustrating task arising out of the survey, and the source of the largest number of coordination problems in the case studies. Engineers operate in an environment where the information needed to perform their tasks either takes too much time to get or is simply not available due to acquisition problems.

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.

7. REFERENCES

[1] Kitzmiller, C. and Jagannathan, V. Design in a Distributed Blackboard Framework *Intelligent CAD.I: Proceedings of IFIP TC/WG 5.2 Workshop on Intelligent CAD*, pp. 223-33, North-Holland, Amsterdam, Netherlands, 1989.

[2] Pennell, J.P. and Winner, R.I. Concurrent Engineering: Practices and Prospects , *GLOBE-COM 89: IEEE Global Telecommunications Conference and Exhibition - Communications for the 1990s and Beyond*, vol.1, pages 647-655, IEEE, New York, N.Y.

[3] Crabtree, R. A. A Study of Problems in a Collaborative Design Environment , Technical Report, Department of Industrial Engineering, University of Toronto Canada, 1993, in preparation.

[4] Kuffner, T.A. and Ullman, D.G. The Information Requests of Mechanical Designers , *Proceedings of the 2nd International Conference on Design Theory and Methodology*, v. 27, ASME, New York, N.Y. 1990, pp. 167-174

[5] Brazier, D. and Leonard, M. Participating in Better Designs , *Mechanical Engineering*, vol.112, no.1, 1990, pp. 52-52.

[6] Biliris, A. and Zhao, H. Design Versions in a Distributed CAD Environment , *Proceedings of the Eighth Annual International Phoenix Conference on Computers and Communication*, pp.354-359, IEEE Computer Society Press, Washington, D.C., 1991.

[7] Sprague, R.A., Singh, K.J. and Wood, R.T. Concurrent Engineering in Product Development , *IEEE Design and Test of Computers*, vol.8, no.1, 1991, pp. 6-13.

[8] Olson, M.H. and Bly, S.A. The Portland Experience: a report on a distributed research group *International Journal of Man-Machine Studies*, vol.34, no.2, 1991, pp. 211-28.

[9] Sinclair, M.A., Siemieniuch, C.E. and John, P.A. A User centred Approach to Define High-Level Requirements for Next-Generation CAD Systems for Mechanical Engineering *IEEE Transactions on Engineering Management*, vol.36, no.4, 1989, pp. 262-270.