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An effective method to analyse chronological information aspects in actual engineering processes

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Abstract

Offering effective computer support during the early stages of the engineering process is a longstanding problem. Research into actual engineering processes is an essential contribution to establishing objective criteria for effective tools. We propose to derive such criteria from observed engineering processes and to test these requirements experimentally. We describe the first series of observations that resulted in data, serving as a reference for subsequent experiments. The control design project was bidisciplinary (mechanical and electrical) and significantly involved conceptual decision making. The experiment focussed on information needs by the designer, information retrieval and information production. Preliminary analysis shows a steep distribution of the time delay between information request and the answer to the request, suggesting a strong influence of information access time on several aspects of the engineering process.

Keywords

Engineering processes, empirical analysis, design information, computer support

1 INTRODUCTION

Computer-aided conceptual design is still known as an extremely difficult goal to achieve. This contrasts the situation for other engineering stages such as mechanical embodiment design, design optimization, analysis and production planning, where the role of computer systems is dominant. The main reason for the lack of computer support during conceptual

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design is the seemingly chaotic nature of the activities. The designer (or design team) is in the process of generating product ideas and concepts, resulting in many different alternatives based on different technical principles. These concepts are usually quickly evaluated, altered, communicated to partners, or rejected. Once a concept has been selected for more detailed consideration and for technical evaluation, more elaborated models need to be created. Not until that stage of design, CAD/CAE techniques come in effectively.

It is recognized that the industry needs adequate computer support during the concept phase because:

1. The early design phase significantly determines the total costs and the success of the new product, and therefore needs much augmentation.
2. The barrier between the non-electronic world of concept design and the world of computerised product models must be lifted to shorten the time-to-market
3. Computer support enables systematic recording of the history of the early design phase, including the process of decision making. This in turn facilitates design information reuse.

Recent evaluations have shown that present commercial and research systems fail to achieve this (Hennessey 1993). To obtain a better understanding of this problem is generally one of the motivations for empirical research into the engineering process.

This problem is central in the Desys project, described in this paper. The main goal is to develop procedures to derive requirements for conceptual CAD from empirical studies, and to apply these procedures in practical situations. In the next section of this paper we give a brief overview of empirical studies into engineering process and the conclusions about supporting computer tools as drawn by the respective authors. In section 3 we motivate and describe the experiment in which we observed engineers at work. Section 4 contains preliminary results from data analysis. In section 5 we propose to use these data for comparative studies with the purpose to determine the impact of computer tools on the engineering process.

2 PAST STUDIES INTO ACTUAL ENGINEERING PROCESSES

Actual engineering projects have been studied in detail and the outcomes generally confirm that engineering design is a complex process consisting of many types of activities, information use and creation, documentation, reasoning and decision making. In addition it turned out that making those studies is very time consuming and expensive. Hence, many published results are rather fragmentary and of qualitative nature.

Stauffer has made a comparison of six empirical studies into the mechanical design process (Stauffer 1988), including his own research carried out at Oregon State University. Additionally, a recent literature survey can be found in (Knoop 1994). It is important to realize that studies of design projects have been made in very different ways on different project scales and on different levels of abstraction. Although these studies can be considered as being complementary, globally aiming at the same goal, they serve distinct research purposes.

Two types of empirical research methods can be distinguished. The first captured design activities in real-time, either by direct observation or by participation. Data was

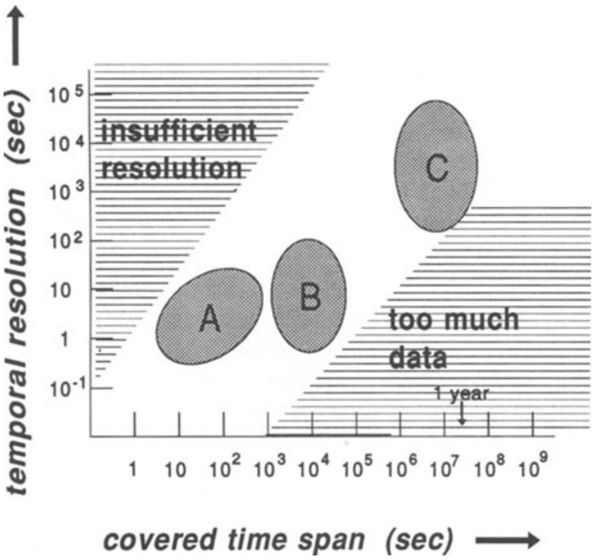

Figure 1: Simplified spectrum of published empirical research in design. The horizontal axis represents the duration of the design process covered by the studies. The vertical axis is the time interval to which a typical empirical datum corresponds, i.e. the temporal resolution of the analysis. The dashed areas are hardly accessible by research, either because the data would too global or because the collected amount of data would become too vast. The research types A, B and C are explained in the text.

usually protocollized and transcribed for further analysis. Due to the large amount of generated data, this type of method was only suited for small size design projects. The other type of method was analysis of retrospective data (interviews, notebooks, design documentation) about past or ongoing design activities. Since retrospective data can be analyzed at very different levels of detail, both small and large design projects can be investigated with this type of method. Figure 1 indicates the clustering of past research with regard to project duration and temporal resolution of the data. Studies of large projects, lasting up to over a year, tend to be based on data integrated over $10^3 \ldots 10^5$ seconds intervals (cluster C), while research based on detailed data ($1 \ldots 10^2$ sec) seems restricted to small design projects (cluster B). Actual measurements of computer tool impacts are mostly in the region of short projects (activities) which are observed in great detail, down to 10^{-1} sec (cluster A). It should be noted that this picture is not strict; for example, the work described in (Blessing 1994) is based on global as well as on some detailed empirical data.

In a few projects the dependence of the data on the subject that carries out the design task was determined. The main reason for this was to detect differences between novice and experienced designers. In addition, an indication could be obtained about the spread of data obtained with supposedly similar subjects. Obviously, subject dependence cannot be measured unless in experimental design projects.

Research projects that report conclusions and recommendations about computer tools for design could be put in three, not completely disjoint categories:

1. The first covers research that takes actual design *projects* as empirical starting points. From research in this category, reported conclusions are relevant for the design project (or task or activity) itself, i.e. without anticipating the introduction of any computer tool. It is this category of research that we consider in this paper. However it is useful to realize that there are two other categories:
2. Research that takes a design *process model* as starting point. Design is described at a certain level of abstraction. In principle, the validity of statements made about the effectiveness of computer tools is restricted to that level and to the situations in which the process model is valid. These statements are sometimes supported by implementation and evaluation of the tools in practice. Obviously, the planning and the conduction of such evaluation is almost inevitably biased by the particular type of tool under consideration.
3. Research that takes existing computer tools as a starting point. Improvements on one or multiple tools are developed and evaluated. Also new types of tools are proposed, developed and demonstrated. If the positive (or negative) impact of the new tools on design is shown, it is usually done by comparison of their performance with that of other tools.

We expect research in the first category to be the most appropriate for deriving requirements for conceptual CAD. We have collected publications of about 16 research projects of this type. Only 6 papers contained comments about CAD or KBS tools. For example Lewis (1981) lists some factors of the design process that should be taken into account for future CAD development (such as allowing user intervention and informal decision making). Kuffner (1991) argues that CAD must be able to make supplemental, non-traditional design information available to designers. Stauffer (1988)indicates the need of making CAD intelligent and Waldron (1988) states that "a flexible tool which can interact, communicate and reason like another designer would be ideal". Stauffer has found evidence for the fact that mechanical design relies little on problem-solving techniques, but much on richness of domain knowledge. He expects that this has implications for future research on design automation.

We did not find any references to empirical studies that resulted in data from which requirements for supporting tools can be derived. This motivated us to set up an experiment with that very purpose.

3 DESCRIPTION OF METHOD AND EXPERIMENT

In the previous section we found that published empirical studies of engineering processes offer global conclusions about requirements for support methods. Our research aims at methods to extract from empirical data such requirements in detail and to test experimentally the validity of these requirements e.g. by showing evidence that a tool made or simulated according to the requirements has the predicted impact on the design process. This sets specific conditions on the way engineering processes must be observed and represented. To gain insight in these conditions and in preparation of the experiment we have made a retrospective study of 6 months of engineering activity by a team of 12 people working on the same project (van Breemen 1994). We then decided to focus our experiment on external information flow, i.e. on information represented by directly observable entities (drawings, written or spoken results). It was also necessary to record, as a function of time, the current engineering activity. No attempt was made to trace the subject's way of thinking, reasoning or mental state.

To capture these data it was not necessary to let the subject think aloud, as is done in some protocol studies. However, the prevailing source of information for the experiment was the subject; he or she can express what the current activity is and which information is needed. We therefore encouraged the subjects to speak only if they had a new information request and/or started a new activity. In addition, at regular time intervals during the session a clock signal reminded the subject to briefly mention his or her current activity and any need for information. For this experiment the time interval was set to 5 minutes. Information requests were handled by an experimenter located near the subject's desk. The experimenter had a set of general technical documentation and some specimen available, and was well prepared to accept questions about the assignment. The role of the experimenter was deliberately restricted to providing simple answers; no advises, hints or judgements about the design itself were given. All questions, answers, activities and results (either pronounced or directly observable) were listed during the session by a second experimenter, watching the session on a video monitor, in a separate room. After the session the drawings and texts produced by the subject were merged with the list. Then, following a well-defined procedure, it was determined which activities were continuations of previous similar activities. This led to the identification of activities and subactivities, discussed further below. Also a search was made for information links, defined as explicit uses of earlier results.

An essential decision for the experiment that no *a priory* categorizations for activities, requests or answers were made. All observables were recorded purely without any attempt to classify them. We did this to avoid the risk of unnecessary data clustering into (perhaps irrelevant) categories. Furthermore this leaves the possibility to discover actual categories in addition to the ones frequently mentioned in the literature.

The engineering assignment in this experiment involved the conception and technical specification of an alternative electrical lighting system for a new type of bicycle. Six technical requirements were listed in the assignment, and the subject was asked to explicitly show that the proposed design could meet those requirements. Since the maximal duration of the session was fixed to 160 minutes, several restrictions were built in to avoid that much time was spent on making too detailed descriptions or illustrations. The technical and functional aspects were emphasized.

10 different subjects, all near-graduate engineering design students, worked on this assignment independently. In advance each subject was asked to work on a smaller assignment, to let him or her get used to the working environment. Before and after the session each subject was interviewed following a list of questions. All subjects declared that they did not feel hampered in any way during their engineering task.

An extensive report about the experimental method is in preparation.

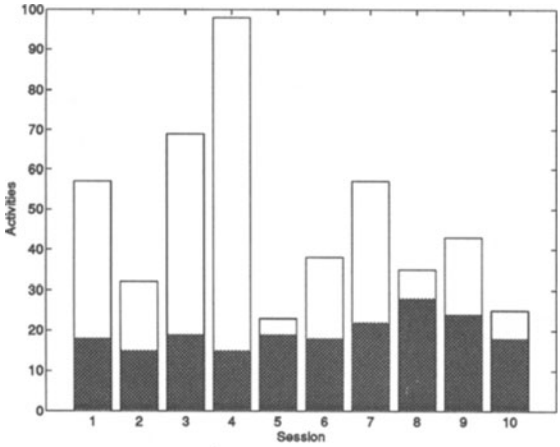

Figure 2: The number of activities (solid bars) shows much less variation over the 10 sessions than does the number of subactivities.

4 INITIAL FINDINGS FROM THE DATA

The design assignment contained very strict directions about the engineering activities; two technical aspects of the new lighting system (power production and mechanical structure) needed to be addressed explicitly by the subjects. This helped to avoid that the 10 engineering processes would become totally different in character and hence incomparable. Although the 10 produced designs are very different (ranging from simple redesign of the existing generator to rather creative inventions), the activities that happened in the 10 processes are largely consistent.

The number of different activities within one session varies between 15 and 28 (Figure 2) corresponding to average durations between approximately 11 and 6 minutes. Very often an activity did not occur in a session as a contiguous activity but it was interrupted by other activities. Hence, a session can be viewed as a sequence of subactivities, where each subactivity is part of exactly one activity. If the number of subactivities in a session is large compared to the number of activities then there have been many interruptions and corresponding switches between activities. In Figure 2 this comparison is shown. Whereas the number of activities remains in the interval 19 ± 5 for all but one of the sessions, the number of switches between activities shows a lot of variation. We find that the 5 longest activities in each session take between 42% and 68% of the total duration of the session. However, only 3 activities occurred in 5 sessions or more. These activities are documenting the design (in 8 sessions), calculating the electric power of the generator (5 sessions) and general study of collected information (5 sessions). This implies that there are significant differences between the sets of dominating activities.

The number of information requests in each session varies between 27 and 89; for eight of the sessions this number stayed within the range 55 ± 14. A significant spread is also found for the number of produced outputs. This is partly due to non-strict interpretation rules during the initial encoding of the data. For some sessions an information output was identified only if the subject explicitly expressed the result. However, on basis of the produced drawings and notes and on the video tape, many more information outputs can be identified, as has been done for some of the sessions. A similar inconsistency has occurred for the information links, representing observed usage by the subject of data that was the result of an earlier activity.

An extensive presentation of the data is in preparation.

In this paper we focus on one aspect of the observations, the information requests of the subjects and the information received upon those requests. As mentioned, a member of the research team acted as an expert and attempted to answer each question as quickly as possible. This effected a steep distribution of the time delay between question and answer, see Figure 3. This articulates the strong influence that access speed to engineering information must have on the engineering process. In a situation that the designer had to find the answers by him or herself, the delay distribution is expected to be much flatter, corresponding to a much longer time to obtain the same design result. Of course it should be taken into account that the presence of the experimenter, in our study, stimulated the subject to ask many questions. Summed over all 10 sessions, of the 557 answers, 299 (54%) were given within 10 seconds and 487 (87%) within 100 seconds. 31 information requests (6% of 480) were never satisfied. It was verified that all these requests did not require an answer or a confirmation by the experimenter. The difference between the number of requests (480) and the number of answers (557) is due to multiple answers (at different times) to the same question. Careful study of the information requests will reveal which of the questions are specific for the session (i.e. dependent on the particular design solution) and which ones are not. A first categorization of the 480 requests showed that only 21 questions (4%) are solution specific, while the remaining questions could have been expected for any design solution. This is a low fraction compared to the 36% found for the redesign study in Kuffner (1991). This might indicate that the designers at work in Kuffner's experiment did, on average, more detailed engineering than the designers in our experiment, where a lot of time was spent on gathering general information.

5 ON MEASURING THE IMPACT OF COMPUTER TOOLS

In view of the findings above, one of the basic questions is whether a contemporary knowledge-based system would be able to play the role of the assisting experimenter, and to which extent. But this is not the only imaginable support for the engineering task of our experiment. Many questions were about the geometrical lay-out of the rear side of the bicycle and about the mechanical interfacing between the (housing of the) new product and the bicycle. Here, a 3D computer simulation system could be more effective than the static drawings, tables and texts available during the experiment. Although tools to support 3D modeling or decision making do exist, two fundamental points of concern remain.

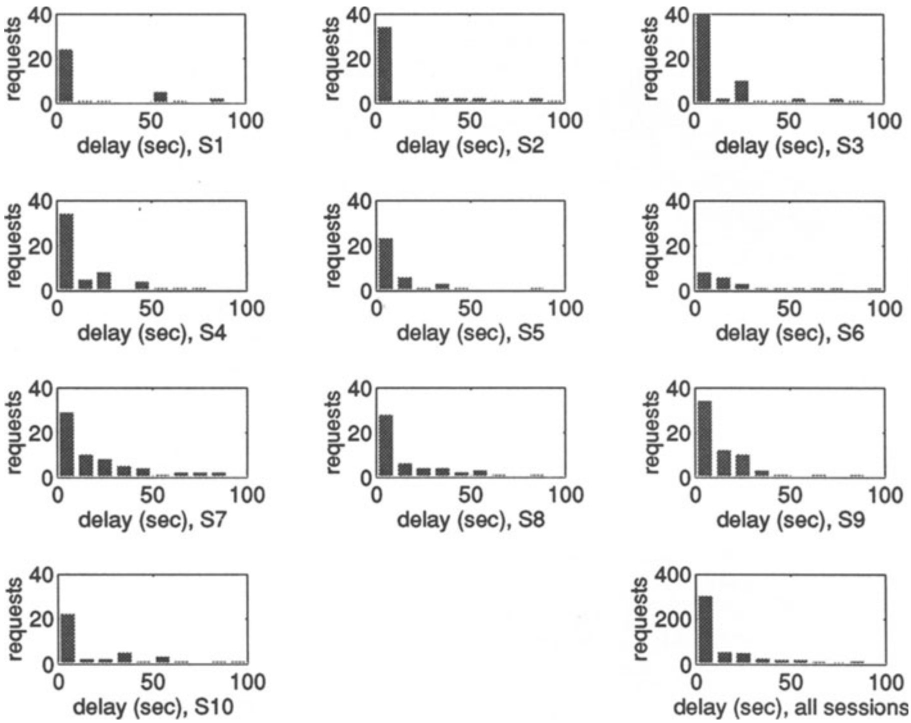

Figure 3: Time delay between information requests and answers. 52% of all answers were provided within 10 seconds, 87% within 100 seconds.

The first is that most existing tools have been developed to perform their specific task and they are often optimized and evaluated as such. This corresponds to research type A in Figure 1. It is the type of research located in the lower-left corner of figure 1, and as we stated before, this research is not sufficient to detect the overall impact of a tool on a design process. What is needed instead is an optimization of tools in a (perhaps simulated) practical situation, rather than retrospective evaluations (often over a many-years' period) by companies that had the tool in use. Unfortunately this is often the only source of information about the effectiveness of support systems in industry. The second concern is that, even if it has been determined that a specific tool is effective in a practical context, the inclusion of another tool could cancel this unless sufficient attention is paid to unify the tools. This topic is being studied as an information technological problem, see e.g. (Smith 1994), but again, any proposal for an integrated system should be tested on its overall impact.

We are still far away from a situation that multiple tools (and for some domains even a single tool) can be effectively used during conceptual design. A contribution to achieve that goal can be made by measuring the impact of (new or existing) tools on the design process in experiments as described above. In its simplest form a number of engineering sessions with and without the tool(s) can be run, of course with different subjects for each session.

6 CONCLUSIONS AND FURTHER RESEARCH

We have presented an experiment procedure to extract timed data about information requests and information flow from actual engineering processes. The method has been applied for a 2 1/2 hour design task, carried out by 10 different subjects. Compared to more conventional protocol studies the data acquisition procedure is fast and non-disturbing. Preliminary analysis shows that among the 10 sessions the spread in the number of activities is much smaller than the variation of other quantities, such as number of activity interruptions, information requests and information outputs. A very small fraction (4%) of the information requests is directly related to a particular design solution.

The main objective of the experiment is to verify that the type of obtained data has the potential to serve as a reference for comparative experiments, for the purpose of tool impact measurement. This verification is one of our current research issues. Initial interpretations suggest that the current series of observations offer a firm grip on the dependence of information access time and engineering progress.

By focussing the observation procedures to even more specific quantities, we expect that larger engineering processes of industrial teams can be traced as well. This will then systematically bridge the gap in Figure 1 between the type B and the type C research methods.

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