A comparison of the results of empirical studies into the mechanical design process

L A Stauffer

Department of Mechanical Engineering, University of Idaho, Moscow, Idaho 83843, USA

D G Ullman

Department of Mechanical Engineering, Oregon State University, Corvallis, Oregon 97331, USA

Six investigations are compared in which the mechanical design process was evaluated by studying human designers. These studies are summarized on the basis of their purpose and evidence followed by a brief discussion. The conclusions reached in all six studies are then compared to show areas of agreement or disagreement and potential for further research needed to gain a better understanding of the mechanical design proccess.

Keywords: mechanical design process, empirical data, design study comparison

While there is a significant body of research in the study of design, relatively little research has been based on empirical evidence, especially in mechanical design. This fact should not be surprising since serious study in design in general has occurred only in the past 25 years[1]. This paper contains a review and comparison of six studies in mechanical design which are based on empirical data [Marples[2]; Ramstrom and Rhenman[3]; Mitroff[4]; Lewis[5]; Waldron and Waldron[5] and the group at Oregon State University: Ullman, Stauffer and Dietterich[7] (in a condensed version Ullman, Stauffer and Dietterich[8]); Stauffer, Ullman and Dietterich[9] and Stauffer[10]]. All but the study by the authors (hereafter called the OSU study) are based on data taken by making observations or by taking retrospective reports of design engineers. The OSU study is based on verbal protocol data, which is briefly described in the next section.

In this paper, each of the studies into the mechanical design process are first reviewed under three headings: 'purpose', 'evidence', and 'discussion'. The purpose and evidence headings contain the purpose for the study and the evidence on which the research is based. The discussion section explains important information on the methods of data analysis, discoveries and theories. Additionally, the conclusions drawn on each study are summarized in Table 1. The last section of the paper is a

0142-694X/88/02107-08 $03.00 © 1988 Butterworth & Co (Publishers) Ltd

comparison of the conclusions to establish points of agreement or disagreement and potential for further research.

THE EMPIRICALLY-BASED, MECHANICAL DESIGN STUDIES

Methods in developing empirical data

Three methods have been used for developing empirical data of mechanical design engineers: direct observation, retrospective reports and verbal protocols (or verbal/visual protocols). Direct observation is a non-intrusive method of watching the engineer perform his or her design activities and noting features of interest to the observer. This type of data recording only captures the naturally verbalized and written performance of the engineer (used by Mitroff[4]). In the retrospective technique, the subject is asked to recall the events of the design process either on a periodic basis (used by Ramstrom and Rhenman[3]) or after the design is completed (used by Lewis[5]; Marples[2]; and Waldron and Waldron[6]). Retrospective data contain what the engineer 'perceived' happened, which is not always what actually happened.

The verbal protocol technique is an experimental method for gathering detailed data on human problem solving. The designer is required to 'think aloud' during the solution process and what he or she says is recorded on audio tape. For mechanical design both audio and video tape need to be recorded (hence the verbal/visual protocol) as designers gesture with their hands and point to their drawings. The recorded data is then transcribed and can be repeatedly reviewed. The data is sufficiently detailed to capture not only the coarse level events of design more accurately than the other two methods, but also finer events about the design process not captured with these other methods. In addition to the OSU study, there has been significant empirical research based on verbal protocol data in the areas of design, namely architecture[11–14] and software engineering[15,16]. (For more details on the verbal protocol technique, see references 7, 8, 10 or 17.)

The OSU Study

Purpose

The OSU study was conducted to develop a detailed model of the mechanical design process suitable for intelligent computer tools and for the evaluation of design strategies. The work is based on the information processing model of Newell and Simon[18], and thus considers problem solving as a transformation of the state of the design through the application of operators. Thus a goal of the research was to develop a complete set of operators sufficient to describe the mechanical design process, a representation adequate for the task, and to identify strategies used to explain the operator sequence.

Evidence

Five mechanical design engineers of varying background and experience were given the initial specifications for a fairly simple yet realistic industrial design problem. The engineers were requested (and briefly trained) to remain verbal during their solution from first reading of the problem to the detailed design stage. This protocol was video and audio taped over a period of 6–10 hours. The design engineer worked alone and only had contact with the investigator, who was an experienced design engineer and effectively the client.

Discussion

The study is directed toward the development of a problem goal structure, design-state representations, operators and strategies for transforming the present state of the design to meet the design goals. The taped data was transcribed and reduced to the level of detail the global design performance of the subjects studied. The results of a 'coarse breakdown' are reported on in references 7–10. These are the basis for the discussion in this paper. Subsequent to the 'coarse breakdown', selected sections of the data were further reduced to find the representation necessary for modelling the design process[19], the operators of mechanical design[20] and the heuristics governing the use of these operators[21]. This subsequent data reduction has been used to partially explain the 'coarse breakdown' observations.

The Study by Marples

Purpose

D L Marples[2] conducted this study to develop an abstract model of the design process. The model shows the search for possible solutions, the strategies for their examination, and the rules for choosing between them. The model applies to problems requiring novel solutions.

Evidence

Marples investigated two industrial design problems:

- the ducts and valves problem of the Advanced Gas-Cooled Reactor for the Atomic Energy Authority
- the fouling of a heat exchanger used in a new powder-producing process

In the ducts and valves problem, he followed the development of the coaxial gas ducts that connect the reactor to two heat exchangers. The entire project involved over 70 people, but this particular project consisted of a team of one professional engineer and one or two designer-draftsmen. The fouling problem involved many chemists and engineers. A process was developed to 'flash dry' a moist product to produce powder. The new process caused fouling problems in one of the heat exchangers. The design team met and introduced a number of solutions to the problem; three of these were investigated simultaneously because of time restrictions on the project. Marples gathered evidence retrospectively from design notebooks, drawings and interviews in both of these problems.

Discussion

Marples considers the two designs together, along with other evidence to describe the design process as a decision tree. He describes the tree as a set of sub-problems, which arise from alternatives to a problem. Each sub-problem can itself have alternatives that result in their own sub-problems until each component of the final design is represented as an alternative of a final sub-problem. The tree that Marples describes illustrates that his model of design can be represented as a sequence of critical decisions, leading from an abstract problem statement to the final hardware specification.

Marples claims that the examination of proposals (proposed solutions) may be conducted serially or in parallel. The second method is preferred as it is likely to be quicker, to give a better insight into the problem and to avoid personal attachment to a particular proposal. If the first method is used it is better to consider the proposals in the order of their expected advantages than of their judged tractability.

Regardless of which level on the decision tree the designer is considering, each proposal will be evaluated as not feasible, feasible but inferior, or feasible and best. With these evaluative possibilities in mind, the designer must first conduct a search for possible solutions and then collect evidence about each one.

The Study by Ramstrom and Rhenman

Purpose

D Ramstrom and E Rhenman[3] had as a goal to suggest a method of describing and analysing the progress of an engineering design project.

Evidence

The study concerned the design of a radiation rig: a metal tube that houses test specimens, which is introduced into a nuclear reactor. This project was considered to be a typical design problem, by the engineering group, yet not routine in nature. The design team consisted of a single engineer with one assistant and support from the group head. The customer in this project was a research and development group at the nuclear facility. Data on the project was gathered through weekly retrospective interviews with the cognizant engineer and through a notebook in which the engineer made daily notes. Since neither Ramstrom nor Rhenman are engineers (they are business professors), a fellow engineer in the group conducted the interviews.

Discussion

Ramstrom and Rhenman base their study on the assumption that engineering is complex problem solving, as opposed to routine and programmed decision-making. As such, it can be viewed as heuristic problem solving.

Ramstrom and Rhenman are the first to label design as a problem-solving process. They also look at design as a group activity, which in turn interacts with the entire organization, and finally with others outside the organization, such as the customer. In trying to describe the design process, they contend that the description of the project depends on the person who does the describing (e.g. manager, customer, engineer, etc.). They refer to these descriptions as the 'dimensions' of the project and spend much of the paper discussing these dimensions.

They summarize the report by stating that 'engineering work consists simultaneously of transforming values from one set of dimensions to another and limiting the alternative courses of action'.

The Study by Mitroff

Purpose

I I Mitroff[4] reports that the purpose of his study is to add to the understanding of 'what design is, what it is that engineers actually do, and what they ought to do . . . furthermore, we also believe that by knowing what a particular engineer can do, we are helping to define what an engineer can be expected to do, and in this sense, what ought to be done in order to improve design'.

Evidence

Mitroff observed the design of a pressure vessel for an experiment in basic physics. The experiment's purpose was to study the reaction of high energy nuclear particles shot from an accelerator. These particles are protons and electrons of liquid hydrogen, which is to be stored in the pressure vessel. Mitroff gathered data through interviews and observations of the engineer, the engineer's supervisor, fellow engineers, and the physicists for whom the vessel was being designed.

Discussion

Mitroff contends the most general conclusion of his work is that design is both a technical and a behavioural process. He is not trying to diminish the technical aspects of design, but rather emphasize the equal importance of individual behaviour; interpreting design in terms of one aspect without the other is incomplete. Design is influenced by the personalities of the engineer and the clients (physicists in this case) and the ways in which they interact together.

Though Mitroff contends that individual personalities play important roles in design, he never specifies the function of these roles other than they make the design process irrational. Additionally, the organization that employs the engineer has an effect on design. In Mitroff's case, the designer was working for the physicists, who had the authority to override the decisions of the engineer and thus affect the process.

The Study by Lewis

Purpose

W P Lewis[5] performed this study to define the role of human intelligence in component design and provide insight on the extent to which it can be simulated or augmented by a computer. His task was to construct an information processing model of component design.

Evidence

Lewis's study was based on the design of a shaft for a rock-cutting machine for the boring of underground tunnels. A mechanical engineer was the consultant to an expert in rock mechanics who needed the shaft designed. The study was not limited to the actual design of the shaft, but also included the client–consultant interaction before the actual design took place. Lewis recognized the methods of Newell and Simon[18] for using verbal reports as data, but decided to use the engineer's notes and sketches on the project and a retrospective report from the engineer instead of taking real-time protocols.

Discussion

Lewis's main effort went into developing an information-processing model[18] similar to that used in the OSU study. Lewis lists five steps for fully developing this model:

- collection of protocols of subjects thinking aloud as they solved the problems
- analysis of protocols into short phrases, each indicating a single task assertion or reference
- representation of the subjects' states of knowledge by nodes in problem behaviour graphs, the links between adjacent nodes indicating the process of transition from one knowledge state to the next
- identification of four basic information processing operators required to generate new states of knowledge from existing ones, i.e. to proceed from one node to the next in the problem–behaviour graph
- construction of production systems equivalent to these operators and capable of expression in terms of elementary information processes and therefore capable of generating computer programs for simulating the observed human problem-solving behaviour

Lewis states that the level of detail to be attempted in his paper was equivalent to the fourth stage. He never mentioned why he used retrospective data-collection techniques as opposed to collecting verbal protocol data as required by the first stage. Nor does he show any evidence of attempting the second or third stages. He only reports his development of the fourth stage: the information processing model.

The Study by Waldron and Waldron

Purpose

This study's purpose was to make observations about design during the conceptual design phase.

Evidence

K J Waldron and M B Waldron[6] studied the design of a single leg-mechanism for an Adaptive Suspension Vehicle (ASV). The ASV is a legged locomotion machine which required several engineers two and a half years to design. The principal investigator of this design study (K N Waldron) was also the chief engineer on the ASV project. The data for this study were collected as a retrospective report by the chief engineer.

Discussion

The Waldrons have no formal method of analysing their data. They include an extensive section of the retrospective report in their paper and highlight the sections that pertain to their conclusions. They provide no other information about design, but do make comments about modes of data collection. This paper is as much a discussion of the retrospective versus verbal protocol methods of data collection as it is a study of design.

A COMPARISON WITH PAST RESEARCH IN MECHANICAL DESIGN

In this section the differences in the studies are discussed and their conclusions are compiled.

Differences between the studies

A comparison of the studies is meaningless without first identifying the differences between them to form a realistic perspective for making comparisons. Six differences between the studies are identified:

- The number of designers working together on a single design project. Some of the studies look at the design process as performed by a single engineer (Ramstrom and Rhenman[3], Mitroff[4], Lewis[5] and the OSU study[7–10]) while others look at the design done by several different engineers working together on the same project (Marples[2], and Waldron and Waldron[6]).
- Of those working on the project, the number used in the study. Evidence for each study is reported by a different number of individual people. Some studies gather evidence from two or more individuals (Marples, Ramstrom and Rhenman, and Mitroff) while others gather evidence from only a single individual (Lewis, and Waldron and Waldron, the OSU study)

for each study. Note that Waldrons' study involves several engineers, but the data come from a retrospective report from only the chief engineer.

- The number of cases upon which the study is based. All of the studies rely on a single example study except two (the OSU research and Marples). Marples' evidence comes from two examples, and the OSU research is based on five.
- The attention given to designer interaction with other individuals. All of the studies address the interactions of the designers with others such as the client, supervisor, or other engineers on the design team, except the OSU study in which the designers worked on their design problems alone and only interfaced with the client/investigator periodically.
- The purpose of the design projects. The study of the design process is of secondary nature to all of the studies except the OSU research. Most of the design projects had already taken place before a study was developed (Marples, Lewis, and Waldron and Waldron). Ramstrom and Rhenman, and Mitroff were able to find projects that were about to start and could thus follow them with the design study goals in mind, yet the need for the design projects was not influenced by the study of them. In the OSU research, the design projects were done for the express purpose of studying the design process. Therefore, the design requirements, constraints, and other factors were relatively well known.
- The types of data gathered. The evidence for the studies exists in many different forms. Most of the data is from retrospective reports, interviews, design notebooks and drawings. Only the OSU research uses the real-time verbal protocols as data. While Lewis, and Waldron and Waldron mention this data recording technique, they do not use it.

While these studies may have many differences, they have the same general purpose: to develop a description of the process of mechanical design. There is surprisingly little disagreement regarding the general conclusions of these studies, and that which does exist is usually due to the differences mentioned above. There is more disagreement between these studies (including the present research) and present design theories[22,23]. This disagreement is understandable since these design theories explain how engineers should design rather than how they actually design.

Observations of global design performance

The six studies led to the formulation of 44 conclusions which describe design performance. Table 1 lists 27 unique conclusions of the total 44 (17 were duplications). The conclusions are primarily from the conclusion section of each published report, though in a few situations the conclusions had to be summarized from the main body of the paper. Also included in Table 1 are numbers that correspond to the studies that make these conclusions (Marples[2]; Ramstrom and Rhenman[3]; Mitroff[4]; Lewis[5]; Waldron and Waldron[6]; the OSU study[7–10]).

CONCLUSIONS ABOUT MECHANICAL DESIGNERS

Table 1 includes a large number of conclusions because they cover such a broad range of topics and are too specific to condense any further without loss of meaning. To make the information in Table 1 easier to understand, the conclusions have been arranged into four groups, each of which has implications on a particular design topic: items 1–12, the algorithmic versus heuristic nature of design; 13–15, parallel versus serial development of solutions; 16–20, the technical versus behavioural nature of design; and 21–27, the dependence versus independence of the design process on domain knowledge. Each of these topic areas is discussed below.

Algorithmic versus heuristic nature of design

Many researchers make a case for an algorithmic view of mechanical design: a specific sequence of steps to solve design problems[22,23]. It appears from the empirical studies presented in this paper that actual design performance is not that well organized yet. If design were algorithmic, it would have a well organized, overall plan based on logical reasons, which does not always seem to be the case. Items 2–7 (from Table 1) imply that there is no strategic plan in design. None of these designers followed any set procedure in the studies. Any procedures that may have been followed were general (item 2 and 12), and the designer's attention usually shifted to critical parts of the problem (item 3) or became opportunistic (item 5). All of these conclusions suggest that designers follow 'rules-of-thumb' to solve problems, which are dependent on the situation at hand.

A term that describes rule-of-thumb, problem-solving methods is 'heuristics'. An example of a heuristic method is means–end-analysis, which was found to be common among designers (item 1). Items 9, 10, and 11 also support the use of the heuristic method of means–end-analysis.

The intent here is not to disclaim algorithmic methods of design; such an approach could possibly improve design. The intent is to show that items 1–12 point to a dynamic, heuristic approach to design as it is actually performed by human designers.

Parallel versus serial development of solutions

The conclusions (items 13–15) that address this topic contradict each other. Item 13 states that solutions to problems are investigated in parallel, while item 14 states that solutions are investigated in series. Marples actually claims that both modes of solution generation occur, depending on the situation. He claims that when a problem is difficult or there is a lack of manpower, solutions are examined in series. If solutions are pursued

Table 1. Global strategies in mechanical design

No.	Conclusion	Reference
1	Engineers commonly employ means–end analysis	3, 7–10
2	Engineers commonly make a qualitative plan for designing without specifying the details	3
3	The initial focus of the conceptual design is on the critical areas	6, 7–10
4	The design process is multidirectional, and there is no clear distinction between conceptual, layout, and detail design phases	6
5	Design is sometimes opportunistic rather than systematic	7–10
6	Designers do not always conduct balanced development, but sometimes pursue a problem in a depth-first manner	7–10
7	Designers develop the functional aspects of the design in stages throughout the problem-solving effort	7–10
8	Designers make decisions based on qualitative, subjective reasoning	3, 5, 6, 7–10
9	Designers evaluate the solution to a problem by evaluating their respective sub-problems	2
10	Goals are formulated during the problem-solving process	3, 7–10
11	The design goals are initially qualitative, but become quantitative as the design progresses	6
12	Designers use functional considerations that remain qualitative, while often the form considerations become quantitative	7–10
13	Problem solutions occur in parallel	2, 6
14	Problem solutions occur in series	2, 7–10
15	Engineers commonly accept a solution that is satisfactory even if it does not represent an optimal result	3, 7–10
16	Design is both a technical and a behavioural process	4
17	Design is influenced not only by the personal abilities of the engineer and the client, but also by how they interact together	4, 5
18	The type of organization that employs the engineer and how it operates has an effect on design	4
19	Initial premises for concept generation are often false	6
20	Individual designers have favourite solutions	6
21	Simulations are made to help evaluate a problem	2, 7–10
22	Knowledge from diverse sources and different individuals is 'integrated' and 'contributes to the collective knowledge base used in the conceptual design'	6
23	Analogies are used as bases for concepts	6
24	Models are used to set mechanical parameters and make configuration decisions	6
25	Designers use notes and drawings for understanding and analysing the problem	7–10
26	Designers use their knowledge to influence how ideas are generated and evaluated	6–10
27	Designers use their knowledge to influence their problem-solving methods	6–10

in parallel, then decisions can be made more quickly and without personal prejudice. Items 14 and 15 describe a serial approach where designers examine a solution to a problem. If it yields a satisfactory answer, then the problem is solved; if not, then a new solution is investigated.

The contradiction in these conclusions can be partially explained through an examination of the studies. Marples, and Waldron and Waldron, who claim parallel development, both characterize design projects that involve several designers. Waldron and Waldron suggest that the parallel nature was a function of different designers looking at different solutions at the same time. Their conclusion on the parallel nature of solutions seems to be more a consequence of the design team's organization than the designer's problem-solving methods. Ramstrom and the OSU study, who claim serial development, investigate single designers. It could be that a designer working alone tends to investigate solutions one at a time, but when working in a group, solutions are investigated in parallel.

Though it appears the contradiction between parallel and serial development can be attributed to whether the designer works alone or in a group, the facts are not conclusive. Possibly Marples's reasons mentioned earlier – solutions are examined in series when there is a lack of manpower or the problem is too difficult to develop more than one solution – are true. This point needs to be specifically addressed in future research.

Technical versus behavioural nature of design

Design is usually treated as a technical subject by both theoretically and empirically-based researchers. Though design is technical, one cannot ignore the behavioural (personality) influences on design. Items 16–21 specifically address the behavioural influences on design, yet many of the other items demonstrate behavioural influences as well. Mitroff is most emphatic on this point (item 16). He does not view each asepct of design as either technical or behavioural, but asserts that design is both a behavioural and technical process, which cannot be studied as though it were one or the other.

Organizations (item 18) and the individuals in those organizations (items 17 and 20) are a part of this behavioural aspect of design. A good example is the previous topic of parallel versus serial solution development and its relation to the organization. Some studies noted mistakes or inefficiencies (item 19) which seem more related to behaviour than technical.

A coordinated study of mechanical design must include its behavioural aspects. Mitroff stands alone in his claim that every aspect of design must be both technical and behavioural. The other studies suggest that design is either technical or may include some independent behavioural aspects. The extent to which behaviour affects the design process is unknown and requires further research.

The dependence versus independence of design on domain knowledge

The authors of systematic design theories present the process as independent of the domain knowledge and suggest an object-independent procedure for solving problems. They believe the design process to be a rational process which should be practised as a completely conscious activity. To do otherwise, claims Hubka[22], results in the "common error of 'jumping to conclusions,' without thoroughly investigating the problem". Hubka advises against relying on intuitive thought for present-day usage, even though this was almost exclusively the thought mode in the past, since present day mechanical design is too complex to rely on the individual techniques of the past. Hubka may well be correct, but items 21–27 contradict an object-independent view of the actual design process. These conclusions show that no one solves problems based on some procedural knowledge independent of the domain knowledge. The subjects of the studies solved problems based on the heuristics they knew, such as in items 23–25. As item 27 makes clear, designers use their knowledge to influence the problem-solving methods.

The theorists' approach of making the design process object-independent is very appealing in that one design method can apply to all design projects. But to accurately represent the way people design, the influences of the domain knowledge must be applied. There must be options for making models, simulations and analogies, for example. A model that can accommodate this behaviour may prove useful.

SUMMARY

In this paper a comparison among empirical studies has shown some areas of agreement, yet many other areas that point to the poor level of understanding about the mechanical design process. Clearly more studies are needed and firmer methods of data collection and reduction are in order.

An additional study by Wallace and Hales[24] may help in resolving some of the questions raised. This study is based on 2.6 years of observation of single design encompassing the work of 37 individuals ranging from the design engineers to staff responsible for marketing and management. In many ways this work is at the other extreme from the OSU study, which focuses on the details of a single designer rather than the activities of a major design project. Unfortunately, only the initial results from the study by Wallace and Hales have been published. There will be continued reduction of the data from both the OSU and the Wallace and Hales studies.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the National Science Foundation under grant number DMC-8514949.

REFERENCES

1 **Cross N** *Developments in design methodology* John Wiley and Sons, Chichester, (1987)

2 **Marples, D L** 'The decisions of engineering design' *IRE Trans. Engineering Management* **EM-8** (June 1961) pp 55–71

3 **Ramstrom, D and Rhenman, E** 'A method of describing the development of an engineering project' *IRE Trans. Engineering Management* **EM-12** (Sept. 1965) pp 39–86

4 **Mitroff, I I** 'A study of simulation-aided engineering design' *Doctoral dissertation* University of California, Berkeley (1967)

5 **Lewis, W P** 'The role of intelligence in the design of mechanical components' *Man–Machine communication in CAD/CAM* North-Holland Publishing Co., IFIP (1981)

6 **Waldron, K J and Waldron, M B** 'A retrospective study of a complex mechanical system design' NSF Workshop on Design Theory and Methodology, Oakland, CA (Feb. 1987)

7 **Ullman, D G, Stauffer, L A and Dietterich, T G** 'Preliminary results of an experimental study of the mechanical design process' NSF Workshop on Design Theory and Methodology, Oakland, CA (Feb. 1987)

8 **Ullman, D G, Stauffer, L A and Dietterich, T G** 'Towards expert CAD' *Computers in Mechanical Engineering* **6**(3) (Nov/Dec 1987)

9 **Stauffer, L A, Ullman, D G and Dietterich, T G** 'Protocol analysis of mechanical engineering design' *Proc 1987 International Conference on Engineering Design*, Vol. 1 (Ed. W E Eder), ASME, NY (1987)

10 **Stauffer, L A** 'An empirical study on the process of mechanical design, *Doctoral dissertation*, Oregon State University, Corvallis, Oregon (1987)

11 **Akin, O** 'How do architects design?' *Artificial intelligence and pattern recognition in computer aided design* (Ed. Latombe) IFIP, North-Holland (1978)

12 **Akin, O** 'An exploration of the design process', *Design Methods and Theories* **13** (3/4) (1979) pp 115–19

13 **Akin, O** *Psychology of architectural design* Pion Limited, England (1986)

14 **Eastman, C M** *'Explorations of the cognitive processes in design' PhD Thesis*, Carnegie-Mellon University, Pittsburgh, PA (1968)

15 **Adelson, B and Soloway, E** 'A cognitive model of software design' *Rep. No. 342*, Department of Computer Science, Yale University, Mass. (1984)

16 **Kant, E and Newell, A** 'Naive algorithm design techniques: a case study' *Proceedings of the European Conference on Artificial Intelligence* Orsay, France, (July 1982) pp 40–51

17 **Ericsson, K A and Simon, H A** *Protocol analysis: verbal reports as data* MIT Press, Cambridge, MA (1984)

18 **Newell, A and Simon, H A** *Human problem solving* Prentice-Hall, Englewood Cliffs, NJ (1972)

19 **Tikerpuu, J, Ullman, D G and Dietterich, T G** 'Computational representation of design parameters' (paper in progress)

20 **Stauffer, L A, Ullman, D G and Dietterich, T G** 'Fundamental processes of mechanical designers' (paper in progress)

21 **Ullman, D G, Dietterich, T G and Stauffer, L A** 'The process of mechanical design based on empirical data' (paper in progress)

22 **Hubka, V** *Principles of engineering design* Butterworths, London (1982)

23 **Pahl, G and Beitz, W** *Engineering design* Springer, London (1984)

24 **Wallace, K M and Hales, C** 'Detailed analysis of an engineering design project' *Proceedings of the 1987 International Conference on Engineering Design*, Vol.1 (Ed. W E Eder) ASME, NY (1987)