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PROTOCOL ANALYSIS OF MECHANICAL ENGINEERING DESIGN

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SUMMARY
While many people have shown how mechanical engineers should pursue the problem solving process, little experimental evidence exists that demonstrates how they actually design. A technique from cognitive psychology, known as protocol analysis, has been used to identify the mechanical designer's thoughts. The method is to record engineers' verbalization of their thoughts while they solve realistic, open-ended mechanical design problems and then analyze the data to identify their problem solving process. In this paper, we report on the protocols, our observations from them, and the implications on future CAD tools and mechanical design methodology.

INHALTSANGABE
Wahrend viele Leute den Prozess des Problemlosens fur Mschinenbauingenieure aufgezeigt habe, so gibt es wenige experimentelle Beweise die zeigen, wie sie wirklich entwerfen. Ein Verfahren aus der kognitiven Psychologie, die Protokollanalyse, wurde benutzt, um die Gedanken des Maschinenkonstrukteurs zu identifizieren. Die Methode besteht darin, die Verbalisierung der Gedanken von Konstrukteuren wahrend der Losung von realistischen, open-end Maschinenbauproblemen aufzuzeichnen und dann die Daten zu analysieren, um den Prozess des Problemlosens zu identifizieren. Es wird uber die Protokolle, unsere Beobachtungen und ihre Bedeutung fur zukunftige Computerunterstutzte Instrumente sowie fur die Methodik der Maschinenkonstruktion berichtet.

INTRODUCTION

There has been little effort to develop a coordinated approach to the study of the mechanical engineering design process. Though there is a significant body of design theories [1,2,3], they largely represent the views of the individual authors and only demonstrate how mechanical engineers should design, not how practicing engineers actually solve problems. An understanding of the actual design process is important for three reasons.

First, there is no objective way to evaluate the design process and no clear way to teach design since the mechanical engineer's design process is complex and poorly understood. Secondly, there is little understanding about how mechanical design can be improved since the process is so poorly defined. Manufacturing productivity has improved many times over since the turn of the century but design productivity has increased only slightly. Thirdly, an understanding of actual design methodology is essential for developing future CAD tools. At present, CAD tools are only useful during the detail and possibly layout design phases. AI tools show promise of aiding the designer in all areas of design and therefore extending the usefulness of CAD. To make the best use of these future CAD tools it is important to understand how mechanical designers solve problems. Computer-based methods need to be as flexible as the designers who will use them. A part of this flexibility is the need for a natural interface between future CAD tools and the designer. If the designer can't follow what the computer system is doing, he is unlikely to make full use of the system. CAD tools need to employ human-like methods so that they can readily assist the designer in all phases of the design process.

To gather data on the design process, we used a technique comman to cognitive scientists for studying problem solving known as protocol analysis [4]; subjects are asked to "think aloud" as they solve problems. The recorded data provide a detailed report of the problem solving effort employed by the subjects. Protocol analysis has been the basis for studies similar to ours in software engineering [5]. While there have been some empirical studies of how mechanical engineers actually design [6-10], these works were usually based on a single subject and the data gathered by informal observation, design notes, or retrospective reporting (sometimes made several years after the fact). Cognitive scientists have shown that these types of reports only tell what the subject or observer perceived happened rather than the sometimes unsuspected, dynamic behavior representative of human thought [11]. Additionally, retrospective reports tend to reveal only summaries rather than details of the problem solving process.

In this paper we will only briefly explain the experiments themselves since this has been done previously [12]. We have been analyzing the data to identify states, operators, and strategies. States characterize the problem solving effort at some point in time, operators are processes that the designer applies to a state to arrive at a new state, and the strategy describes how the operators are applied. This state-operator-strategy breakdown is the basis for the heuristic search method which models human problem solving [11]. In this paper, we will only report on some of the strategies and their implications on future CAD tools and mechanical design methodology.

PROTOCOL DATA DEVELOPMENT

We developed two open-ended mechanical design problems taken from industry, with incomplete, high level specifications. One, which we call the flipper-dipper, involved designing a mechanism to grasp and position a thin aluminum plate onto the surface of a chemical bath. To solve this problem required knowledge of kinematics and some actuation technology, such as pneumatics, or small electro-mechanical transducers. It was a one-off type problem, since only three of these machines were to be built. This problem was based on a consulting contract completed by one of the authors. The other, known as the battery-contacts problem, required subjects to design the contacts and compartment for three button batteries, connected in series to power a time clock. To solve the battery-contacts problem required knowledge of thin metal springs, very basic electrical theory, and plastic injection molding. The project was product oriented, as 1.8 million units were required to be built. This problem was developed with the cooperation of a major computer manufacturer. A full description of both problems appears in reference [12].

We presented the problems to a total of six subjects: two graduate students with limited industrial design experience and four experienced designers presently employed in industry. To preserve anonymity, we refer to them as S1, S2, etc. A summary of which subjects worked on which problems is shown in Table 1.

Table 1. Distribution of Subjects

Problem	Grad Student	Professional
battery-contacts	S1	S2 and S3
flipper-dipper	S4	S5 and S6

These subjects were requested to think aloud as they solved the problems. The protocols were video-taped to capture as much data as possible, which included not only their verbalizations but sketches and hand motions as well. Each subject spent between six and ten hours on his/her problem to arrive at a set of working drawings specific enough to send to a model shop. We analyzed the data by developing coarse and fine breakdowns. These were made by watching the video tape while reading a transcript of the subject's verbalizations. The purpose for developing the coarse breakdowns was to show the flow of the design process, identify the subject's attention to particular forms or functions, familiarize us with the problem solving effort, identify design strategies, and identify areas for fine breakdowns. The fine breakdowns typically included less than ten minutes of protocol data and were made to look at individual sub-problems to identify the state-operator-strategy properties of problem solving. From the fine breakdowns we could identify changes to the state of the design, the operators the subject used to change the state and his strategy for employing these changes. While most of the information needed to understand what the subject was thinking was in the verbal transcript, some things needed to be inferred from the video tape. (The subjects worked extensively with sketches and would often refer to a part as "this" or "that" while pointing to the part in the sketch.) A more complete description of the experiments and processing of the data can be found in reference [12].

STRATEGIES OF MECHANICAL DESIGN

Five strategies were reported on the basis of partial analysis of protocols from S2, S5, and S6 in reference [12]. These findings were that our designers:

* often pursued a single conceptual design both at the level of the overall design problem and at the level of individual subproblems.
* used notes and drawings for understanding and analyzing the problem, not just to record final design decisions.
* progressed from systematic to opportunistic behavior as the design evolved.
* did not always conduct balanced development but sometimes pursued a problem in a depth-first manner.
* sometimes repeated previous efforts in solving the problem.

In this report, we have listed additional strategies based on the complete protocols of S1, S2, S5, and S6. The quotes from the subjects are representative of the evidence found to support these assertions. We can only claim that the strategies we have identified are characteristic of these four mechanical designers; we do not know if these strategies are characteristic of all designers. Yet if not typical, then it is just coincidental that all four happened to exhibit the same characteristics or the protocol analysis procedure was somehow responsible. However, Ericsson and Simon [4] have shown that protocol analysis techniques cause the subject to work slower than normal but that the problem solving process remains virtually the same. Since it is unlikely that all four of these subjects simply exhibited these characteristics coincidentally, we believe the strategies listed here are fairly typical among mechanical designers. It is with this understanding that we have described the implications of these findings on the development of future CAD tools and mechanical design methodology.

1. Form and Function are Interrelated in the Design Process. - Form defines the geometric and topological components of a mechanism. Each component may be referred to as a form of the mechanism. Function characterizes the problem a mechanism must solve or the purpose of a form. Other problems such as how the mechanism moves, ergonomics, power, and cost considerations are also functions of the mechanism. For example, a typical function designers must often address is to build a mechanism within some time or cost budget. We have identified two relationships from the data between form and function that differ from present design theories.

1a. Designers develop the functional aspects of the design in stages throughout the problem solving effort. - Some present design theories [1,3] recommend a systematic functional development of the entire problem during the initial problem solving effort. They require an expansion of the problem and then a development of functional structures or solution principles to accomplish the expanded problem. This initial groundwork becomes the basis for form development. Our subjects did not attack their problems in this fashion. They made shifts between form and function during the entire problem solving effort and the design developed in stages. Though our subjects did consider functional aspects of the design during their initial problem solving effort, the amount of time each subject initially spent considering functions varied from virtually none to 36 minutes (out of a possible 10 hours of solution time). After this brief functional development, a conceptual form was then quickly established and the subjects became form oriented, that is, the problem solving effort focused on developing each individual form.

Though the subjects worked on designing individual components after a initial conceptual design was made, they did shift back to the functional requirements of the problem. For example, nearly two hours into the design, S5 began to concentrate on function again. He did this for 22 minutes before developing the forms again. This shifting continued to occur, throughout the problem solving, though rarely during the detail design phase. This was true of all of the subjects.

Just what caused this shifting between form and function is not fully known at this time, though we saw repeated evidence that progress in problem solving tended to have peaks and valleys of effort. During one of these peaks, the subject would be working intensely as some particular form took shape and gained proper proportion. Subjects always documented these changes in a sketch. Once the sketch was completed, they would "back off", sometimes literally leaning back in their chair, and their thoughts became functional. A typical example would be the simulation of the form they just designed as it interacted with the rest of the mechanism. During this time, they made sure that the form they just designed would perform the functions they intended it to. Once satisfied, the subject verbalized new functions relating to another form and set new goals, possibly rereading parts of the problem statement and acquiring a better understanding of the problem. Then the cycle would repeat as the subject concentrated on developing the mechanism.

<u>1b. Functional considerations remain qualitative while often form considerations become quantitative during the problem solving effort.</u> - Some design theories [1,2,3] recommend that the designer quantify the problem functions as much as possible before considering a form. Our subjects often did not do this but left original functional considerations qualitative. An example came from S5 when he was trying to get the aluminum plate to enter and leave the water with a lead-in angle. He never quantified the function to "leave the water bath with one edge leading", yet he created a detailed drawing of the form to perform this function. As a way of satisfying this problem without quantifying the function, he made the form adjustable. Through this and other examples, we have found that subjects do not often quantify function.

Future CAD tools need to respond to these form-function relations. If the theorists are correct that a initial detailed functional development is beneficial to design (further research is needed to determine this), then CAD tools are needed to help the designer develop functional considerations before proceeding to the form design. Yet if CAD forces the designer to fully develop the functionality of a problem during the initial effort, he may be reluctant to use the design tool. If the actual behavior of our subjects proves to result in more efficient design than the methods recommended by the theorist, then these patterns can be incorporated into a CAD system that aids the designer in thinking functionally in stages throughout the entire design process.

2. Our Designers Base Many Decisions on Qualitative Rather Than Quantitative Reasoning During All Phases of Design. - To arrive at a design decision, our subjects often evaluated their ideas based not on quantitative factors such as an analysis of stress, cost, or manufacturability but based on very qualitative, subjective reasoning. One would expect trained engineering subjects to strive for the most complete and technical reasons practical for evaluating ideas, yet they often based decisions on rules-of-thumb and personal preferences. This finding agrees with Waldren and Waldren [8] and Mitroff [6] who concluded more specifically, that design was both a technical and behavioral process.

An example from our protocols of such subjective reasoning came when subject S6 was deciding on the wall thickness for the plastic envelope that surrounded the batteries. He found some guidelines in his design manual which recommended that a typical thickness of 60 thousandths but that thinner walls can be used over smaller areas. He said: "There's a little bit of Kentucky windage on picking my, uh, material thickness. I'm going to go around 30 thousandths for much of that wall." Later, while adding another section to the wall, he stated: "That's a problem in that, uh, I could face a little bit of creep, a slight amount of creep here at the front. Rather than go in and calculate it, what I'll do is, uh, add as much thickness as I can stand anyway up here." (Creep describes the permanent deformation of the plastic wall over a long period of time.) So rather than size the thickness of the wall via reasoning based on a quantitative creep analysis and calculations, he simply sized it based on his experience or subjective preference.

Our subjects seemed quite comfortable with this apparently casual decision making. In practice, designers simply do not have the time nor patience to quantify everything. Apparently, a lot of domain knowledge that is hard to quantify is essential for design. AI methods need to be applied to extract this knowledge for future CAD tools. We believe that tools should be developed that will help the designer use quick and easy quantitative reasoning and as well as tools based on qualitative reasoning. Methods for qualitative reasoning are currently under active investigation in the AI field [14].

The inclusion of qualitative reasoning is essential for explaining mechanical design, yet it adds enormous complexity to the subject of design methodology. A way of defining when qualitative reasoning is adequate and when the problem needs to be quantified is essential. This task will be difficult since the qualitative reasoning identified in our protocols was based, to a large extent, on the subjects' domain knowledge.

3. Knowledge Controls the Design Process. - We have identified from the data three ways in which the subject's knowledge played a key role in the problem solving process.

3a. The designer's knowledge influences the generation of ideas for problem solutions. - Our designers did not employ a domain independent procedure to generate ideas, such as solution principals to satisfy functional constraints [1]. Rather we found that our designer's knowledge controlled the generation of ideas and they would base ideas on past experience. For example, we gave all of our subjects a practice problem that required the design of a flush mechanism for a toilet in a restricted space. After reading the problem statement, one of them immediately said, "Well the first thing that jumps into my head, is that when traveling in Europe I saw where they had the tank up very high so they got a good, a good head." And another said, "Let's put a tank in the ceiling, why not. It's not a new idea, they used to do that back in the old Victorian times." They immediately became fixed on ideas that were familiar to them. Waldren and Waldren [8] also found that knowledge influenced the generation of ideas.

3b. The designer's knowledge influences how ideas are evaluated. - Our subjects did not evaluate ideas in a consistent manner because they evaluated ideas based on their knowledge. An interesting comparison concerned the attachment of spring contacts to the plastic envelope in the battery-contacts problem. S1 decided early in the session to glue the contacts to the plastic envelope and said: "Probably just glue it on...and then just have them glued on in the assembly of the envelopes." Then later, a lack of knowledge was stated when S1 said: "Okay, I don't know much about adhesives, so I'm going to have to read most of this." When faced with the same problem of attaching the contacts to the plastic envelope, S2 said:"...I want to design this so that it's automated and so that it goes together in a very predictable way and uh I'm going to choose to approach my design so that no glue will be required either uh, uh an adhesive type glue or a solvent type glue." When explaining why he said "... I'm going to simply prejudice my approach from the beginning uh, from a background of experience...adhesive is not predictable in, with respect to several things..." S1 accepted the glue idea, S2 rejected it, deciding to snap the contacts into place instead. Each subject's knowledge, not his/her problem solving methods, led him/her to evaluate the idea differently.

3c. The designer's knowledge level influences the problem solving methods. - When subjects possessed little knowledge in a particular domain, they often thumbed through catalogs to find what was available off-the-shelf, to check the properties of some form, or simply to spark some ideas. S2 needed to pick a material for the envelope. He picked up a catalog and said:"I'm looking...(pages turning) I'm going to look through the material ...and just look, look over some of the characteristics (pages still turning) of, uh, what's available." After picking ABS plastic, he decided to look up information on minimum wall thickness as he was considering this earlier in his design, and said: "They don't talk about minimum wall thickness (pages turning). I have to go hunting... I'm just going hunting for a while. You have to do that." While searching for this information he turned a page and said: "Oh, here's an interesting note here giving me a guideline of, uh, on fourth of the material thickness or 15 thousandths as being the fillet radius to use throughout. Might as well copy that down here." In this case, his knowledge level was great enough to recognize that he could use the information on fillet radius;thus his strategy became opportunistic [4,12].

The use of domain knowledge to control the generation and evaluation of ideas along with the problem solving process itself, points to many CAD concepts. In generating ideas, future CAD systems can be developed to help designers by presenting them with a catalog of designs organized by function. These catalogs do exist in text form but only in specific domains such as kinematics. Another concern for future CAD tools is how to keep the tools flexible enough to accommodate each designer while being cognizant of their knowledge level. CAD will need substantial amounts of domain knowledge (including knowledge of past designs) in order to be able to help generate and evaluate potential design ideas. Therefore, it is essential that a knowledge-based system approach be used to build future CAD tools.

One of the essentials of a design method is that "it must be applicable to every type of design activity, no matter in what specialist field" [1]. Yet our subjects made little distinction between a procedural knowledge and domain knowledge in the way they solved problems (ie. the example of opportunistic strategy). This topic must be researched further to understand what role knowledge should play, if any, in a methodology of design.

4. Our Designers Made Simulations as an Aid to Understanding Problems and Evaluating Solutions. - We have observed that our subjects made three types of simulations: mental, visual, and physical. Each type referred to the way the simulation was represented during the problem solving effort. Simulations were defined as occasions when the subject was trying to "visualize" a particular idea or form, along with trying to grasp how that form moved, could be manufactured, or configured. Mental simulations occurred in the subject's mind. Visual simulations were two-dimensional representations such as sketches on paper that the subject could see with his/her eyes. Physical simulations were accomplished with three-dimensional, physical representations that the subject could feel, hold, and move.

When the subject was thinking about a particular form, he did not hold the name of that form in his mind but a mental image of the form. This was evidenced by S2 when he said: "I'm just imagining this problem in my head. I know that I've got to have some kind of uh, spring finger assembly." Mental simulations were rarely reported in our protocol data. This could be because the simulations did in fact not happen often, occurred too quickly to be consistently reported, or were too abstract or unimportant to verbalize. (From our own experience, being designers ourselves, we believe that mental simulations do occur but because any idea worth pursuing can quickly overload one's mind, they are often abandoned in favor of a visual representation.)

Visual simulations occurred often when a form was represented as a sketch on paper. These visual simulations were not for making a dimensioned drawing, but for helping the subject "get a feel" for the situation. This was evidenced by S6 when he stated: "So, basically, I'm going to just sketch mechanically how the piece might be handled."

Physical simulations occurred when a form was represented by some three dimensional, physical object in space. These objects were usually the subject's hands, a nearby book or pencil to represent a particular form. One subject actually made paper cut-outs of some components. An example of physical simulation occurred when S5, while performing a physical simulation with a paper cut-out, said: "I'm really hung out as far as...how far off center to put it, because I don't know, what, how much that film is going to float this up on the water...I can see as it's coming by it's gonna, it's gonna pick up the edge and kiss the film and then flatten out on the surface as it comes back up again, but the angle is going to be determined by the amount of, amount I have this off center." He used this physical simulation to provide a less abstract insight into his problem than his previous visual simulation.

Indirectly related to this strategy of simulation was that, when the problem solving progressed to the point of making detailed drawings, all subjects wanted to make full-scale drawings. The subjects solving the flipper-dipper problem complained that the standard size paper they were given was too small and the mechanism too big so they had to use quarter-scale. One subject brought in his own drafting paper so he could at least draw half-scale. The subjects solving the battery-contacts problem complained that their mechanism was too small, that the double or triple scale drawings were deceiving, and that they couldn't get a good feel for what was happening.

Our findings emphasize that there is a need for real time simulation in CAD. Unfortunately, present CAD tools are too rigid to be useful during the early stages of design when many of the simulations occur. CAD systems need to be highly versatile with respect to making changes, sketching forms in three dimensions, connecting them and moving them around on the screen in real time. Also implied in this finding was that the subjects often looked for a more true-to-life representation, often progressing from mental to visual and then to physical simulations. Our subjects also desired to make more true-to-life or full scale drawings. Present CAD systems can only aid the designer in making visual simulations on a computer monitor. CAD could be a great aid to the designer if he could, or at least could appear to, actually reach into the computer monitor with his hands and create three-dimensional forms and manipulate them. In this way, CAD could help perform the physical simulations our subjects were seeking.

<u>5. Designers Usually Found Satisfactory Solutions Rather Than Optimal Solutions.</u> - Present theories on mechanical design [1,2,3] stress the importance of optimizing the problem solving process at all levels of design. Love [2] states: "An amateur designer is satisfied with anything that works. The professional designer not only wants to get the best under the possible circumstances but knows how to do it." Optimization may be defined as achieving the best design with the time, technology, and other resources available to the designer. We found that our subjects, even the experienced ones, did not strive for optimal solutions. Instead, they looked for solutions that worked or simply satisfied the requirements. This approach was used not only during the layout and detail stages of individual components, but during times of conceptual design as well. This finding supports that of Ramstrom and Rhenman [10] who found that "a solution is accepted when it is considered ¶good enough' or ¶satisfactory' even if it does not represent an optimal result."

If a subject were to look for an optimal solution, one would at least expect to see in the protocols possibly two or more solutions to a problem introduced and then a comparison, to develop the best one. Or possibly the subject working with only one solution but iterating on it until the solution became the best design practical. But these behaviors were rarely observed. For example, S6 had his first conceptual design sketched out within the first 15 minutes of his six hour total effort. He never introduced another idea for the overall operation of his design. He simply altered his first design, adding and changing as necessary, until he satisfied the design requirements. At a more detailed level, S5 generated two possible solutions to a particular problem. He picked the first over the second, not because it was better or more optimal, but because he wasn't sure how to calculate a required dimension in the second solution. He wasn't too enthusiastic about his choice and said: "Might look ugly but it'll probably work." Yet he did not try to determine the required dimension in the second solution but stayed with his choice as it satisfied the problem. More often than not, the subject would generate only one idea and use it or alter it only until it worked, not to make it work better.

There are many possible explanations for this type of behavior though none are obviously conclusive. Too little time could have been a factor, but we did not pressure any of the subjects; we let them work at their own pace. Maybe their everyday work environment is such that time always is a factor and therefore they naturally pressure themselves so that they rarely can take the time to optimize. It is possible that our subjects did not optimize because the design was never to be built. However, we find this unlikely because the subjects were also aware that they were being video-taped and thus recorded for all time. This would have encouraged them to take the experiment seriously. Perhaps in some cases, looking for an optimal solution is not always necessary and the first satisfactory idea is all that is needed to produce a good design.

If optimization should be pursued, then CAD tools need to be developed to encourage the user to optimize. Since our subjects were reluctant to optimize, these tools must be flexible, easy to use, and fast. If optimization is not always appropriate, then CAD should know the limits and steer the designer towards finding a satisfactory solution only.

A coordinated approach to optimization needs to be incorporated into a design methodology. If it is assumed that finding optimal solutions is critical to the design process, then the lack of optimization in our protocols could signal a wide spread problem. It may also be true that in many circumstances, solutions that are only satisfactory are sufficient. In that case, design methods need to distinguish when optimal or satisfactory solutions are most useful.

CONCLUSIONS

Mechanical design is an extremely complex task and not well understood. Though theories exist for a systematic method of design, the actual practice appears to be anything but systematic. Through the use of protocol analysis, we have gained a better understanding of mechanical design. Our observations provide insight as to how design can be improved through the use of future CAD tools and an improved methodology. We have found that our designers:

*developed the functional aspects of the design in stages throughout the problem solving effort rather than during an initial functional development stage called for by many design theories.
*used functional considerations that remained qualitative while often the form considerations became quantitative during the problem solving effort.
*made decisions based on qualitative, subjective reasoning at all phases of the design.
*used their knowledge to influence the generation of ideas for problem solutions.
*used their knowledge to influence how ideas were evaluated.
*used their knowledge to influence their problem solving methods.
*performed mental, visual, and physical simulations as an aid to understanding problems and evaluating solutions.
*attempted to find satisfactory rather than optimal solutions.

These observations show that mechanical designers do not always approach problem solving according to established design theories. Many of the strategies that we have identified have been viewed by design theorists as being poor methods of design, yet there may be very good reasons why humans work in these ways. A way of evaluating the effectiveness of the design process needs to be developed. If the theorists are correct, then we must determine whether these human actions are the result of poor training, cognitive limitations, or other factors. If any of the methods we observed make for better design, then they should be incorporated into a methodology of design.

AI-based CAD tools need to assist the designer in a more coordinated approach to design. Tools need to be developed that will assist designers to shift efficiently between form and functional considerations if appropriate. They must help the designer think functionally, perhaps by cataloging solution principles according to functions. The role of each individual's knowledge suggests that the problem solving process may be a very individual process. CAD tools need to be cognizant of each designer's domain knowledge while assisting in heuristic methods of problem solving. In addition, CAD tools need to provide the designer with real-time simulation techniques with true-to-life representations of the design components. Finally, CAD tools need to encourage the designer to optimize or simply satisfy design constraints when appropriate.

It is our hope that further analysis of our protocol data will help us develop a more comprehensive understanding of design and sharpen the observations mentioned above. The development of an empirically-justified theory of design will provide a sound basis for the development of future CAD tools and for the training of future mechanical engineers.

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REFERENCES
1. Pahl, G. and Beitz, W., Engineering Design, Springer-Verlag, London, 1984.

2. Love, S.F., Planning and Creating Successful Engineered Designs, Advanced Professional Development, Inc., Los Angeles, 1980.

3. Hubka, V., Principles of Engineering Design, Butterworth Publishers, London, 1982.

4. Ericsson, K.A. and Simon, H.A., Protocol Analysis: Verbal Reports as Data, MIT Press, Cambridge, MA, 1984.

5. Adelson, B. and Soloway, E., A cognitive model of software design, Rep. No.342, Department of Computer Science, Yale University, 1984.

6. Mitroff, I.I., A study of simulation-aided engineering design, Doctoral dissertation, University of California, Berkeley, 1967.

7. 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.

8. 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.

9. Marples, D.L., The decisions of engineering design, IRE Trans. on Engineering Management, Vol. EM-8, June, 1961, 55-71.

10. Ramstrom, D. and Rhenman, E., A method of describing the development of an engineering project, IRE Trans. on Engineering Management, Vol. EM-12, Sept., 1965, 79-86.

11. Newell, A. and Simon, H.A., Human Problem Solving, Prentice-Hall, Englewood Cliffs, NJ, 1972.

12. 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.

13. Hayes-Roth, B. and Hayes-Roth, F., A cognitive model of planning, Cognitive Science, 3, 1979, 275-310.

14. Bobrow, D.G., Qualitative Reasoning About Physical Systems, Elsevier Science Publishers B.V., Amsterdam, 1984.

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