How Understanding The Mechanical Design Process May Change Engineering Education

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1. Introduction

There is a recent resurgence of interest in trying to understand the mechanical design process. This is not the first time that researchers have tried to rationalize this "creative" effort. However, the impetus behind this effort is American industry and the National Science Foundation and not just an academic curiosity. It is generally acknowledged that the design process, as practiced in the United States, is an impediment to efficient product development due to its slowness and dependence on extensive redesign in the prototype and preproduction phases. Through computer science developments and human problem solving understanding from cognitive psychology, tools and techniques are available and emerging that may be usable to improve the efficiency of the design process and the quality of the resulting designs. These have the potential to change how we perform design and how we teach design.

The goal of this paper is to present an overview of this resurgence of interest, it's roots, current research and results to date. The paper will conclude with conjecture on the effects this research may have on academia.

2. A Brief History

To talk about mechanical design, some terminology needs to be established. The term "mechanical design" is most often defined as "the creative decision making process for specifying or creating physical devices to fulfill a stated need." This definition describes what mechanical design is but gives no indication as to how it is done. The term "design theory and methodology" is often used to denote the study of the design process itself where "theory" implies studies on philosophy or principals and "methodology" implies the development of techniques, measurements and vocabulary.

Prior to World War II, engineering design education was a major part of the mechanical engineering curricula. The education was primarily hands on design and fabrication and was often oriented to the copying of existing designs.[7] Technological changes during and subsequent to the war brought about the disciplines of engineering science. The development of understanding and the ability to apply physics and mathematics to engineering analysis legitimized the engineering sciences. This "scientific legitimacy" even spilled over into the design of specific components. However, no such theories or methodologies developed for the design process itself. Thus, because of a combination of scientific respect, less expense to practice and more efficient use of faculty time, the study of the engineering sciences pushed design out of the curriculum.

Only in recent years has design begun to make its way back into the mechanical engineering curriculum at most colleges and universities.

Part of the reason for the above situation is that the actual process of mechanical design is not very well understood. There are a number of books of long-standing popularity that present theories on the subject (e.g., Buhl[2] and Love[6]). In Europe there has been significant interest in the subject (Hubka[5] and Pahl and Beitz[10]). These works represent an effort to "rationalize" the design process, to give it a formulaic structure, to make design a science. Essentially, they have received little attention in the USA until recently. Typically, all of these works provide some hints as to how to organize the design process, but are, by necessity, very general theories based on the authors' own techniques. These books are really texts on what the design engineer should do during design, but they are not based on studies of how designers do design, and there is no evidence that following the espoused procedures is of value.

3. A New Focus on Understanding

Interest in the study of the design process is being fostered by the NSF Design Theory and Methodology Program. The intellectual foundation for this program was established in a September 1985 workshop cosponsored by the AICHE, ASCE, ASME, IIE and IEEE. The results of this workshop were reported in "Goals and Priorities for Research in Engineering Design"[1] and "Design Theory and Methodology - A New Discipline."[11] This workshop defined design theory and methodology as

> "an engineering discipline concerned with process understanding and organized procedures for creating, restructuring and optimizing artifacts and systems."

Expanding on this definition, two subareas of design theory and methodology were identified as: conceptual design and innovation; and quantitative and systematic methods. Conceptual design and innovation "comprise the process by which concepts are created and introduced into practical use. This is a broad and eclectic sub-area, incorporating aspects of engineering, creativity, psychology, sociology and business." Quantitative and systematic methods are the results of trying to rationalize as much of the design process as possible. This includes physical system modeling, computer based simulation, and quantitative methods for assessing design configuration quality, complexity, and manufacturability. Disciplines that support these areas are knowledge-based systems, information integration and management and human interface aspects in design.

As a part of the workshop, a survey was taken of engineering deans and research center directors. Although the sample was small, some of the observations made were:

> Most design activities on campus are not concerned with innovation or unstructured programs, but deal with optimization of idealized models of existing or specified components or devices.
>
> There is a preoccupation with CAD (see comments on CAD's place in the design process in section 4.1)
>
> Most deans and many department heads do not understand or support design.
>
> There is an overwhelming feeling that design is essential and research on it and its role in education must increase.

The above observations illustrate that there is not a clear discipline of design and thus not a consistent attitude toward it in academic administrations. This is further evidenced by the fact that faculty who teach design receive no credit for doing design. They have, in the past, performed research in fields adjacent to design and only recently have design academics begun to receive credit for studying design itself. It would seem the study of the design process needs to establish itself as a respected discipline before the teaching and the administration of design are consistent with industry's and NSF's view.

4. Efforts at Influencing the Design Process

Current efforts toward influencing the mechanical design process will be discussed in four groupings: intelligent computer aided design tool development; artificial intelligence tool development; human studies as a basis for design aids; and design theories.

4.1 Intelligent Computer Aided Design Tool Development

For the purposes of this paper, the term CAD is defined as the use of interactive computer graphics to help solve a mechanical design problem. Current CAD tools aid the mechanical design process in four ways: as an advanced drafting tool; as an aid in the visualization of hardware and data; as a data organizer and communicator; and as a pre- and post-processor for computer based analytical techniques (i.e., finite element analysis, weight and mass properties calculations, kinematic analysis, etc). It is an important point to note that CAD systems only affect the latter stages of a design when the form of the designed components is well established. They are of no help in conceptual design and only aid in the refinement of design details. Thus, current CAD tools have little or no effect on the design process itself. As noted above, there seems to be a preoccupation with CAD systems in design courses even though CAD tools have no influence on the fundamental process itself and are of no aid in creativity or innovation. However, a new generation of CAD-like tools may affect the design process.

Within the last year a new computer design aid has appeared on the market - parametric design tools. These systems allow a designer to perform parametric studies on his design in a way only hinted at with conventional CAD tools. These tools still require a design that can be reduced to geometry and equations but enables the designer to iterate on the design (CAD mainly records). Although these tools push into the realm of layout design, in which form concepts are patched and refined to the point that detailed drawings can be made of them, only designs that are geometrically determined and have an analytical representation can be explored on these parametric systems. Since they can be used earlier in the design process, they may have an effect on it. This effect is unknown and may be positive or negative.

4.2 Artificial Intelligence Tool Development

In the artificial intelligence (AI) community there are systems being developed to aid in mechanical design. Many of these systems use expert system shells to perform simple tasks. However, for all but the most routine of design tasks, inference techniques beyond those in the currently available shells need to be developed. Much of the research on these intelligent design systems is being performed in an ad-hoc manner. A problem is selected, a program is developed that solves the problem, then the method of solution is generalized for other similar problems. This method not only leads to tools to solve the problem at hand, but to an understanding of the specific problem. In the effort of generalizing the results, knowledge about the design process is realized (hopefully). A number of examples of this approach are in the literature. Primary among them is the development of the XCON system (also known as R1).[9] This system, developed at Rutgers, is in daily use by DEC to configure VAX computers. The problem solved by the system is to place the various components required by a customer's order into a standard enclosure in such a way that the order is complete, all wiring connections can be made, and all spatial relations between the components is complete. In developing this tool, the researchers at Rutgers developed techniques for logically dealing with a class of problems that require the physical placement of components in an enclosure where the components have limited, but known functional interaction. This is typical of many other design problems. Thus the researchers have taken the knowledge gained in developing XCON and applied it to the selection and placement of components in designing elevator systems.[8]

With each of these ad-hoc efforts more is learned toward rationalizing the design process over some limited class of problems; ones where the design effort is fairly routine and the problem decomposable into relatively independent, relatively basic subproblems. Potentially, enough of these studies may lead to an overall design theory for mechanical design. Realistically, however, these tools will only solve a small class of routine type problems and the remainder of the design tasks will remain dependent on human problem solving. These efforts must be combined with studies that start at the other end of the problem, the human end; so the process can be understood in a way that allows the development of man-machine design teams, a realistic goal.

4.3 Human Studies as a Basis for Design Aids

Relatively little research on the design process has been based on empirical evidence, especially in mechanical design. In fact, serious study in design in general has only occurred in the past 25 years.[3] An overview and discussion of six empirical studies in mechanical design can be found in reference 13. These studies offer many potential benefits which can not be obtained without using the mechanical design engineer as the source of the data. The reasons for this are:

1. Human problem solving is flexible and robust: current computer design aids are not. Thus, by starting with the human problem solving techniques, the needs for computer systems become better defined.

2. A system may be developed that learns from human designers and thus an understanding of their process is essential.

3. It is important to understand the human design process to improve industrial efficiency so that higher design productivity can be achieved with designs of greater quality. This consideration is irrespective of the development of computer design aids.

4. Design is so poorly understood that it is difficult to teach in the engineering design schools.

Based on these reasons, formal studies of the mechanical design process are underway. Among these are the research of Hales;[4] Waldron and Waldron;[20] and Ullman, Stauffer and Dieterich.[12-18] In each of these studies humans were observed in the act of design with a goal to determine the methodology of their design process. The work by Hales was a 2.6 year observation of the design of a high-pressure, high-temperature system for testing materials in a simulated coal gasification environment. Hale tracked every major design decision in a systematic manner. In a more detailed study, the work by Waldron and Waldron used a retrospective analysis of the design of the leg of the Adaptive Suspension Vehicle, a walking machine designed at Ohio State University. The most detailed work to date on mechanical design has been by Ullman and fellow researchers at Oregon State University. A brief overview of this work follows.

Five mechanical design engineers of varying background and experience were given the initial specifications for one of two fairly simple, yet realistic, industrial design problems. The engineers were requested to think aloud as they solved the problems. Their verbal reports, sketches, and gestures were video- and audio-taped for a period of 6-10 hours. The taped data were then transcribed to obtain a "protocol" of the design session. The protocols were then analyzed in a variety of ways to provide the data for study.

The two problems used in the study were the "battery contacts" problem and the "flipper-dipper" problem. The battery contacts problem statement, in abbreviated form, is the following:

> Design a plastic envelope (dimensions provided) and the electrical contacts to accept three batteries to power the time clock in a new computer. The batteries (detailed dimensions provided) must be connected in series and to an adjacent printed circuit board. The external dimensions of the envelope are provided as are needed contact pressures. The volume is 50,000 units/month for three years and the assembly will use a robot.

The flipper-dipper problem statement, in abbreviated form, is the following:

> Design a mechanism that will accept a 10"x10"x.063" aluminum plate from a worker, lower one side so that it just touches the surface of a chemical bath (to receive a chemical coating), lift the plate off the bath surface, flip it over, lower and coat the other side, and present it to the worker for removal. There were only to be 3 of these built.

More details on these problems can be found in references 14,15,17 and 18.

To date, protocols have been taken on two subjects solving the battery contacts problem and three subjects solving the flipper-dipper problem resulting in approximately 46 hours of data. All of the data was transcribed and analyzed to determine the general problem flow. Several detailed analysis techniques were tried on selected parts of this data in an attempt to develop an analysis method that provided insight into the goal structure of the design. It was found that an analysis based on tasks, episodes, and operators (defined below) was most revealing and was reasonably repeatable by different researchers. Four general types of tasks were identified: conceptual design, layout design, detailed design, and catalog selection. In each protocol, all instances of each of these tasks were identified. Then one instance of each task was selected at random for detailed dissection. This yielded 18 sections (one subject never performed a catalog selection task) constituting 204 minutes of data (8% of the total data). A model of the design process has been constructed from the detailed analysis of these 18 sections.

The result of this study is an improved but incomplete understanding of how mechanical engineers perform design. The study has given a good understanding of an engineer's goal structure, handling of constraints, the importance of levels of abstraction and a set of 10 operators which an engineer uses to progress from state to state throughout the entire design process. One of the more useful results is that engineering designers solve problems in one minute focuses of attention called episodes. In other words, designers make a design decision on the average of once a minute and then begin a new problem to satisfy a new subgoal. Not all these episodes result in decisions that appear in the final design. Some decisions are parts of design dead ends and others result in rejected ideas. A complete discussion of these concepts can be found in references 14 and 18.

Another aspect of design that the results allow study on is the development of constraints. Some constraints are given in the initial problem specification, others are dictated by the domain (rules of thumb, material properties, manufacturing tolerances, and etc) and others are derived as a result of design decisions. Through mapping the development of these constraints, the evolution of components and the effects of designer knowledge and approach are being studied.

One importance of the above findings is that any computer design assistant that may be developed needs to be able to deal with a high volume of information. Humans do a poor job of handling all the data generated in a design and thus often don't find design errors until prototyping or production. To assist the designer, researchers at Oregon State University are developing a design history tool. This tool will record the design decisions and constraint development from the initial problem statement to the final detail design. These will be recorded and indexed in a way that the designer can inquire why certain design decisions were made and identify the effect changing one decision will have on other parts of the design.

Another result of this study is the importance of drawings or sketches in the design process. Five uses of the act of drawing and sketching in the design process have been observed. These are:

1. To archive the geometric form of the design.
2. To communicate ideas between designers and between the designers and manufacturing personnel.
3. To act as an analysis tool. Often, missing dimensions and tolerances are calculated on the drawing as it is developed.
4. To serve as a completeness checker. As sketches or other drawings are being made, the details left to be designed become apparent to the designer. This, in effect, helps establish an agenda of design tasks left to accomplish.
5. To act as an extension of the designer's short term memory. The designers often unconsciously made sketches to help them remember ideas that they might otherwise forget.

In support of the last item, for example, it was found that throughout the design process, engineers made a sketch, note or drawing of the result of nearly all episodes that ended in an accepted design decision. This recording of the results was necessary because the designer's ability to keep chunks of information in his conscious mind (his short term memory) is limited to about seven items.[14] Thus, these drawings and sketches were vital to the design effort as they were used throughout the design process to record the results of a majority of the episodic subgoals. This observation means that CAD tools need to be more than tools to record well thought out and structured results. They also need be used with more abstract ideas (usually represented as sketches) and have the ability to deal with ideas at various levels of abstraction. Additionally, CAD tools need to manage constraints and insure constraint satisfaction as it is evident that human designers are cognitively limited in this ability. Lastly, it would be helpful if CAD systems could check for completeness and aid the designer in determining when the form is not physically realizable.

The need for a CAD system to function at all stages in the design process and to be a usable sketching tool has encouraged the development of the Conceptual Design Capture System, CDCS. This tool is in the early stages of it's development.

Essentially it is a computer system that allows the user to sketch his/her ideas on a tablet in 3-D. It then interprets these sketches as a solid model relying on knowledge of the users domain. Thus, a user can sketch abstract ideas and refine them throughout the design process.

In engineering training, the results of the human experiments point to the importance of representing design concepts graphically. It appears that the very design process itself is limited by the ability to use graphics as a cognitive extension. This implies not only the need for training in the standard drafting skills, but additionally, for training in the ability to represent concepts that are more abstract and best represented as sketches.

4.4 Design Theories

As mentioned in the introduction, there have been many attempts at design theories that have not been very formal. The German efforts to fully rationalize the design process are an exception. These theories have lead to the development of a "standard" for design, VDI 2221.[19] Unfortunately the value of this standard and of the design theories in general is unproven. Hales[4] has attempted to verify the validity of the Pahl and Beitz[10] method (virtually the VDI 2221 method) through his study. However, his work does not act as test of the method. The industry Hales studied did not use the techniques as part of their regular design process, follow them rigorously, nor was there any type of control for comparing the results. There have been no other experimental efforts to verify any of the design theories and thus their potential for formalizing the process in any useful way is suspect.

5. The Effect on Mechanical Engineering Education

For the sake of argument, assume that the above efforts continue to generate useful results and the study of the design process is not a transitory research discipline. The evidence above suggests that this assumption is true. If so, then what effects can be expected in mechanical engineering and in mechanical engineering education in particular.

The first effect is that the design process will become better understood. This could mean that it will be understood to the point that it can be automated, but this is doubtful. More realistically, certain parts of it can be automated and the rest will remain in the hands of human designers. This separation of the drudgery (what can be rationalized and codified on computers) from the creative (what can't be explained and thus remains best accomplished by humans) is a prime goal of the research. The development of design assistants will allow human designer to be more creative and solve only the hard problems. Further developments will make it easier to prototype unrefined, conceptual designs leading to a greater ability to explore the design space. This claim is already being made by the manufacturers of the parametric design tools.

With this understanding will come measures for what is a good design and a good design process. Currently there is no way to measure the quality of a design until it is at least in the prototype stage of development. A quality product is evident to most consumers. This product probably resulted from many costly iterations after the design was supposedly completed. It is one goal of the research on the design process to develop measures or heuristics that can be applied as early in the design as possible and thus reduce the cost of product development.

The second effect will be the recognition of design theory and methodology as a formal discipline. This is already underway with the NSF's strong funding for research in this field; the recent (Nov 1987) organization of the ASME Committee on Design Theory and Methodology as part of the Design Division[†] and the recent commitment of a major publisher to bring out a journal on the subject in 1989. It must be noted that the ASME committee already has over 60 members and has begun a quarterly news letter. Recognition of the study of the design process as a formal discipline by others in mechanical engineering will take time since it is hard to judge the quality of the research in a new field, there is always reluctance to accept interdisciplinary fields, and there is a historic vision of design studies being about the design of components (gears, bearings and etc) not of the process itself.

A third effect will be the ability to more rapidly prototype design concepts. In the era before WWII, student and professional designers could bring their concept to realization in the shop and then refine it until it worked. With more complex designs and manufacturing techniques this becomes more difficult. One way of dealing with this problem is with computer prototyping, the effective result of the current design tool development. It will be interesting to see if a designer can get a "feel for the steel" on the computer.

A fourth effect of the design process studies will be better teaching methods resulting in a firmer teaching discipline and more objective ways to evaluate students. Let's assume that the parametric design tools become as readily available as the CAD of today and tools like the routine design and design history tools, and the conceptual design capture system (CDCS) become developed to the point of being usable. These tools, when used together, will allow for the rapid prototyping of designs and the monitoring of the design process.

[†]Information on this committee can be obtained from the author.

As an example consider the following scenario. A student is given a design problem to solve. To do this he/she explores the potential solutions by sketching concepts on the computer tablet. The CDCS system, then develops a solid model of each. At the same time, the design history tool records the decisions made and the development of constraints. When a design is roughed in to the point that it's operation can be simulated, the parametric system can be used to associate equations with the basic geometry developed. The configuration can then be simulated and patched until a successful design is obtained or it is abandoned. Throughout this procedure the design history tool is recording the process for playback to the student and evaluation by the instructor.

With a system such as this, it would be possible to monitor the design process for every student and determine the quality of the approach to design, not just the results of the analysis on a design. Currently, it is not possible to measure and evaluate design skills. However, with the developments discussed above this will be possible. Thus, while potentially enhancing the opportunity for creativity in design, we will be able to identify the students with good design skills and reward them in the same way we have rewarded those students with good analysis skills.

Thus the effects of this research on engineering design lies both in the understanding and the resulting tools. It is difficult to know if any of the systems discussed will come to pass or even if they are desirable. However, it is clear that there is an opportunity for the discipline of mechanical design to legitimize itself as a formal study and potentially develop tools that can change, for the better, the way we do and teach mechanical design.

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