Relating design process to design outcomes in engineering capstone projects
by Vikas Kewal Jain

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Industrial and Management Engineering
Montana State University

Abstract:
Design has traditionally been an important part of an engineer's training. In the past decade, increasing importance is being placed on design as the focus of engineering curricula. Large engineering companies and accreditation agencies alike have taken an aggressive stand as to what they need and expect from engineering graduates. Unfortunately, design may also be one of the least understood fields in engineering education.

This thesis focuses on better understanding design processes, specifically those used by mechanical engineering students at Montana State University. Data on design processes were collected from journals students kept as a part of their capstone design projects. The projects were characterized by time coding the entries in these journals using a 3x4 matrix of design variables. Process outcomes were then measured by a client satisfaction index (measured through a survey) and an assessment of the design quality by industry professionals. Data collected from 15 projects were then modeled using principal component analysis and artificial neural networks. A virtual design of experiment was then conducted to obtain estimates for design process factors that significantly affect the client satisfaction and design quality.

The results indicate that the effects of process variables on design outcome may not necessarily be in agreement with the popular representation of a "good" design process. We hypothesize that because student design engineers are novices and differ form professional industry designers, the training they presently receive may need to be modified and tailored in specific domains to advance their careers as better designers.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

LIST OF TABLES

LIST OF TABLES - Continued

TABLE Page

LIST OF FIGURES

FIGURE Page

ABSTRACT

Design has traditionally been an important part of an engineer's training. In the past decade, increasing importance is being placed on design as the focus of engineering curricula. Large engineering companies and accreditation agencies alike have taken an aggressive stand as to what they need and expect from engineering graduates. Unfortunately, design may also be one of the least understood fields in engineering education.

This thesis focuses on better understanding design processes, specifically those used by mechanical engineering students at Montana State University. Data on design processes were collected from journals students kept as a part of their capstone design projects. The projects were characterized by time coding the entries in these journals using a 3x4 matrix of design variables. Process outcomes were then measured by a client satisfaction index (measured through a survey) and an assessment of the design quality by industry professionals. Data collected from 15 projects were then modeled using principal component analysis and artificial neural networks. A virtual design of experiment was then conducted to obtain estimates for design process factors that significantly affect the client satisfaction and design quality.

The results indicate that the effects of process variables on design outcome may not necessarily be in agreement with the popular representation of a "good" design process. We hypothesize that because student design engineers are novices and differ form professional industry designers, the training they presently receive may need to be modified and tailored in specific domains to advance their careers as better designers.

INTRODUCTION

Design has always been an integral part of an organization with innovation as a core competency. It is through design that creative ideas and needs are translated into hardware and new technology. However, the nature of design is as complex as the resulting technology. "Design is that area of human experience, skill and knowledge which is concerned with man's ability to mould his environment to suit his material and spiritual needs" (Archer, 1973). On a more formal engineering basis, the accreditation board for engineering and technology defines design as the process of devising a system, component, or process to meet desired needs (ABET, 2003).

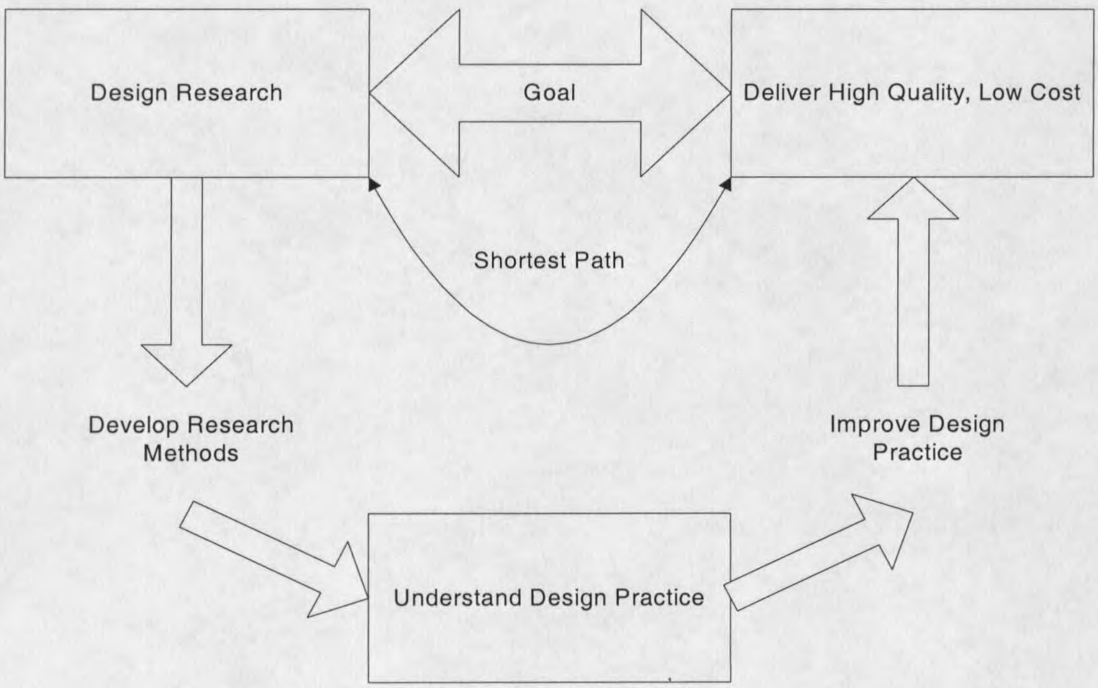
While design has always been a part of human developments, it has only recently been viewed as a science in itself. The focus of design research during the nineteenth and the twentieth century was on the formal engineering sciences required for design, not on the process itself (Birmingham, Cleland, Driver, Maffin, 1997). Only after the 1960's has design been studied extensively and numerous journals dedicated to design theory and methodology have surfaced. The objective of much of the research being carried out in the field of design theory and methodology is to develop a better understanding of the engineering design process. This understanding can be used to develop new methods and services to improve design practice in industry and design education at academic institutions. However, the complexity of the design process offers numerous challenges in accomplishing these objectives.

There are many directions possible for conducting design research, as is evident from the number of academic disciplines involved in it, such as engineering, anthropology, sociology, management and psychology, among others. As a result, design research is published in a large variety of literature sources. Numerous design models, prescriptive and descriptive, have been proposed through the decades; however most of these models are developed based on the processes of practicing or experienced engineers. Little research has been done in the field of studying the design process using quantitative measures, especially in the student design arena. The work done in this thesis is focused towards acquiring a deeper insight into the framework of the student design process through mathematical modeling.

Thesis Problem Statement and Research Question

Developing methods to study and understand engineering design, and using this understanding to build services to support this process is essential for developing high quality products at low cost (see Figure 1).

Figure 1: Design Process



Economic pressures to shorten product development cycles and improve market responsiveness have increased interest in the study of design theory and methodology in industry, in academia and in design education. In academia, one of the principal objectives of capstone design courses is to live a major design experience within the undergraduate curriculum. In view of the fact that many of the students from these courses go immediately to industry and work on real time design projects using their classroom coaching experience, understanding their design processes is imperative to improving capstone courses, and more importantly the overall quality of the engineers produced.

The central aim of this thesis is to gain a better understanding into student design processes through investigating the process characteristics that tend to be associated with good design outcomes versus undesirable design outcomes. This work thus addresses the need for new methods required in design research for improving design process understanding. The study is also significant in that the conclusions drawn from it could be tested by another study and could be applied to help the future student engineering design teams, and answers to the questions posed will help gaining a better understanding of not only the student design processes but also the real-world industry design processes.

Design processes can be characterized in several ways. Past studies in the field of design theory and methodology have identified several process and outcome variables. For example there are a number of factors like the level of abstraction of a design activity, the scope of work, team characteristics, and others that can typically be associated with any design process. Similarly there are numerous ways to measure the "goodness" of a designed product or process like reliability, creativity, customer satisfaction, and others. Incorporating all these process and outcome factors into a single design process model would be difficult for a parsimonious model and beyond the scope of the work done here. Only certain key process factors and outcomes measures will be used in this study. Once a simpler model is identified and validated it can be expanded to incorporate other factors.

More specifically, the study focuses on modeling the relationship between the design process variables such as the resources spent on concept, system or detail design and on problem definition, idea generation, engineering analysis and design refinement activities, versus the respective outcome of student engineering design projects. The four central research questions addressed here are:

1. How do the process variables affect the final design outcome?
2. Which variable or variables are likely to be more important than others?
3. What effect does changing a given variable by a certain amount cause?

4. What are the combinations of variables that significantly increases or decreases the likelihood of success of the design project?

Brief Overview of Prior Work

This thesis is a part of the ongoing NSF sponsored research project, "The Role of Representation in the Synthesis Process", headed by Dr. Durward. K. Sobek, II at Montana State University. The project started in May of 2000 with tenure of 5 years. The research proposed was a cross-disciplinary study of the design processes used by student design teams at Montana State University. The study unit was to be the senior design (or 'capstone') projects in 5 engineering disciplines and 2 non-engineering disciplines (Sobek, 1999). It was hypothesized that the weakness in design in engineering education stemmed from a knowledge gap regarding the synthesis process (Sobek, 1999).

To kick off the project, a pilot study was conducted in the Fall 2000 and Spring 2001. The course chosen for the pilot was ME 404, the Mechanical Engineering senior capstone course. This 4-credit, one-semester course consists of 10 – 12 design teams each comprising of 3 - 4 students. A faculty member advises each team. The projects are industry sponsored and there is usually a budget associated with them. Each team must interact with their client to define his/her needs, devise a solution to meet those needs, and deliver a product (set of engineering drawings and specifications, written report, oral report, and sometimes a hardware prototype) by semester's end. The course is organized and conducted to simulate, as best as possible, the environment and conditions which one can expect to find in the professional world (Sobek, 1999).

Design journals were re-introduced in ME 404 from Fall 2000. Students were asked to keep individual design journals (notebooks) to document their work over the semester as a part of this project. The design journals were aimed at capturing everything and anything related to the design project. It was left wide open for the students to decide what information to record and in what form (Sobek, 2002). However, students were given examples of good and poor entries through in-class training and personal feedback. A journal-grading rubric was used to evaluate the design journals and students were given specific feedback on the expectations and quality of their journals. Finally, the journals constituted to 15 % of the final course grade

At the end of the design project these journals are collected from the students. With an aim of characterizing the design process (and eventually modeling it), a dual coding scheme (Sobek, 1999) was used to quantify each entry in the design journals. The coding technique uses a two-dimensional coding rubric, which codes every entry present in the design journal in terms of the level of abstraction (Concept, System or Detail) and the design activity (Problem Definition, Idea Generation, Engineering Analyses & Design Refinement). The non-design activities are categorized as PM (Project Management), PP (Project Presentation), and RW (Report Writing).The data was quantified based on the aggregate amount of time spent on each of these variables. These data constitute the process data collected and analyzed in this thesis.

Thesis Introduction

This thesis is divided into 6 chapters. Following this introductory chapter, Chapter II reviews the current literature on design research. The first part of the chapter formally defines design and discusses the various design process theories to date. The next part discusses the various design research methodologies that have been to study the design process. A brief introduction of the modeling techniques used in this study is included at the end of chapter II.

Next, Chapter III describes the collection of data and the development of data collection tools on the process and the outcomes measures used in this study. The first half of this chapter is dedicated to the description of the process data collection scheme and the second half describes the development, validation and implementation of the two outcomes measurement survey tools developed in this study to collect data on client satisfaction and the design quality of the students' project outcomes. Chapter IV is dedicated to the description of the data analysis techniques used in this study. Various data modeling techniques are discussed and an appropriate technique is chosen to model the explanatory variables against the response variables. The development of the technique that uses a special type of hybrid artificial neural networks to construct a virtual experimental design metamodel is illustrated in this chapter.

Chapter V presents the research results, including: the descriptive statistics and correlation analysis of the process and outcomes variables, the two neural network models constructed for this study, and the virtual experimental design metamodel. The results are then discussed along with possible interpretations. The chapter concludes with a fairly lengthy discussion of the limitations of the study and the techniques. Finally, Chapter VI, Conclusion, summarizes the research and presents a discussion of some of the implications of the findings and outlines possible continuations of this work.

We now turn our attention to the history of design research and reports the various design research methods that have been used to study design processes.

DESIGN RESEARCH

Authors have been describing design for many years, and numerous definitions and process models have been proposed. In the broadest sense, design is the thought process comprising the creation of an entity (Miller, 2001). A design process may be defined as the series of activities that take a design problem from an initial specification to a finished artifact that meets all the requirements of the specification (Johnson, 1996). In general, a design process can be broken down into a sequence of fundamental operations called tasks. Greater understanding and insight into these tasks and the factors which determine success can enable us to closely represent the design process as a model and addresses the particular risks and problems associated with each process. As a result, the process of design has been studied through decades by many researchers from different perspectives.

In order to evaluate and compare these design process models proposed by the researchers, it is helpful to identify the content and sequence of the procedures outlined. The flowchart representation commonly employed by authors shows discrete tasks or their results connected by transition arcs. In some examples, the "start" and "end" points of these processes can be evaluated, while other process structures imply the lack of a fixed opening or closing. In either case, the individual elements identify tasks, procedures, or results important to the completion of the design process. Each complete structure provides a qualitative definition of the process described by the given model. The following section provides a short chronological review of design theories/models proposed by several researchers over the past several decades.

Design Research History

Pre 1960's: A desire to 'scientise' design can be traced back to the 20th-Century Modern Movement in design. Protagonists for the movement espoused a desire to produce works of art and design based on objectivity and rationality, that is, on the values of science (Cross, 2000). The focus of design research during the nineteenth and the twentieth century was on the formal engineering sciences required for design (Birmingham, et. al., 1997). It was however, the application of scientific and computational methods to the novel and pressing problems of the World War II that led to the revolutionizing of the era of design research.

1960-1970: The "Conference on Design Methods", held in London in 1962 (Jones and Thornley, 1963), is generally regarded as the event that marked the launch of the design methods movement and design methodology as a subject or field of enquiry. A second conference, on "The Design Method", held in Birmingham in 1965 (Gregory, 1966a), tried to relate 'the design method' to 'the scientific method' and began specifically to refer to "design science".

The focus during the early 60's was on the more aesthetic and creative aspect of design, and was solution oriented in that the procedures suggested conceiving a likely candidate solution to the problem and then using this to derive more information relating to the specific problem being addressed (Birmingham, et. al., 1997). Hence Birmingham, et al. (1997) refer to the design process models during this era as first generation models.

Arthur D. Hall (1962) proposed one of the earliest "first generation" models. He suggested a two dimensional view of project development through the phases of life-cycle of the product and the problem-solving. Other authors like Asimow (1962) and Gregory (1966) also proposed similar design theory models during this period.

From this perspective, the decade culminated with Herbert Simon's outline of "the sciences of the artificial" and his specific plea for the development of "a science of design" in the universities: "a body of intellectually tough, analytic, partly formalizable, partly empirical, teachable doctrine about the design process" (Simon, 1969).

1971-1980: Although some researchers began to question the concept of a science of design during the early years of this decade, many were contributing to its development. A couple of models to understand the design process were proposed during this decade. One of the first examples being L. J. March (1976). March argued that the essential logic of the design process required that the two conventionally understood forms of reasoning, inductive and deductive, only applied to the analytical and evaluative activities of design. In his methodology, the designer, at the first stage of productive reasoning, draws on the possibly vague solution. On the basis of this initial proposal, the designer can deductively analyze the design and then inductively evaluate its performance.

Another model of the design process was proposed by Drake (1978), which advocated that a designer uses potential solutions at the early stages of the process in order to elicit more information about the problem from the client. Also in 1978, Johnson proposed a sequential design process model. The model had 8 phases starting from problem recognition and ending with production and distribution, with four feedback points.

This decade saw the development of the "Architectural – generator-conjecture-analysis" and "Engineering – analysis – synthesis – evaluation" type of design process models. The architectural models depicted design as a spiral process with cycles of cognitive processes. Their models were mostly descriptive and stress the importance of use of existing knowledge believing that design is an "ill-defined problem". On the other hand the engineering schools depicted the design process as linear with sequence of stages. The models in this school were mostly prescriptive and believed that design is a "well-defined" problem. These two schools did not necessarily agree on a universal theory of design and the argument continued to the next decade.

1981-1990: Paul and Beitz (1994) were the early contributors in the design theory and methodology arena. A similar model was proposed by Hubka (1982). Other models introduced during this decade were Corss's (1989) "Process Model" and Pugh's (1988) "Total Activity Design Model". Cross's model comprised of seven stages positioned within the problem/solution model. The model integrated procedural aspects of design with its structural aspects. The procedural aspects were represented by the sequence of methods while the structural aspects are represented by the commutative relationship between problem and the solution. Finally, Pugh's total design activity model emphasized a broad design core, which is always enveloped by product design specifications. The model showed two different types of input to the design core: discipline/technology dependent and independent. Shinley (1989) also introduced his sequential design model in 1989. However there was still a great deal of discrepancy between the two schools of design, i.e., the engineering type school and the architectural type school by the end of this decade.

1991-2000: There was an emergence of a third phase in the design theory evolutionary process, with the introduction of the Hybrid models (Birmingham, et al., 1997). Design models developed and published during this decade include the Lawson's (1990), Dym's (1994) and Samuel & Wier's (1999). Lawson's was more of the engineering type model. This model comprised of three stages in a design process, viz., the analysis part, synthesis and the evaluation part. On the other hand Dym's model was the hybrid type with 14 phases that starts with task formulation, functional, form design, and result phases and ends with evaluation steps. Finally Samuel and Weir's model is of the sequential type with seven major phases and individual sub-tasks associated with each major phase. The five critical stages in this model emphasizes, need, goal, divergence, convergence, and solution

2001-2003: The last decade has been one of the most productive in the field of design theory and methodology. Several design process models have been proposed with increasing complexity. Some of the design models proposed in the past few years include Pahl & Beitz's model (2001), Saeed Moaveni's model (2002), Yousef Haik's model (2003) and Ullman's Model (2003).

The Paul and Beitz's model illustrates that the design process comprises of seven main phases that include clarification of task, conceptual design, embodiment design and detail design. At every step a decision must be made as to whether next step can be taken or whether previous steps need to be repeated. Next, Movani's model is of the hybrid type with eight main phases that start and end at recognizing the need to presenting a solution respectively. The phases map closely to definition of problem – generation of ideas – analysis – refinement. Another model presented by Movani in the same year presents the design process sequentially, which is similar to Drake or Lawson's models discussed previously. Haik's model is more of a product development model starting at needs identification and ending with product marketing. It must be emphasized here that the various design process models discussed in this chapter are not similar to each other because some are designed keeping the product development cycle in mind (i.e., the design-manufacturing/production – marketing aspect) while others are designed with just the design process in mind (i.e., problem –solution aspect). Finally Ullman's model is the most recent addition to the design theory models. Introduced in this year it is a sequential model that comprises of 5 main phases and 25 sub phases. The model starts at forming design teams and ends at product retirement and hence is broader that other models described previously. The major phases are separated by decisions to pass, reject, or return for refinement to a previous point. This is one of the most prescriptive and detailed models of engineering design.

Summary: From the above review it follows that the academic field of design has evolved rapidly over the past thirty years, and in the more recent generations of hybrid models continue to produce further insight. Table 1 summarizes the various models discussed so far.

There is a trend for increased complexity of products, technological improvements and more demanding requirements while, at the same time, product life-cycles are reducing and there is a need for faster responses (Blessing, 1994). With this it can be observed through the above discussion is that the general structure of the process models proposed through the decades seems to be increasing in the complexity from Drake's (1978) first generation model with just three main stages to Ullman's (2003) with 5 main stages and 25 sub stages.

Table 1: Design Process Characterizations

Author	Year	Order	Phases	Orientation	Start	End	Comments
Hall	1962	mixed	49	Time vs Logic			7 x 7 matirx with sequential activities versus logical operations
March	1976	flexible	9	Activity	Production	Induction	Production, induction, deduction
Darke	1978	sequential	3	Activity	Generator	Analysis	
Johnson	1978	sequential	8	Task	Problem Recognition	Production-distriution, etc	4 feedback points, 3 points to reject idea focuses on development of one idea
Pugh	1988	sequential	6	mixed	Market	Sell	Similar to Hall, maps activity type along the sequence of design mfg
Cross	1989	flexible	7	Scope vs Task	Overall Problem /Clarify Objectives	Overall Solution /Improving Details	Similar to Pugh, but emphasizing problem /subproblem evolution
Lawson	1990	sequential	3	Activity	Analysis	Evaluation	analyze, synthesize, evaluate resembles Darke closely
Dym	1994	mixed	14	Task	Task	Product	4 phases: task formulation, functional, form design, and result phases 2,3 end with evaluation steps
Samuel & Weir	1999	sequential	7 with subtasks	Task	Recognize prob	Implement	5 stages: need, goal, divergent, convergent, solution
Pahl & Beitz	2001	flexible	7	Task	Clarify Task	Documentation	Similar to Johnson, but more flexible, and includes dividing prob into modules
Saeed Moaveni	2002	flexible	8	Task	Recognize Need	Present Solution	"Steps not independent" identify best solution in step 6: evaluation maps closely to PD-IG-EA-DR sequence
	2002	sequential	6	Task	Initial Design	Final Design	Resembles Darke/Lawson
Yousef Haik	2003	flexible	10	Task	Need	Marketing	Steps are iterative, separated by decisions
Ullman	2003	sequential	5 with 25 subtasks	Task	Form Team	Retire Product	Major phases separated by decisions to pass, reject, or retrun for refinement to a previous point

The above suggests that researchers are focusing towards more detailed description of what lies in the design process and how one can achieve better designs following their models. However, it seems that these design models are developed based on the experiences of the authors, and not on actual observed activities of designers. Hence, these models in general seem to provide only an overall approach for the design process, but do not supply designers with strategies to design at a problem solving level. Finally it also seems that little research has gone into evaluating the validity of these models.

Still certain trends seem to emerge across the models discussed above. All models seem to agree on the fact that design is an iterative task which consists of certain basic steps like identifying the problem space, proposing solutions and evaluation them. Researchers then delve further into these steps and propose sub steps. However these sub steps tend to change considerably from model to model, an inconsistency that perhaps stems from the fact that these researchers come from diverse academic fields and experiences. Next, two distinct types of models can be observed. The first is the one that focusses only on the design process (ending at proposing a feasible and tested design), while the other type is expanded to encompass manufacturing marketing and even product retirement. Finally there seems to be a consensus after much debate that design is in face an ill-defined problem, across all fields of study.

As a summary, it follows here that although a universally accepted integrated model is some way off, people are offering proposals which represent attempts to move towards one. One criticism that has to be leveled at all design models is that there is no widespread acceptance in industry that might to give credence to the theoretical studies. This is in part due to the historical fact that many industry-based engineers received little, if any formal training in design studies. Indeed the formal university education of many engineers still lacks grounding in the fundamentals of design (Birmingham, et al., 1997). This is a situation that must be rectified if widespread acceptance is eventually to be achieved through a universal model, which is supported by academics and practicing industrialists alike.

Design Research Methods

The previous section summarized the literature on the current design process theories. This section focuses on design research methodologies. It must be noted that the techniques discussed in this review are not mutually exclusive nor collectively exhaustive. The various design research techniques discussed in this chapter are listed in Table 2. A brief discussion on each of these techniques is presented in the following section.

Table 2: Design Research Methods

1. Interviews / Surveys
2. Retrospective Method
3. Brain Scanning
4. Design Error Analysis
5. Signal Flow Graphs
6. Protocol Analysis (Verbal & Discussion Protocols)
7. Depositional Method
8. Process Observation
9. Design Structure Matrix (DSM)

Interviews / Surveys

There are two basic types of methods used to study design process: one in which the researcher is in control, the other in which the designer is in control (Waldron & Waldron, 1992). The first type includes methods based on interviews. Unlike process tracking methods that can actually provide accurate chronological information about how the design may have proceeded, this technique provides information about functional relationship, rules and the rationale behind different rules. Interviews are one of the oldest techniques used to characterize the design process.

A prior knowledge / expertise in design and design process literature is imperative to the success of this technique. The methodology basically comprises of a researcher implementing either a structured or non-structured questionnaire on the designer or the design team. The questions can be open, closed or probing and depending to which the responses could be either descriptive or quantitative. Finally these interviews themselves can be descriptive, problem-oriented, or directed.

Typically, questionnaires / surveys require designers to answer a set of questions about their design experience after the artifact is completed. The information can then analyzed to determine correlations between different aspects of the design process. Johnson and Brockman conducted experiments using student designers in which surveys were used to help determine why some designers produce better designs in less time (1996). In one experiment, ninety sophomore students were asked to design a computer program to perform a "Knight's Tour" of a chess board using three different heuristics. After the project was completed, the students were asked to complete a survey analyzing both their and another student's design. A statistical package was then used to tabulate their answers. The results showed that there were definite correlations between how the students went about creating their programs and the total time it took to create working designs. Furthermore, students that produced the best solutions in the least amount of time employed different methodologies than the general population. Successful methodologies included early analysis of the problem away from the computer and effective utilization of debugging tools.

While surveys give more flexibility to designers during process execution, it raises the issue of accuracy. Without realizing it, designers may rationalize specific design decisions that they made or the amount of time spent that was spent it each task prior to reporting results. This can cause inaccurate information about the design process to be collected. Without accurate data, any type of analysis and improvement would also be inaccurate. Another disadvantage to surveys is that in many cases the questions on the survey are not based on a process model and consequently do not fully characterize the process. Without using a process model to develop the survey, there is a high probability that the process data collected will be incomplete. Nevertheless, since more and more design activities are being accomplished with the use of a computer, it would seem logical that these issues could be resolved by collecting the process information automatically.

These techniques are generally more useful to study human behavior and develop case studies. However the data collected from using this technique are generally superficial, inaccurate and may omit detailed (and possibly more important) information like critical strategies for decision-making. Another disadvantage to surveys is that in many cases the questions on the survey are not based on a process model and consequently do not fully characterize the process.

Retrospective Method

This method also studies finished design processes. Waldron and Waldron (1992) proposed this method of studying design processes through recall and reference to written records as an improvement over the case studies method. Case studies analyzed design processes through reports/ documents of completed design. The case studies method however is limited because the generally sketchy process information is unavailable or lost. The researchers have to derive a process model using this limited information and hence the results obtained for the case studies are typically not very accurate.

The technique proposed by Waldron and Waldron (1992) overcomes the above limitation (at least to some extent) by making the technique interactive. Thus the designers use a written trace, suitably coded, showing the major events of the design, including the design decisions, and completion of sub phases that directly impact the design process. The researcher after reviewing the material then interacts with the designer to obtain the details of the process information.

This method differs from the interview technique in the degree of control exercised by the researcher over the designer. The advantage of this method over protocol analysis (discussed) is that larger design problems can be accommodated.

Finally the disadvantages of this method included and are not limited to the loss of memory (of the designer), incomplete written records, inability to estimate the errors, dead end paths and incomplete overall information.

<u>Brain Imaging</u>

Another approach to study and compare the design processes of different designers was used by Mehmet. H. Goker. The researcher used medical tools to study the brain activity of the designers. There are several techniques to image the human brain, and two of the primary constraints have been the degree of resolution (2D versus 3D) and the invasiveness of the technique. Goker, at Darmstadt University, for example, conducted an electroencephalography study to compare brain activity of novice and expert designers while they were solving simple design problems (1997).

The above technique uses FMRI (functional magnetic resonance imaging technique, which is non-invasive and has high 3D resolution) that is based on two key ideas: 1) during brain activation the oxygen content of venous blood increases in the region of activation; 2) when a human is placed within a magnetic resonance field, the increased blood flow causes an increase in magnetic resonance signal intensity.

The resulting techniques of brain imaging essentially allows the researcher to explore structure-function relationships in the brain, i.e., how activities in distinct neural processing come together to perform complex tasks such as reasoning, reading, remembering, and visualizing. In recent years, a number of physiological studies, which have shown strong implications for design performance, have been reported in the literature.

However, a major limitations of these studies is the fact that they require constant and rather unconventional intervention of the design process hence making the technique expensive almost impossible logistically for larger design projects.

Design Error Analysis

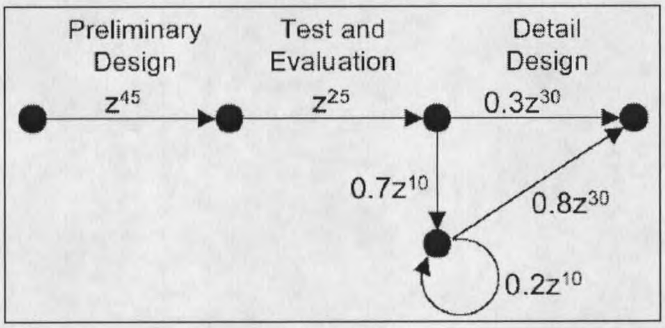
Another approach to studying design is to analyze the errors made while solving a design problem. Design experiments have been used to assess both the quality of the design process and the design artifact itself by helping to identify the location and cause of errors that occur during the process. For example, Aas, Steen, and Klingsheim (1994) performed an experiment to investigate the development of error rates for a group of designers. In their experiment, a group of student designers was asked to manually synthesize a programmable logic array design and then verify the design's functionality through simulation. Each designer tracked design errors, such as using the wrong gate type or incorrectly placing nets, and an average error rate for the entire design team was calculated. The authors then described how the error rate could be used to estimate the design quality of future projects using that same team of engineers. This technique can also be used to model the design process using error distribution (frequency or time).

A similar experiment involving the error analysis of an actual product was performed by Hobson (1995). The objective of this experiment was to analyze design errors with the hopes of improving the quality of future products. As errors were found in the design, the step in which the error occurred and the root cause of the error was recorded. The root cause of errors ranged from insufficient simulation to incorrect documentation. Using this error information, methodologies were put in place to eliminate the same errors in future processes. Although collecting data on design errors can be a difficult task this technique can be a good source of fault diagnosis.

Signal Flow Graphs

The signal flow graphs are well known as a method for circuit and systems analysis in electrical engineering and for modeling discrete-event systems. Eppinger, Nukala, and Whitney (1997) present SFG's as a powerful and flexible tool to model and analyze design processes. The signal flow graph itself is composed of a network of direct branches that are connected by nodes. The branches represent the design activities, and the nodes represent states of the process and may involve a probabilistic choice as to which subsequent branch to follow. A special type of branch is one, which goes back to a previous state of the process, i.e. design iteration. Figure 2 shows a signal flow graph model of a simple design process.

Figure 2: Over Simplified SFG



The model includes the lead times and success probabilities of the tasks. This technique has applicability in the evaluation of design process alternatives and alternative design strategies (Isaksson, Keski -Seppälä and Eppinger, 2000). It is also one of the few available quantitative design process modeling techniques available today.

However, there are many assumptions made when a SFG model is used. The first and major assumption is that the design process can be described as a number of design activities and design iterations. The second assumption is that it is possible to gather lead-time data for the design activities. How iterations affect the lead-time for the repeated activity is difficult to assess. Other limitations include the assumption that the path probabilities will always be available and reliable.

Protocol Analysis

Protocol analysis was developed to help understand how individuals use their cognitive abilities to solve problems in a design process. A frequently used analysis technique involves having the individuals "think aloud" while solving the problem so that their cognitive processes can be recorded. The recorded protocol is then analyzed to try and understand how the individual went about solving the problem. This technique was validated by Ericsson and Simon (1984) and is commonly known as verbal protocol analysis.

There are three general phases to verbal protocol analysis: data transcription, encoding, and data analysis. Data transcription involves either audio or video taping the individual as he or she works through the problem. The tape is then transcribed into a series of segments in which the irrelevant comments are edited out. A coding scheme is then used to encode the remaining protocol. An example of the coding scheme is illustrated in Table 3.

Table 3: Encoding Scheme for Protocol Information

(Adapted from Waldron & Waldron, 1992)

Classification R, H, W	**Focus** P, C, K, S, D, I, X	**Level** G, S	**Terminology** N, T	**Concept** 1
Requested Data Historical or assumes data Knowledge to manipulate data	Product Component PacKage ProcesS Distribution Environment Internal EXternal	General Specific	Non-Technical Technical	1 Concept Introduced

A common approach to reduce the biasing of information during encoding is to have more than one person encode each protocol. Once an encoded protocol is available, both quantitative and substantive analysis can then be performed. This analysis may involve studying the actual content of the protocol to identify trends that occur during the process or investigating the frequency in which specific codes exist.

Several experiments have been performed in which verbal protocol analysis was used to investigate engineering design. For example Atman, Bursic and Lozito (1996) at the University of Pittsburgh have used verbal protocol analysis to investigate how engineering students solved open-ended engineering design problems. In their experiment, a group of freshman and senior engineering students were asked to design a playground for a fictional neighborhood. The objective was to utilize verbal protocol analysis to compare student design practices as they enter and leave the university in an effort to help evaluate the how design is taught in the curriculum. The author's have developed a set of techniques to study an individual's progression through the design process and shown that verbal protocol analysis is a useful tool for documenting various approaches to solving open-ended design problems.

While verbal protocol analysis can provide valuable insight into the cognitive processes of designers, its applicability is limited because it is obtrusive. Many designers would feel threatened if they had to have their design practices recorded verbatim. Protocol analysis focuses primarily on the conceptual design and does not consider what occurs during the actual development of the artifact. Also, logistics in transcribing tapes indicates only problems with limited scope can be studied.

This is a significant omission for three main reasons. First, the main purpose of design is to create an actual product. Therefore the development of the artifact is as important as the conceptual design itself. Second, in many cases the conceptual design phase is linked with the development process. As the artifact is being developed, changes to the conceptual design might need to be made and vise-versa. Finally, unless the product is actually built, there is no way to validate the correctness of the design. Therefore, it is important not only to understand conceptual design but also analyze the actual development of the artifact.

The verbal or think aloud protocols are generally used to record individual design activities, on the other hand discussion protocols are specially suited in the analysis of group design activity. In this method two or more designers engage in a design through discussion. These discussions are recorded for use in analysis of a similar kind as described above.

These protocols provide researchers with two extra kinds of design process information, the decision-making alternatives and the strategies for resolution of conflict during design. Nevertheless, a major additional limitation of this method as opposed to a single person verbal / think aloud protocol is the fact that shared knowledge between teams may not be verbalized during the discussions. This will mean the loss of some very basic (and potentially vital) design information and hence the technique will not lead to a true representation of the design process under consideration.

Depositional Method

Another method to study proposed by Waldron and Waldron (1992), combines the interview and protocol analysis to produce a more effective technique to study the design process. Here, the designers basically have the control of the process, but must provide the researcher with a rationale for their action