# Describing Student Design Behavior*

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## Abstract

Open-ended design behavior can be characterized in part by the transitions a designer makes through steps in the design process. For example, a designer may define a problem, gather some information, develop several alternatives, then move back to reexamine the original problem definition before continuing with analysis. Each movement from step to step can be defined as a transition. Another way to describe design behavior is by the percentage of time spent in each of the design stages. These behaviors distinguish different types of processes that a designer might use. To study how engineering students approach and solve design problems, we collected data from seniors while they designed a playground for a fictional neighborhood. In this paper we will discuss the design behavior of these students by investigating the relationship between the percentage of time spent in various design stages, the number of transitions per unit time and how well the students were able to meet the constraints in the problem.

## Introduction

Design is a key element of any undergraduate engineering curriculum. Much has been written about the importance of teaching design effectively [1-5] and many authors have studied the design process [6-15]. Curriculum changes in engineering are being made across the U.S. and many schools now introduce design in the freshman year [16-21].

The overall goal of these changes must be to ensure that graduating seniors can effectively approach and solve "real-world" open-ended engineering design problems. But, what is design? What steps are necessary in the design process? Many authors disagree. Walton [22] defines design in terms of what the professional engineer actually does. Thus he defines it as "the art of applying scientific theory and principles to the efficient conversion of natural resources for the benefit of humans, to satisfy their perceived needs and desires" (p. 24). Ullman [23] defines the design *process* "as a map for how to get from the need for a specific object to the final product " (p. 3) and notes that "The designer's knowledge of the process and the problem's domain determine the path" (p. 4). All engineers design, whether it be a factory layout, a new computer system, a major construction project, an improved production process, an electronic subassembly or a new material. It is the core of the engineering profession. Wright [24] notes that "engineering design is as varied as the engineering profession, and it is as broad as the problems facing humankind. An engineer's designs may be as small and intricate as a microchip for a computer system or as large and complex as a space shuttle" (p. 95).

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Thus, to accomplish the goal of effectively teaching design, we must be able to understand and compare the engineering design processes that students use while they solve design problems. In this research we use verbal protocol analysis to document a group of senior engineering students' approaches to an open-ended engineering design problem. Using our analysis, we can demonstrate what it is that students do (and don't do) in the design process after four years of an undergraduate engineering education. In this paper, we compare the design processes students used to the effectiveness with which they met the constraints in the problem.

**Literature Review**

Other researchers have studied design behavior and drawn conclusions about successful designers' approaches to problems. Guindon [13] studied experienced software designers to determine whether top-down decomposition of a problem is effective in the early stages of design. The author analyzed the verbal protocols of three professional software designers (the designers were asked to "think aloud" as they solved a software design problem). He used problem behavior graphs to demonstrate how the designers moved through design activities and levels of abstraction and then drew conclusions about the effectiveness of these approaches. He found that opportunistic decomposition is better suited to handle the ill-structured nature of design problems. Opportunistic decomposition consists of 1) immediate handling of inferred or added requirements that change the design goals, 2) immediate development of partial solutions to the new requirements, 3) immediate recognition of partial solutions in various parts of the solution decomposition, 4) drifting, and 5) solution insights triggered by different scenarios in the problem domain. In other words, the successful designers iterated frequently through various design stages rather than using a linear design process. Using protocol analysis, Purcell, et al., [9] also found this type of behavior in experienced designers.

In a study of 50 designers of varying levels of expertise and experience, Fricke [7] set out to investigate the individual process of design. The subjects were asked to individually design a wall-mounting for a given motion rod of an optical instrument. By analyzing 13 of the designer's verbal protocols in detail he found many factors that influence the design process and some statistically significant correlation to the quality of the designer's solution. The significant factors included good spatial imagination, solid engineering knowledge, and high heuristic competence. Fricke went further in his analysis to determine specific strategies and tactics used by the successful designers. Overall, he found that a flexible methodical style of working (where prescribed guidelines are not strictly followed yet designers stay within the bounds of working steps) was successful.

Thus, these authors do not dispute any standard prescribed steps for the design process, however, they find that successful design behavior does not consist of following the steps in a strictly linear fashion. We also use verbal protocol analysis to describe the behaviors of our student designers and determine whether the more successful students (i.e. those that better meet the problem constraints) use a process that differs from less successful students.

Ullman, et al. [25], not only used verbal protocols of experienced designers to study the design process, but also to develop a model of the behavior of designers. The overall goal of the model was to explain why the design process succeeds in some cases and fails in others and to provide estimates of the resources needed to develop good designs. Five experienced mechanical designers solved two real industrial design problems while thinking aloud. The model that was developed from the protocols consisted of two fundamental components: the design state (including the level of abstraction, proposals, and constraints) and design operators (classified as generate, evaluate, decide). The authors found that, to be successful, designers must choose a good conceptual design during the early stages of the design process, must be able to generate and select good refinements throughout the design, and must be able to identify constraint violations. In addition to other observations, they also found that designers typically pursue only a single design proposal and there was no observable transition between layout and detail design.

Brockman [26] studied and evaluated student design processes used in a software design assignment. Using surveys and some automatic data collection techniques he analyzed how students spent their time during design projects and determined those factors that limit designer efficiency. The author studied four stages in the design process: conceptual design, coding, compilation, and testing, then modeled the transitions between these tasks. He found a correlation between the amount of time spent in conceptual design and the likelihood of iteration. He concluded that better conceptual design can lead to shorter design time. Note that as defined in his paper, iterations (or transitions between the four stages) are often needed for reasons such as correcting errors or adding new lines of code. Thus better conceptual design leads to less iteration between coding, compiling, and testing and contributes to the shorter design time.

Another stream of research focuses on studying the design process used in concurrent engineering, where various design and development steps are done in parallel instead of as a serial progression [27]. The goal of this research thrust is to develop design process models that reduce the product conception to market time. Our research interest lies more in the pattern of behaviors that individual designers use while designing rather than in the overall time to market.

**Method**

In this study, students were asked to give a verbal protocol (think aloud) as they solved a playground design problem. This problem is a revised version of a term-long design project used by the University of Maryland (part of the National Science Foundation's ECSEL coalition [21]). The text of the problem is presented in Figure 1. The experimental procedure consisted of several steps. First, subjects solved two practice problems out loud to familiarize themselves with the process of thinking aloud. They were then given the playground problem and asked to read it out loud. Subjects were given up to three hours to complete the problem and were encouraged to request information regarding the problem from the experiment administrator at any time during the three hours. (This information was prepared in advance and included information about the budget, neighborhood, material costs, safety, etc.) If the subject fell silent during the protocol, the experiment administrator prompted the individual to keep talking. Once a subject completed the playground problem, he or she read a one page description of the design process. Subjects were also asked to comment on their performance with respect to this description and provide demographic information about themselves. Both audio and video tapes were used to collect subject protocols. Transcription, segmenting, and coding of the text from the audio tapes allowed us to describe student design behavior. In addition, we were able to determine the amount of time that subjects spent in various steps of the design process from analysis of the video tapes.

The subjects in this study included 29 freshmen engineering students (3 of whom could not be completely analyzed due to poor tape quality) and 24 senior engineering students at the University of Pittsburgh. The freshmen students participated in the study just prior to the start of their first semester or a few weeks into the semester, before any design concepts were covered in the freshmen Engineering Analysis course. Seniors participated during their last semester of school. Subjects were paid thirty dollars each for their participation. In this paper, we limit our analysis to the 24 senior engineering students and the patterns of behaviors they used while developing their playground designs.

**Designing A Playground**

You live in a mid-size city. A local resident has recently donated a corner lot for a playground. Since you are an engineer who lives in the neighborhood, you have been asked by the city to design a playground.

You estimate that most of the children who will use the playground will range from 1 to 10 years of age. Twelve children should be kept busy at any one time. There should be at least three different types of activities for the children. Any equipment you design must:

- be safe for the children
- remain outside all year long
- not cost too much
- comply with the Americans with Disabilities Act.

The neighborhood does not have the time or money to buy ready made pieces of equipment. Your design should use materials that are available at any hardware or lumber store. The playground must be ready for use in 2 months.

Please explain your solution as clearly and completely as possible. Someone should be able to build the playground from your solution without any questions. The administrator has a lot more information to help you address this problem if you need it. Be as specific as possible in your requests.

For example, if you would like a diagram of the corner lot, some information about the lot appearance, etc., you may ask for it now. If you think of any more information you need as you solve the problem, please ask for it.

Remember, you have approximately 3 hours to develop a complete solution. The administrator will tell you how much time is left while you work.

Figure 1: Student Instructions for the Playground Design Problem

The analysis in this paper will focus on what we termed the "design step" variable. Once each verbal protocol was transcribed and segmented into codable units of text, the coding scheme shown in Table 1 was applied to each segment of text. Segmenting and coding were both done by two analysts, checked for reliability, and argued to consensus. The ten coded design steps are based on a content analysis of seven introductory engineering design texts [28]. To simplify the analysis of transitions (defined as moving from one design step to another), we grouped the ten originally coded steps into three stages as follows: 1.) *Problem Scoping* which consists of need, problem definition, and gathering information. (Due to the nature of the experimental situation, the code "need" was never assigned since the need is clearly defined for the students.) 2.) *Developing Alternative Solutions* which consists of generating ideas, modeling, feasibility analysis, and evaluation. Finally, 3.) *Project Realization* which consists of decision, communication, and implementation. (Again, due to the nature of the experimental situation, the implementation code was never assigned.) These will represent the 3 major stages of the design process in our data analysis.

| Design Step | Design Stage |
|---|---|
| **Need**: Identify basic needs (purpose, reason for design)<br>**Problem Definition**: Define what the problem really is, identify constraints, identify criteria, reread problem statement or information sheets, question the problem statement<br>**Gathering Information**: Searching for and collecting needed information | **Problem Scoping** |
| **Generating Ideas**: Develop possible ideas for a solution, brainstorm, list different alternatives<br>**Modeling**: Describe how to build an idea, how to make it, measurements, dimensions, calculations<br>**Feasibility Analysis**: Determining workability, verification of workability, does it meet constraints, criteria<br>**Evaluation**: Comparing alternatives, judgment about various options, is one better, cheaper, more accurate | **Developing Alternative Solutions** |
| **Decision**: Select one idea or solution among alternatives<br>**Communication**: Define the design to others, write down a solution or instructions<br>**Implementation**: Produce or construct a physical device, product, or system | **Project Realization** |

Table 1: Design Step Codes and Design Stages

To assess the quality of the design, we scored each subject's solution based on whether a subject satisfied each of the seven specific constraints outlined in the problem statement and shown in Table 2. The decision of whether a constraint was met is based on a review of the transcript, assigned codes, and any drawings or other output given by the subject. A subject is given one point for each constraint met, thus, the quality score can range from zero to seven. Note that this quality score is a measure of the product produced and not the processed used to produce it. Scores were generated separately by two individual analysts, checked for reliability, and any disagreements were resolved.

1. This design allows at least twelve children to be kept busy.
2. There are at least three activities provided.
3. Equipment can be used outdoor all year.
4. Materials are available at any hardware or lumber store.
5. Playground can be completed in two months time.
6. The cost of the playground does NOT exceed $3800.
7. An effort has been made to allow handicapped children to be able to use the playground.

Table 2: Quality Scoring Constraints

In this paper, we are interested in studying the design behaviors of the student subjects. Specifically, we are interested in the amount of time spent in each of the three design stages. A content analysis of seven introductory engineering design texts demonstrates that many texts emphasize the Developing Alternative Solutions stage of the design process [28]. Our hypothesis regards the need for designers to spend adequate time in each design stage in order to develop high quality solutions (consistent with references 25 and 26). Thus we hypothesize that subjects who spend a greater proportion of their time in Problem Scoping and Project Realization (relative to the amount of time spent in Developing Alternative Solutions) will meet more of the quality constraints. Using the timestamped verbal protocols, we calculated the proportion of time each subject spent in the three design stages. In this analysis, we compare the time that a subject devoted to Problem Scoping to the time spent in Developing Alternative Solutions (which we term the "problem scoping ratio"). We also compare the time devoted to Project Realization to the time spent in Developing Alternative Solutions (which we term the "project realization ratio").

Another way to describe design behavior is by the pattern of transitions a designer makes while solving a design problem. Because of the varying length of each subject's verbal protocol, we analyzed the average number of transitions per minute while the subject completed the playground design. This is calculated from the time when the subject first reads the problem statement to the time the subject notes that he or she is finished. Our interest in the number of transitions per minute is based on the hypothesis that design processes having higher rates of transition will produce higher quality designs than those having lower rates of transition (consistent with references 7, 9 and 13). In other words, subjects who made more transitions per minute among the three design stages will meet more of the quality constraints than subjects who performed fewer transitions per minute among design stages.

**Results**

No relationship was found between the project realization ratios and the quality scores. We calculated correlation coefficients between each of the variables: problem scoping ratio, transitions per minute, and quality score. We used the Spearman Rank correlation since the data violated the normality assumption needed for the Pearson correlation. These results are shown in Table 3. Both the problem scoping ratio and the transitions per minute show a moderate positive correlation with the quality score as well as with each other. This suggests that in addition to contributing to the quality score, the two process measures are not independent. Further evidence for this is provided by an attempt to model the relationship between these variables (quality score as the dependent variable and problem scoping ratio and transitions per minute as the independent variables) in a stepwise multiple regression. Either one of the two independent variables is significant alone but using the second variable does not increase the significance of the model. Model results will be presented in a future paper once additional independent variables in the data set have been calculated and added to the model.

| | Transitions per Minute | Quality Score |
|---|---|---|
| Problem Scoping Ratio | .63 | .64 |
| Transitions per Minute | | .47 |

Table 3: Spearman Rank Correlation Coefficients

Figure 2 depicts the relationship between the problem scoping ratios and the quality scores. Figure 3 depicts the relationship between transitions per minute and quality scores. Note that we have highlighted four subjects that are outliers on either the problem scoping ratio, the transitions per minute or both. The data for these four outliers are shown in Table 4. Outlier number one did very well on the quality of his playground design (the product) but had a low to moderate score on both process variables. This type of student could be called a "natural designer", one who might produce a good product regardless of the process used. Outlier number two, on the other hand, measured high on the quality score and both process variables suggesting that the process variables may have contributed to his high quality score. He may have learned to spend time in problem scoping and to iterate through the steps in the design process as an engineering student, providing some evidence for the importance of teaching the design process.

Although Outlier number three scored very high in terms of transitions per minute, he did not spend a significant portion of time on problem scoping. This could explain the quality score of 5 out of 7 and provides some support for suggesting that both of these process variables are necessary for good designs. Outlier number four measured very high on the problem scoping ratio and in the middle range in terms of transitions per minute, also suggesting a focus on the process, yet scored only 5 on the quality score. Although this subject spent the largest amount of time in problem scoping (nearly twice as much as the next highest subject), he did not ensure that the final product met problem constraints, again suggesting that both process variables are important. In general, we see wide variation in the approaches that students take. Engineering educators recognize that variations in student approaches will also be seen in the engineering classroom. It is therefore important that we learn to recognize and respond to these variations.

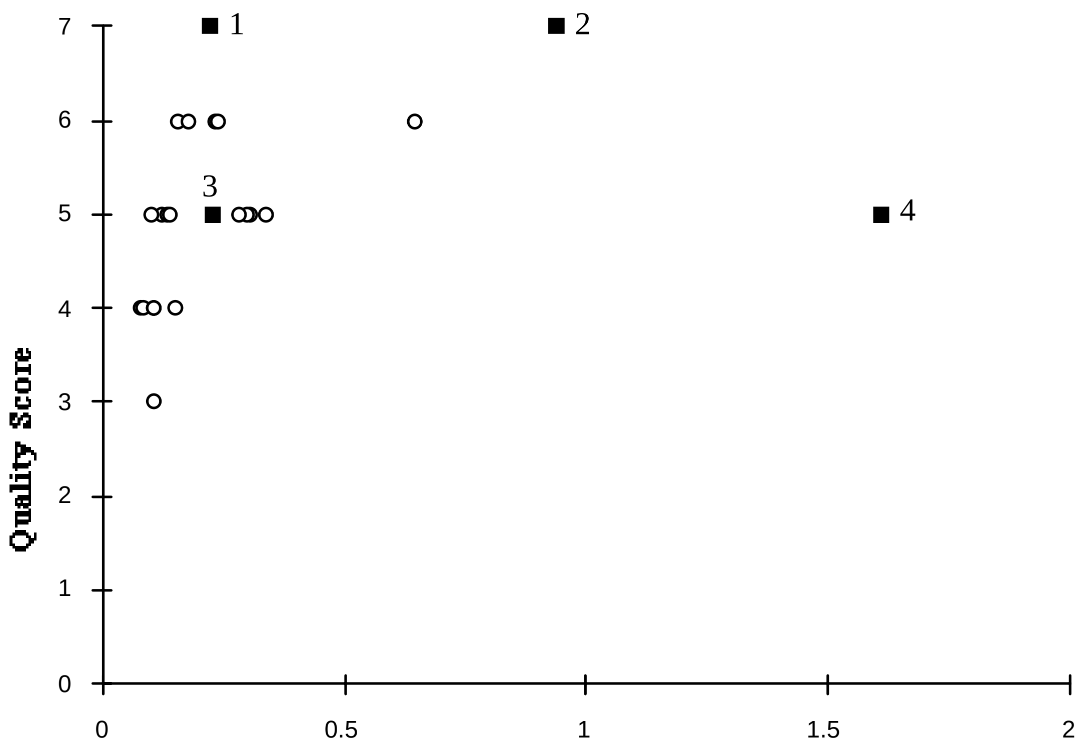


Figure 2: Relationship between Problem Scoping Ratio and Quality Score

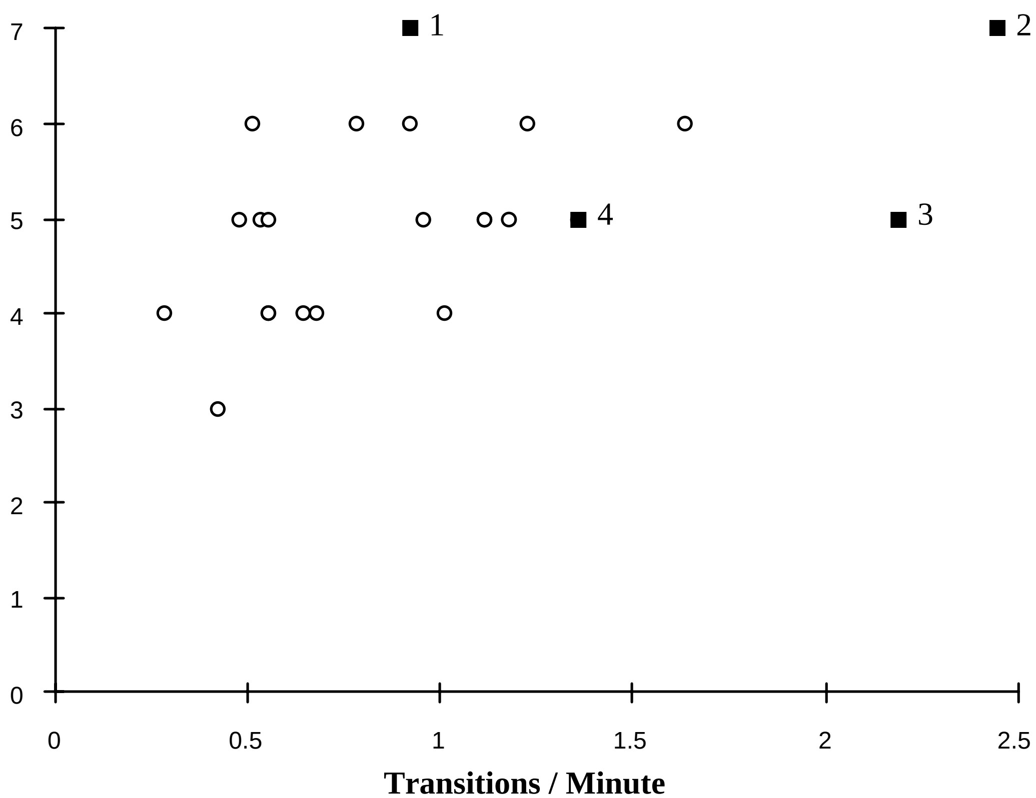


Figure 3: Relationship between Transitions per Minute and Quality Score

| Subject | Quality Score | Problem Scoping Ratio | Transitions per Minute |
|---|---|---|---|
| Outlier One | 7 | 0.22 | 0.92 |
| Outlier Two | 7 | 0.94 | 2.45 |
| Outlier Three | 5 | 0.23 | 2.19 |
| Outlier Four | 5 | 1.61 | 1.36 |

Table 4: Data for Outliers

These results suggest that process measures could be contributing to the quality of the playground designs. In other words, subjects that spent more time problem scoping (defining the problem and gathering information) and/or moved more frequently among the three design stages tended to score higher on the quality of their playground design.

## Conclusions

Few studies have examined the relationship between the design process and final product quality [14]. In this study we are seeking to identify process variables that can predict product quality so that we can identify important attributes of the process to teach to engineering students. We are identifying multiple process variables in the rich data set described in this paper. Two variables that were expected to show positive relationships to product quality showed moderate positive correlation with product quality and with each other. These variables are the ratio of time spent in problem scoping to that spent in developing alternative solutions and the number of transitions per minute among design steps. Initial analysis shows that for this design problem there is a relationship between process measures and final product quality.

Our preliminary results support Guindon's [13] and Fricke's [7] findings that opportunistic decomposition (with iteration and drifting) or a flexible methodical style is more effective than top-down decomposition for design problems. Our data also suggest that more adequate time spent in the Problem Scoping stage of design will lead to stronger solutions. This is consistent with Brockman's [26] finding that more successful programmers (those needing less debugging) produced stronger conceptual designs for their programs before coding, compiling, and testing.

We will run full multiple regression models once additional process variables have been fully analyzed to determine what process variables most adequately predict product quality. This data set is very rich, enabling an unusually detailed look at engineering student design processes. One obvious observation is the variation with which students approached the process. Three categories of student processes are described as the “natural designer”, “the case for teaching engineering design”, and the student who is “focused on the process.” As we analyze the rest of the data we will attempt to identify student variables (e.g., major, GPA, courses taken, etc.) that may enable us to recognize students that may fall into each of these categories.

How can the information discussed in this paper be useful to the classroom instructor? Most problems given to students are well-defined and require little information gathering. In contrast, the open-ended design problems they face upon graduation are ill-structured, require constant redefinition and require the designer to gather pertinent information. The results from this study will hopefully encourage instructors to teach students to iterate among design stages and to spend time in problem scoping before proceeding to develop alternative solutions. As a community, we need to evaluate the way design is taught in the classroom and test various methods such as guided design for their effectiveness in teaching the design process.

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