Verbal Protocol Analysis as a Method to Document Engineering Student Design Processes

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ABSTRACT

Undergraduate engineering programs have faced numerous challenges in recent years. One of these challenges is to improve the way open-ended design is taught. Although changes are underway in schools throughout the United States, not enough evaluation has been done to determine the impact of these changes. In this paper we describe a research tool that can also be used to assess student learning: verbal protocol analysis. In particular, this tool can be used to document the processes that engineering students use to solve open-ended engineering design problems. The objective of this paper is to demonstrate the use of verbal protocol analysis as a method to assess student design processes. We also discuss the research questions that can be addressed by verbal protocol analysis and the opportunity to include this type of study as part of an engineering program evaluation.

I. INTRODUCTION

Design is a fundamental aspect of any engineering curriculum.[1] In a recent report, the National Research Council's Board on Engineering Education recommended a number of actions that are needed to improve the engineering education system. One action is to "pursue undergraduate curricular reform, including early exposure to 'real' engineering and more extensive exposure to interdisciplinary, hands-on, industrial practice aspects, team work, systems thinking, and creative design."[2] Similar recommendations have been made by other panels and individuals that have studied the engineering education system.[3-5]

Many curriculum changes are already being implemented in engineering programs across the nation, due partly to the National Science Foundation's undergraduate engineering education coalitions whose purpose was to create "revolutionary" changes (see references 6-14, for example.) These changes include guided design, active learning in the classroom, project and team-based courses (as early as the freshmen year), integrated curricula, cooperative learning, and the use of multimedia software and the worldwide web. A goal of many of these innovations is to teach students how to solve engineering design problems. In order to determine the effectiveness of these curriculum changes on student design learning we must have adequate measurement techniques. In brief, we need to understand how students approach and solve design problems.

Although concerns about the need to assess design problem solving skills date back at least 20 years[15], the need for assessment methodologies has become more pressing in recent years. The new criteria for accrediting programs in Engineering in the United States issued by the Accreditation Board for Engineering and Technology (ABET) make it clear that schools must address these issues. Specifically, ABET expects engineering graduates to possess "an ability to design a system, component, or process to meet desired needs".[16] In order to assess this ability in students, educators must be able to understand and document student design processes.

One tool that can be used to document student design processes is verbal protocol analysis. This is a research method in which subjects think aloud as they solve problems or perform a task. The subjects' thought processes are captured on audio and/or videotape. The transcribed text from those tapes then forms the data for analysis. This method allows us to study the content of what a subject says, organize that content, and analyze it.[17] Analysis of these data can be used to gain an in-depth understanding of the processes students use to solve engineering design problems. Comparison of verbal protocol data can be used to evaluate differences between groups of subjects. For example, approaches by one group of students can be compared to other student groups, to "expert" designers, or to prescriptive models of the design process. For the purposes of program evaluation, groups of students can be tested and compared to a control group in order to determine if specific classroom experiences affect student design processes.

The objective of this paper, then, is to demonstrate the application of verbal protocol analysis as a tool to document the processes engineering students use to approach design problems. We first define verbal protocol analysis and describe some previous studies that have applied this method. We then present a detailed application of verbal protocol analysis to an engineering design problem. An in-depth examination of two sample subjects from this study demonstrates the type of analyses that are possible and the kinds of questions that can be addressed by verbal protocol analysis. The purpose of this paper is to provide an example of a verbal protocol study, and we do not attempt to draw specific conclusions about student design processes. We also discuss the value of using this tool as one of the many assessment tools that can be used to evaluate an engineering program.

Although verbal protocol analysis is too time consuming to use as a method for routine student assessment, the insight it provides into student processes can be very useful to classroom teachers. Therefore we conclude the paper with a brief description of other methods that can be used to provide insight into student processes.

II. Verbal Protocol Analysis

Verbal protocol analysis requires subjects to give a verbal protocol (or "think" aloud) while solving problems or performing a task. Once the verbal protocols are collected on audio and/or videotape, they must be:

- transcribed;
- segmented into codable units of subject statements;
- coded according to a coding scheme; and
- analyzed to answer specific research questions.

We can then use this analysis to describe the process subjects use to solve problems.

Ericsson and Simon[18] have demonstrated the validity of verbal protocol analysis and argue that concurrent reports are a valid method to collect data about thinking processes. They also argue that think-aloud procedures do not influence the sequence of subjects' thoughts and that the resulting data can be treated as objectively as any other data. Information is collected from short-term memory while subjects are prompted to "keep talking" with minimal interference from the experimenter. To maintain the reliability of the data we have used a pre-defined coding scheme that requires minimal coder interpretation and inference.

III. Verbal Protocol Analysis Applied

Several studies of the design process have been conducted using verbal protocol analysis. These include Christiaans and Dorst[19], Ennis and Gyeszly[20], Guindon[21], James et al.[22], Rowland[23], and Sutcliffe and Maiden.[24] These studies have primarily focused on documenting the process designers use. Among other findings, these researchers found that:

- information acquisition is important in design;[20]
- novice designers tend to seek less information than experts[19,23] and tend to decompose the problem more than experts;[19]
- poor problem scoping and lack of hypothesis testing contribute to poor performance;[24] and
- opportunistic decomposition is better suited for design than top-down decomposition.[21,24]

These results were reported for a variety of designers including industrial design engineering students and students of systems analysis, experienced packaging systems designers, experienced software designers, and students and experts in digital design and instructional design.

We have used verbal protocol analysis to document the process engineering students use when they solve short open-ended design problems. We found that student design processes improved after just one semester in engineering.[25] Specifically, in comparison to incoming freshmen, students that had completed their first semester of engineering spent significantly more time solving the problems, had significantly more transitions among steps in the design process, and considered more criteria in their design process. What experiences in the first semester led to this improvement? These students took calculus, physics, chemistry, a humanities course, and a freshman engineering course that introduced the design process. Many elements of this curriculum or the university experience could have contributed to this change, although one would hypothesize that the freshmen engineering course was an important component.

In a second study, we have begun to learn what could have caused the significant results in the semester-long study.[26] We found that reading a design text improved student performance in solving open-ended engineering design problems. In this study, we asked half of ten subjects (students in an introduction to engineering course) to read aloud from a chapter about design in a freshman engineering text.[27] They then solved three short open-ended design problems while talking aloud. The other half of the subjects solved the same problems without reading the text. The results of this study showed that the subjects that read the design text before solving the problems demonstrated more sophistication in their problem solving approach. That is, the subjects that read the design text before solving the problems had significantly more transitions between design steps, spent significantly more time solving the problems, generated more alternative solutions, and considered significantly more design criteria as they developed their solutions than did the group that did not read the design text. These two studies demonstrate that verbal protocol analysis can be used to measure design processes and can show differences between subject groups.

Verbal protocol analysis has also been used to assess the effects of new curricula and courses on student learning. Some researchers have done experiments that use verbal protocols to compare students that complete traditional courses with those that have taken new courses. Rogers and Sando[28] video-taped groups of students solving a design problem. The groups either consisted of students that had been through a new curriculum or of students that had not been through a new curriculum and were matched on characteristics such as grade point average. Preliminary results showed little differences between the groups.

Thus, verbal protocol analysis has been used in a variety of studies focused on design. We now illustrate the verbal protocol method of analysis through a detailed example.

IV. An Application Example

A. The Experiment

To demonstrate the use of verbal protocol analysis in detail, we consider two student protocols from what we term the "playground study." In this study, students gave a verbal protocol as they approached 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).[7] The text of the problem is given in Figure 1.

The experiment consisted of several steps. First, subjects solved two practice problems to familiarize themselves with the process of thinking aloud. They were then given the playground problem and asked to read it aloud. Subjects were given up to three hours to complete the problem and were encouraged to request additional information as desired from the experiment administrator at any time during the three hours. Each subject gave a verbal protocol while he/she solved the problem. If the student fell silent during the protocol, the experiment administrator prompted the individual to keep talking. Once a subject completed the playground problem, he/she read a one page description of the design process. Subjects were then asked to comment on their performance with respect to this description and provide some demographic information about themselves. Both audio and video tapes were used to collect subject protocols.[29]

This study included results for 29 freshmen engineering students (3 of which cannot be completely analyzed due to poor tape quality) and 24 senior engineering students at the University of Pittsburgh. The freshmen participated 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 course. Seniors participated during their last semester of school. Subjects received thirty dollars each for their time.

A detailed description of the application of the verbal protocol method to this problem is provided elsewhere.[29] Here we briefly describe the steps involved and then present an in-depth description of two subjects' design processes. The method involved:

B. Transcription

Each subject's verbal protocol was transcribed from the audio tape. The video tape is used to "timestamp" the protocol once it has been imported into the software described below. The video tape is also used as a back up for any inaudible portions of the audio tape.

C. Segmenting

The purpose of segmenting is to break the verbal text into units (or segments) that can be coded with a pre-defined coding scheme. For this study, a sentence formed the basic unit to be segmented. If a sentence contained more than one idea, it was segmented into two or more parts. Segmenting is done separately by two analysts, parts are checked for reliability, and any differences are resolved. Once the segmenting was complete, the transcript was imported into MacSHAPA,[30] a software tool that assists with analysis of verbal data. MacSHAPA creates a database that includes the segmented verbal text as the first variable (or column). Each segment is represented as a cell (or row) in the database.

D. Coding

Four variables were chosen to describe each student's problem solving process. The resulting coding scheme is presented in Table 1. The first variable, called "design step," identifies the step in the design process in which the subject is working. The design process steps that were used as codes in this study are based on a content analysis of seven freshmen engineering design texts.[31] The second variable, "information processed," identifies what information the subject is addressing in the segment. Examples include budget, material costs, safety and so forth. The third variable, called "activity," is used to identify what the subject is doing during the segment such as reading or calculating. Finally, "object " identifies what equipment the subject is working on, for example, the subject may be designing a swing or working on the landscape. Coding is done separately by two analysts, checked for reliability and any coding differences are resolved.

E. Description of Sample Subjects

Two subjects are used to illustrate how the verbal protocol method enables us to document the student problem solving processes. The subjects are not meant to be representative of any particular subject group. The intention is to demonstrate that verbal

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.

protocol analysis can effectively capture differences in student approaches to design problems. Both subjects selected were freshmen. Subject One worked through the problem for about 30 minutes, then read the one page description of design once, did some minor additional work on the problem, then read the text again. Subject Two solved the problem, read the one page description of the design process, and then commented on his performance. Subject Two spent two and one half hours working on the problem. We will only consider each subject's problem solving before he or she read the design text.

In the following sections, we provide a general description of each subject's design process, present timelines of the design step variable for each subject, consider what each subject does during each of the steps in the design process, and compare the two subjects.

F. Profile of Subject One

Subject One, a female freshman, spent a considerable amount of time identifying the constraints in the problem and attempting to design a playground that met those constraints. For example, in the early stages of her design process she stated: "Okay, the restrictions. Twelve children have to be kept busy at a time, so we need enough rides to keep at least twelve children busy. They're from one to ten years of age..." Here she was identifying the constraints to provide a clear definition of the problem. About five minutes later, she made

Variable Name	Codes
Design Step	**Need**: Identify basic needs (purpose, reason for design) **Problem Definition**: Define what the problem really is, identify constraints, identify criteria, reread problem statement or information sheets, question the problem statement **Gather Information**: Searching for and collecting needed information **Generate Ideas**: Develop possible ideas for a solution, brainstorm, list different alternatives **Modeling**: Modeling, describe how to build an idea, how to make it, measurements, dimensions, calculations **Feasibility Analysis**: Determining workability, verification of workability, does it meet constraints, criteria, etc. **Evaluation**: Comparing alternatives, judgment about various options, is one better, cheaper, more accurate **Decision**: Select one idea or solution among alternatives **Communication**: Define the design to others, write down a solution or instructions **Implementation**: Produce or construct a physical device, product, or system
Information Processed	**AGE**: References to **age** of children, occupancy of equipment, or number of activities **NGH**: References to **neighborhood** conditions and area, facilities such as bathrooms, or utilities **DEM**: References to **demographics**, opinions, or supervision **HA**: References to **handicapped accessibility** **SAF**: References to **safety guidelines** **LEG**: References to **legal** liabilities **MNT**: References to equipment **maintenance** **LAB**: References to the costs and availability of **labor** or the amount of time needed to build the playground **OCON**: References to **other constraints** on supplies from hardware stores, ready made equipment, outdoor equipment, and explaining the solution clearly **PA**: References to the layout of the **park area** **MAT**: References to the type or kind of **materials** needed, material specifications, technical references, material availability, or body dimensions **DIM**: References to **dimension** for any piece of equipment or part of the layout **MC**: References to **material costs** **BUD**: References to the **budget**
Activity	**Read** **Assumption** (Explicit or Implicit) **Constraints** (Meeting, Identifying, or Dealing with) **Calculate** **Other** (includes flags for self-assessment, requesting information that is not available, and other unique aspects in the transcript)
Object	**Layout** **Sandbox** **Equipment** **Bench** **Swings** **Landscaping** **See-Saw** **Bathrooms** **Monkey Bars** etc. **Slide** (Unlimited Choices)

Table 1. Codes for playground experiment.

decisions about what equipment and activities could be put in the playground, for example "no baseball, no too young." This subject did not do any detailed technical analysis but primarily worked on the overall layout of the playground. For example:

"The slide, we don't want the slide facing the street. Hmm, does it matter to make it look closed in the way I have it facing, facing the checker board tables; slide, the swing set, the sand box in the middle. The younger children will be, the jungle gym, facing the grocery store parking lot."

The only information Subject One asked for was the general layout of the park.

G. Profile of Subject Two

Unlike Subject One, Subject Two, a male freshman, spent most of his time performing actual calculations and designing specific pieces of equipment in his playground. The calculations primarily consisted of determining the amount of material needed and the cost of the materials (rather than more technical calculations such as force or stress calculations.) Early in his design process, Subject Two began to gather information to get a better definition of the problem. For example, he asked:

"Do you have like any information like about the population of the town?..OK the population is...150,000 people. OK 150,000 people...hmm... ages are going to range from one to ten years of age..."

He also asked about more general background information, "Do you have information about where this town is located...like the location... as far as like the weather, the climate?" About 20 minutes into his design process, he began to focus almost exclusively on analysis and calculations. For example, as the subject designed a set of swings, he stated "...we have 4 swings here and we're going to need at least... 6 times 4... 24 for the rope..." He spent a great deal of time designing what he termed a "tire wall" for the children to play on. Toward the end of his design process he began adding trees, trash cans, and signs: "...trash cans...here they will put pitch inside...on the fence... pitch inside on the fence...now we are going to need signs which are inside here..." As he proceeded with his design, this subject asked for much more information than did Subject One.

H. Description of the Protocol Data

Figure 2 presents the timelines for both subjects' behavior with respect to the design step variable. Time proceeds from left to right in the figure. Each block in the timeline represents a coded segment from the subject's transcript and is proportional in size to the amount of time spent in the particular design step. All subjects start out reading the problem, which is coded as problem definition, then proceed to various steps in the process. As a subject progresses to other steps in the design process, a block is added in the diagram and labeled accordingly. This process is repeated to construct a diagram that represents all the steps in the design process the subject included as well as the order in which he/she visited each step. Note that the percentages given in the figure indicate the proportion of time each subject spent in the particular design step.[32] The percentages do not sum to 100 since some portions of time (some segments in the transcript) are not coded as a step in the design process and are left blank. From Subject One's timeline, we can see that she spent a significant amount of time in a variety of the steps in the design process, including problem definition (11.0% of her time), generate ideas (10.2%), modeling (23.6%), and feasibility analysis (17.1%). We can also see that Subject One iterated through the steps and frequently referred back to problem definition.

The timeline for Subject Two clearly shows a significant amount of time spent in modeling; in fact 58.2% of his time was spent here. No more than 8% of his time was spent in any of the other specific design steps. This indicates that Subject Two spent the majority of his time developing ideas about various pieces of equipment, selecting materials, determining dimensions, and calculating costs. Note

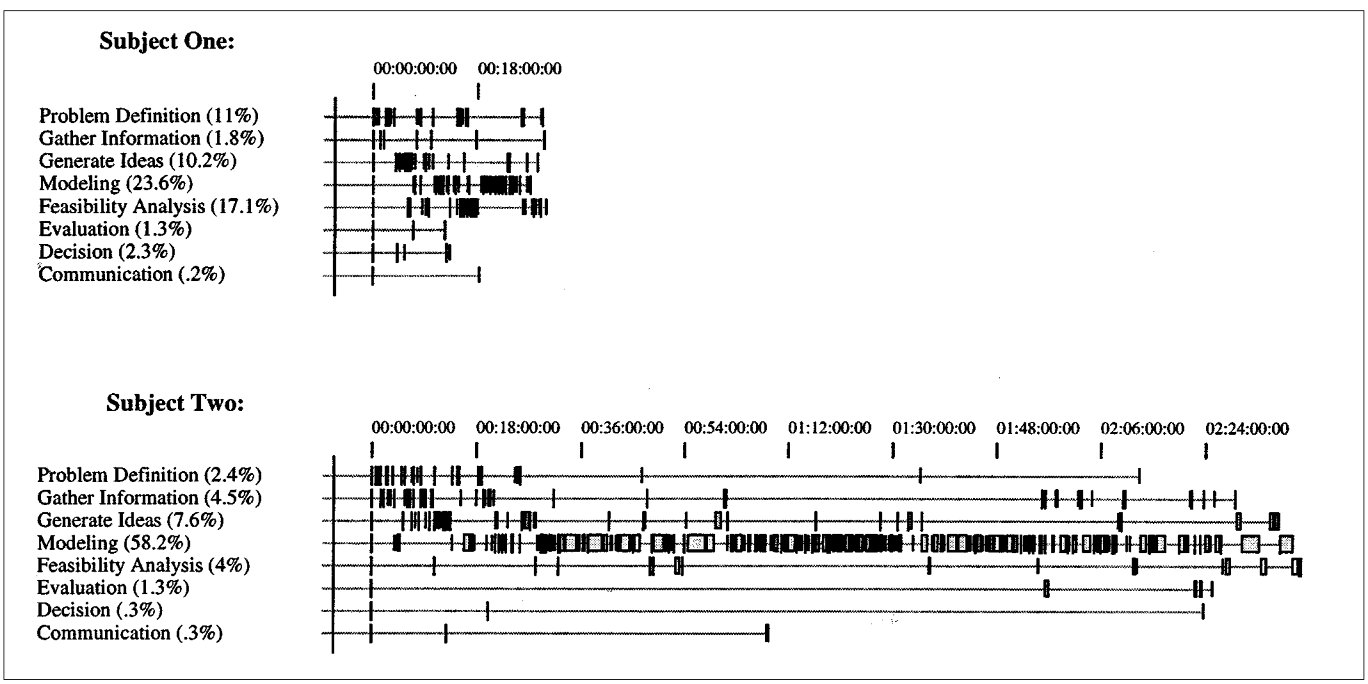

Figure 2. Timelines of design step variables.

that, although he spent much more time working on the problem, Subject Two did not iterate as frequently as Subject One through the steps in the design process and only briefly returned to problem definition at a few points in his design process.

In addition to reviewing timelines for the variables, we can also develop a content report that shows the percent of time that the subjects spent in each of the codes of the variables. Table 2 provides this information for the information processed, activity, and object variables for both subjects. The table shows that the information processed by Subject One was from a variety of sources with the highest concentration being the park area (21.5%) which consists of references to the overall layout of the park. The primary types of information processed by Subject Two were dimensions (30.6%), materials (22.1%), and material costs (7.9%). Neither subject addressed legal, maintenance, or labor issues to any meaningful extent. In terms of activity, Table 2 shows that Subject One spent a large amount of time addressing constraints (26.7%) as opposed to doing calculations (less than 2%) while Subject Two focused his activity on calculations (33.3%). For the object code, we also see that Subject One spent most of her time on general issues such as layout (19.8%) and equipment (16%) while Subject Two spent more time on specific pieces of equipment such as swings (19.7%) and a tire wall (19.3%).

Another way to look at this data is to compare the information that is addressed during each of the design process steps. This is shown in Figure 3 for Subject One and Figure 4 for Subject Two. The percentages represented in these figures indicate the proportion of the total number of segments in the transcript that are coded with both the corresponding design step and information processed codes. For example, Figure 3 indicates that 16% of Subject One's segments were coded modeling and park area. Note that Subject One processed information on items such as the park area, handicapped accessibility, safety, and age throughout each of the design steps. In contrast, most of Subject Two's effort was focused on materials and dimensions in the modeling phase.

Finally, we can compare the activity that is performed during each of the design process steps. This is shown in Figure 5 for Subject One and Figure 6 for Subject Two. The percentages represented in these figures indicate the proportion of the total number of segments in the transcript that are coded with the corresponding design step and activity codes. Subject One only read at the beginning of her design process while Subject Two read information requested from the experimenter throughout the process. Subject One made assumptions when gathering information, generating ideas, and modeling while Subject Two only made assumptions when gathering information. Subject Two typically asked for information, then made assumptions only if the information was not available. Subject One asked for little information and instead made several assumptions. Both subjects dealt with constraints throughout their design process, although Subject One spent more time addressing them. And, clearly, Subject Two did more calculating, although this was primarily in the modeling stage.

In addition to comparing the two subjects on process measures, we can also consider the quality of each subject's final design. We developed a scoring measure for the quality of the playground designs. The final score is based on three parts. As previously described,[32] the first part of the score is based on forty criteria that all playground designs are expected to meet. Seven of these criteria are based on those given in the problem statement such as "this design allows at least twelve children to be kept busy" and "the cost of the

INFORMATION PROCESSED	Subject One	Subject Two
Age of Children	5.2	2.9
Neighborhood Conditions	1.1	1.2
Demographics	1.8	2.0
Handicapped Accessibility	11.5	3.2
Safety Guidelines	5.0	0.2
Legal Liabilities	0.1	0.0
Maintenance	0.1	0.0
Availability of Labor	0.3	0.2
Other Constraints	3.9	0.8
Park Area	21.5	2.9
Materials	1.7	22.1
Dimensions	0.2	30.6
Material Costs	0.1	7.9
Budget	3.3	2.4
Other	0.1	0.0
Total Percent of Time Coded	55.8	76.4

ACTIVITY	Subject One	Subject Two
Read	6.6	4.3
Assumption	1.0	0.6
Constraints	26.7	7.8
Calculate	1.7	33.3
Other	1.3	0.3
Total Percent of Time Coded	37.3	46.2

OBJECT	Subject One	Subject Two
Layout	19.8	4.7
Equipment	16.0	2.6
Swings	1.2	19.7
See-Saw	0.6	3.1
Slide	0.3	0.0
Sandbox	1.1	0.0
Tables	10.0	0.0
Garbage Cans	0.0	1.4
Signs	0.0	3.8
Tire Wall	0.0	19.3
Other	0.6	2.4
Total Percent of Time Coded	49.5	57.0

Table 2. Percent of time devoted to information processed, activity, and object codes.

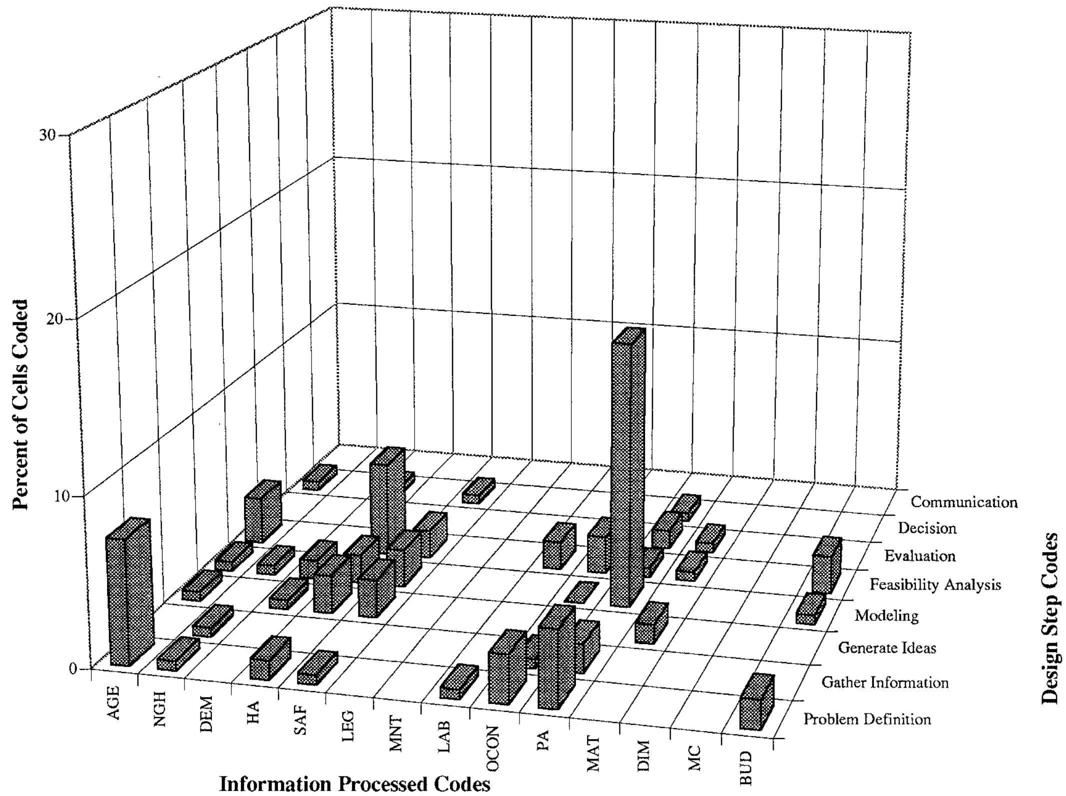

Figure 3. Information processed during each design step—Subject One.

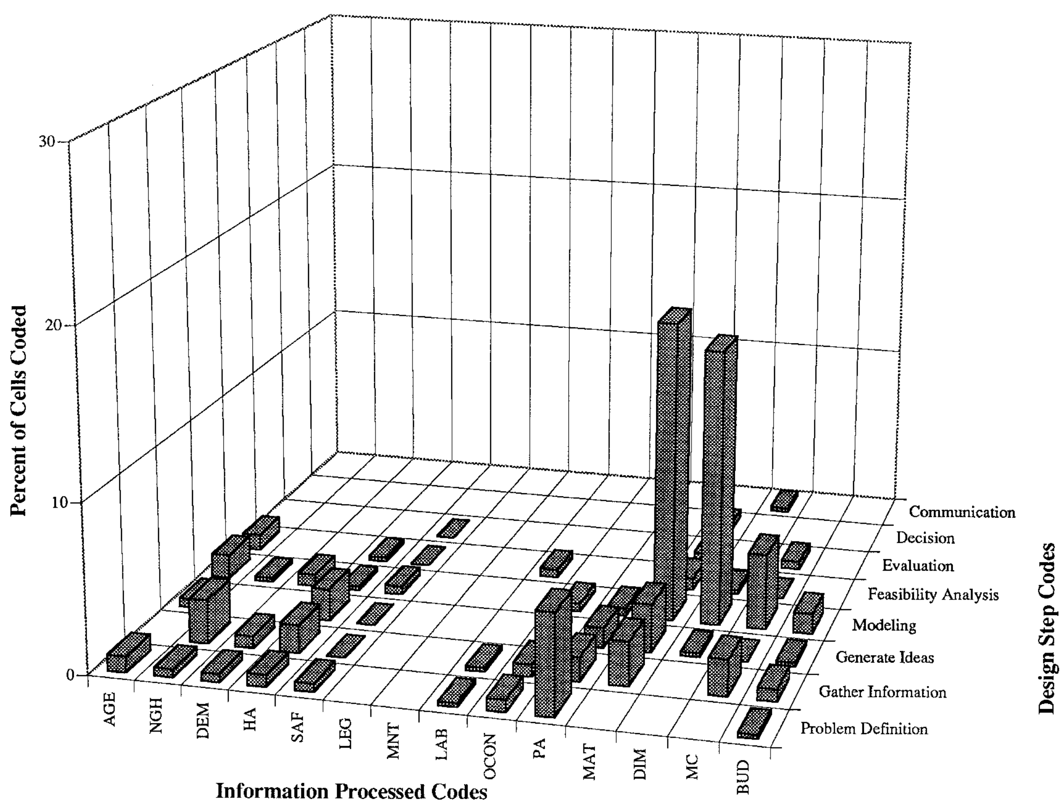

Figure 4. Information processed during each design step—Subject Two.

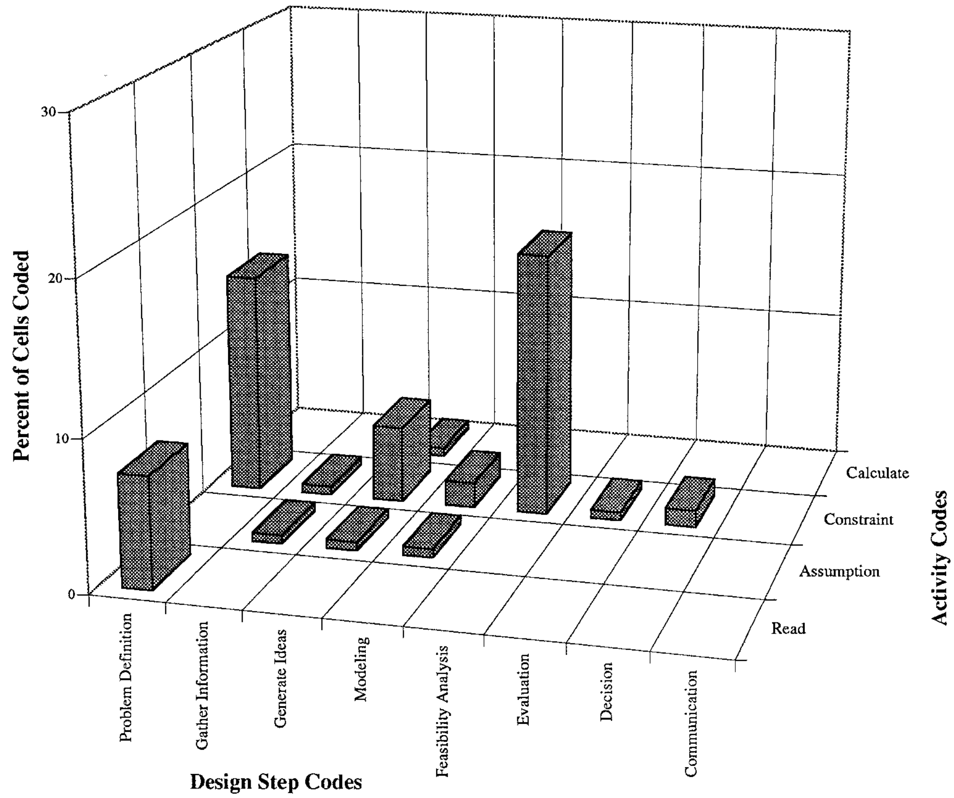

Figure 5. Activity performed during each design step—Subject One.

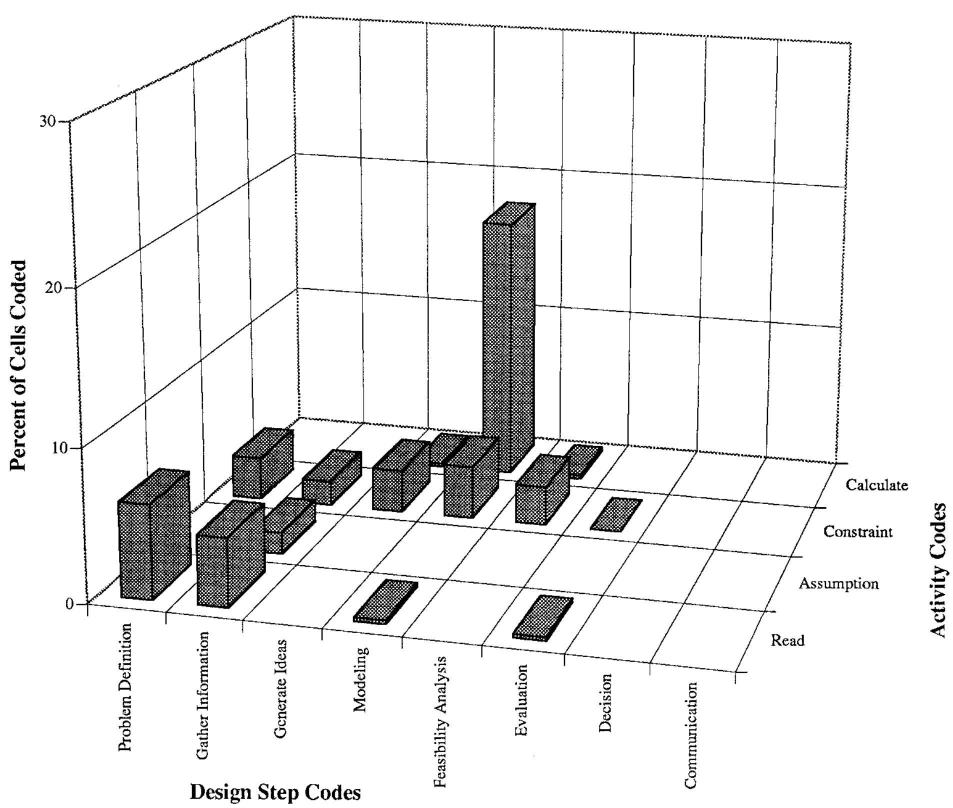

Figure 6. Activity performed during each design step—Subject Two.

playground does not exceed the budget." The remaining criteria are based on fulfillment of expert design criteria as outlined in the book Play for All.[33] These include such requirements as "location of play area allows minimum contact between children and traffic," "play area provides challenges to stimulate upper body strength," and "fall zones of adjacent pieces of equipment do not overlap." The expected criteria cover accessibility, safe challenge, graduated challenges, flexibility, materials, and safety.

The second part of the score is based on applicable supplemental criteria. For example, a subject who includes a swing would be scored on criteria such as "only single axis swings are used" and a subject who uses metal would be scored on "metals other than aluminum must be treated to prevent rusting." Subjects that do not include these items are not scored on these criteria. Supplemental criteria in areas such as wood, metal, ropes, moving joints, finishes and paints, equipment higher than six feet, moving equipment, climbing equipment, slides, swings, stairways, ramps, and guardrails can be included. Subjects receive one point for each of the expected and supplemental criteria that are met. Finally, the designs are scored on several qualitative ratings including diversity of activities, aesthetics, protection from injury, uniqueness, and technical feasibility. The ratings are scored on a scale of 1 to 5.

The decision on whether a criterion is met and how to rate one of the five factors is based on a review of the transcript, assigned codes, and any drawings or other output given by the subject. The first two parts of the score (expected criteria and supplemental criteria) are determined by dividing the number of criteria met by the number expected. The ratings part of the score is determined by summing the individual ratings for the five factors and dividing by 25. The final score is obtained by weighing the three parts equally to obtain an average score that can range from 0 to 1.[32]

Subject One scored 13 points for the 40 expected criteria, 2 points out of 30 applicable supplemental criteria, and 16 out of 25 on the factor ratings. This gave Subject One a quality of design score of $[13/40 + 2/30 + 16/25)]/3 = 0.34$. Subject Two scored 18 points on the 40 expected criteria, 16 on 29 applicable supplemental criteria, and 18 on the ratings, giving Subject Two a score of 0.57 computed in the same manner. Subject One spent most of her time on the overall layout of the playground and did not go much beyond selection of simple equipment. Since she did select equipment, 30 supplemental criteria became applicable. Unfortunately she did not meet most of these criteria. Subject One did address constraints and considered factors other than cost and dimensions. This is reflected in her expected and supplemental criteria scores. Subject Two spent more time considering appropriate materials and dimensions on the pieces of equipment that he included and as a result scored better on supplemental criteria. He also did well on the ratings and better on meeting the expected criteria than did Subject One.

I. Comparison of the Two Sample Subjects

The timelines show a clear difference between the two subjects. Subject One spent more time iterating through the steps in the design process while Subject Two spent the majority of his time in modeling. In fact, in measuring the number of transitions (or movements from one step in the design process to another), Subject One averaged 2.07 transitions per minute, while Subject Two averaged only 0.76 transitions per minute. Subject One clearly concentrated effort on problem definition (reading and constraints) with little effort devoted to designing specific pieces of equipment. While she worked on the problem, Subject One did not request any information from the experimenter beyond the information on the park layout. Subject Two's concentration was in analysis on the material aspects of particular pieces of equipment. Subject Two asked for a variety of pieces of information including information on demographics, material availability, and material costs. We also see a difference in the quality scores between the two subjects.

In summary, when we compare these two subjects using verbal protocol analysis we see two different approaches to solving the playground design problem. The step variable shows that Subject One spent a greater proportion of time scoping the problem while Subject Two spent a greater proportion of time in detailed calculations. In terms of information processed, Subject Two concentrated on materials and material costs while Subject One addressed a wider variety of issues such as safety and handicapped accessibility. In terms of the activity variable, Subject One clearly spent more time addressing constraints while Subject Two spent more time doing calculations.

J. Analysis of All Subjects

Once the transcripts for all the subjects have been coded and analyzed, we can begin to make comparisons between subject groups. Specifically we can compare freshmen to seniors to determine if four years of an undergraduate engineering education have changed the way they approach and solve design problems. We can also evaluate the quality of all of the subjects' playground designs. This will allow us to develop models to determine if any factors we have measured in the student problem solving processes are correlated with the quality of the final product.

Early results of the playground design experiment (based on all 50 student subjects) show that students take a wide variety of approaches. One consistent finding is that most of the freshmen and senior subjects do little information gathering. Their requests for information are concentrated on material costs and do not encompass the broad range of information that is available.[33,34]

Once the data analysis on all 50 student subjects is complete, the data from this verbal protocol analysis experiment will allow us to answer a variety of questions such as those listed below.

About the Design Process - General:

- How long do students spend working on the problem?
- With what patterns do students move through the steps in the design process?
- How much time do they spend in each of the design stages?

About the Design Process - Specific:

- Do students adequately define the problem or do they go directly to analysis and evaluation?
- Do students check to ensure that they are meeting problem constraints?
- How much information do students gather?
- At what stage in the design process do students gather information?
- Do they make assumptions?
- Are the assumptions explicit or implicit?
- Do students generate multiple alternative solutions and select the optimal one, or do they develop one idea and refine it?
- Do students adequately evaluate their designs?
- Do students test hypotheses about their alternatives?

About Design Products:

- Do student designs fulfill the constraints and criteria in the problem?
- What is the quality of the student designs in terms of technical accuracy, safety, aesthetics, and so forth?

Comparisons:

- How do freshmen compare to seniors?
- How do student processes compare to prescriptive models of the design process?
- Which approaches lead to better quality designs? (More modeling and evaluation, more problem definition and scoping, asking for more information, etc.)

Research Directions:

- What teaching interventions and strategies are suggested by the results of the experiment?
- What does the research suggest about student approaches to solving engineering design problems and their ability to propose creative solutions to "real-world" problems?

V. Other Ways to Study Design Processes

Using verbal protocol analysis, we can document and perform in-depth analysis of student approaches to engineering design problems. This method allows us to address numerous research questions within the broad domain of engineering design problems. Verbal protocol analysis is clearly a time consuming research method. There are other ways to gain some insight into student problem solving processes that can take less time. Some suggestions include the following:

- Collect a full verbal protocol but isolate that part of the design process of greatest interest. For example, to gain an understanding of how much problem scoping students do, an instructor can focus on how much students reflect on the problem statement and what information the students gather. The entire protocol then does not have to be analyzed. Rather the instructor simply considers what questions students asked and how often they returned to the problem statement. As another example, an instructor may be interested in knowing how many alternative solutions the students propose before developing their final solution. This information can be found by analyzing portions of the protocols.
- Protocols of students solving problems do not have to be transcribed in their entirety. The data can be used to create a script that identifies specific aspects of the problem solving approach. This is particularly useful for students solving problems in groups, where more than one student may be talking simultaneously. For example, rather than transcribing a conversation word for word, one can simply record who was talking to whom, about what, and when.[35]
- Lochhead and Whimbey[36] have suggested the use of thinking aloud pair problem solving (TAPPS). This is a method that can be used in the classroom where one student is the problem solver while another is the listener. The listener makes sure the problem solver keeps talking and attempts to understand every step and every diversion or error made by the problem solver. This allows the instructor to verify that students are performing the task correctly and allows the listening student to learn critical listening skills.
- Millar et al.[37] had faculty give oral exams to students from both an experimental and a traditional freshmen chemistry course to assess the effectiveness of the new course. The authors found that the students that had taken the experimental course were ranked as more competent than those that had taken the traditional course.
- Instructors can also gain tremendous insight into student problem solving approaches by listening to audio tapes or watching videotapes of students solving problems. Leifer et al.[38-40] describe a research method known as video-based interaction analysis for studying human activity. They have used this qualitative method in the classroom to study student design processes.

VI. Conclusions

Verbal protocol analysis is a powerful tool that can be used to understand the design process. Of the eleven specific skills that ABET expects engineering graduates to possess, at least five are purely process skills while most of the others contain some process components. The VPA method described in this paper can be used to effectively measure process skills. Specifically, VPA can be used to determine a student's "ability to design a system, component, or process"[16]

Analysis of a verbal protocol enables us to look at a subject's process in detail rather than simply "grading" a final solution. That is, we can now grade the "process" as well as the final design. In essence, it provides us with a measure that can be used to assess student process skills. In the cases illustrated in this paper we can also rate the quality of the subjects' playground designs. By measuring both the "product" and the "process", we can then explore whether a relationship exists between the type of process a student uses and the quality of the final design. Knowing this relationship, we can then distinguish between good and poor processes and indicate specific problems that must be addressed as we teach design.

Verbal protocol analysis is a very time consuming analysis technique that is used most frequently as a research tool. The in-depth information provided about student design processes by studies such as those described in this paper can be invaluable to faculty and administrators to guide curriculum changes. These curriculum changes can then be assessed using less time consuming methods suggested by other authors in this issue.

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