Graphical Representations of Engineering Design Behavior

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Abstract - Engineering design is a necessary skill for all graduating engineers. As educators, we must develop ways to represent engineering design behavior that allow us to assess alternative methods of teaching design. Using verbal protocol analysis, we are able to document and analyze student design processes. When analyzed, design process data reveal differences in student approaches and allow researchers to make comparisons across students. Here, we present alternative methods of displaying design process data from verbal protocols and discuss the types of analyses that are possible from each representation.

Introduction

For research purposes, graphics are used to present data and results in ways that are easy for readers to understand. Here, alternative forms of data representation are treated as a means to inquiry into engineering student design behavior rather than a presentation of final results. Eisner suggests that “alternative forms of data representation promise to increase the variety of questions that we can ask about the educational situations we study [1].”

Much research has been done on how to best display data [2-7]. We are applying concepts of multiple data representation to the study of student design behavior. The design processes and their relationships to the product quality of two senior engineering students are studied using the following alternative forms: timelines, cumulative time charts, stacked bar charts and three dimensional bar charts. These graphical representations are used to highlight previous results and suggest new directions of analysis.

Design Process Data and the Design Problem

Verbal protocol analysis (VPA) has been used to document and describe student design processes. VPA is a research method in which subjects think aloud as they perform a task. Researchers have successfully used this method to study processes like the student design behavior discussed here [8-13]. A detailed description of the application of the research done to collect the data displayed in this paper can be found elsewhere [8]. Rigorous data collection and analysis of verbal protocols can lead to a detailed understanding of a cognitive process like engineering design.

In this study, students thought aloud as they individually solved a playground design problem. The problem is a revised term project used by the University of Maryland and the National Science Foundation’s ECSEL Coalition [14]. The designers analyzed in this study included 26 freshmen and 24 senior engineering students at the University of Pittsburgh. The freshman students participated in the study before any design concepts were presented in their first term Engineering Analysis course. The seniors participated in the study during the last semester of their senior year.

Variables that describe the design process have been analyzed with respect to design quality and used to compare the processes of freshmen and seniors [15]. Senior students making more requests for information while solving the playground problem produced better solutions. The process variable most highly correlated with quality among seniors was the number of objects worked on or proposed during the design. For the playground problem, objects were coded as “swing”, “seesaw”, “slide”, etc.

In order to explore different representations of the playground problem data, two example senior subjects were chosen. Senior One had a quality score of 0.60 and considered 23 different objects during his design. This was the greatest number of objects coded among the 24 senior designers studied. Senior Two considered only eight objects and had a mediocre quality score of 0.47. The average quality score of the subjects was 0.51. The average number of objects coded among the seniors was 11.5.

Graphical Representation

Our goal is to learn as much as we can about individual student design processes. We do this by using multiple representations of design process data. We now present a series of graphical representations of the design process data and discuss the types of observations that can be made from each. The representations include timelines, cumulative time charts, stacked bar charts and three dimensional bar charts.
Figures 1 and 2 display timelines that describe aspects of the design processes used by the two subjects. A timeline displays a subject’s allocation of time in process variables throughout their design. Time increases from left to right.

**Figures 1. Timelines For Type Of Object Worked On**

**Senior One**

General

Environment

Specific

**Senior Two**

General

Environment

Specific

**Figure 2. Timelines For Design Step**

The design step timelines in Figure 2 show the steps in the design process used by the students. Process steps include Problem Definition, Gather Information, Generate Ideas, Modeling, Feasibility Analysis, Evaluate, Decision and Communication. Timelines effectively show the iterations or transitions a designer makes between design steps or levels of specificity. Also, it is valuable to see what steps and levels are being addressed at what times.

The most obvious difference between these two subjects in the object timelines is that Senior Two did not consider any environment aspects during their playground design process. Senior One iterated more frequently in the beginning of his design and did include Environment objects. Senior One’s object behavior may suggest a better ability than Senior Two to approach the playground design problem with an understanding of “the big picture.” He alternates between general, environmental and specific issues before settling into the details of designing play equipment. In contrast, Senior Two considers the physical aspects of his design in more defined blocks of time throughout, not showing an ability to move easily between thinking about different aspects of the playground design. This may be an important characteristic of the number of objects considered and its relationship with quality.
process as well as between steps in the object variable. This student displayed a high degree of iterative behavior for more than the first half of his design before moving into the modeling step. Even after he spent much of his time in the modeling step, he continued to periodically generate ideas, gather information and communicate aspects of his design. This ability to gather information throughout the process may lead to a higher quality design. In contrast, Senior Two seems to settle into modeling much sooner in his process and gathers relatively little information after doing so. There is also an apparent lack of time spent generating ideas. Such a focus on modeling is common among the 50 students in this study. Students are used to reading a well-defined problem with all relevant information given and the answer “in the back of the book.” This means that the modeling step in the design process is likely to be the step that is most comfortable to the students.

Cumulative Time Charts

The charts in Figure 3 exhibit the cumulative time each student spent in each design step. Observations were made at specific time intervals for each of the two seniors. The cumulative time chart is comprised of eight different curves. Each curve describes the total amount of time a subject has spent in each design step, at certain points during the life of their design. They can be thought of as the cumulative counterpart to the previously presented timelines.

Cumulative time charts show when designers divide their time equally between design steps and/or when a particular step overtakes the process. Also, individual curves composed of many different lines indicate a higher transition rate. At any point in time, one can measure the amount of time a designer has spent in each step of the design process. For example, follow the curves for modeling (signified by a letter “x”) and generating ideas (signified by a triangle) in Senior One (Figure 3). At time point 4, the student has spent slightly more time modeling than generating ideas. Between time points 4 and 5, we see that the student spends more time generating ideas, and so this curve increases at a greater rate and comes closer to the modeling curve. Between points 5 and 6, this behavior continues until the curves approximately cross, where the subject has spent an equal amount of time in both generating ideas and modeling.

These graphs show more varied process behavior in Senior One. Both students spent most of their time modeling, but Senior One did so later in his process and spends more time gathering information and generating ideas before settling into modeling. Notice in the cumulative time chart of Senior Two where the modeling curve “breaks away” from the other design steps and becomes the only one growing remarkably. In contrast, Senior One’s chart shows that the growth of the modeling step corresponds with other steps until later in the life of the design, when the modeling curve departs from the others.
Figure 4 presents a more traditional representation of the time each student spent in design process steps. Stacked bar charts make it easy to compare the total time spent designing. Also, one can determine directly how much the different steps in the design process contribute to the total time spent on the design. Note that the total times represented by the stacked bar charts are less than their corresponding timelines. This is because timelines display every moment designers spend from the beginning to the end of their work, while stacked bar charts show only the time spent in the defined steps of the design process not including pauses and interaction with the experimenter.

Seniors spent an average of about 57% of their time modeling. The stacked bar charts illustrate an interesting fact related to the issue of modeling and its possible dominance over other important steps in the design process. For every minute Senior One spent defining the problem, gathering information and generating ideas, Senior Two spent 3.2 minutes modeling, and since Senior One scored higher on the quality of his solution than did Senior Two, one might ask “what was Senior Two modeling?” These results suggest that some of the time Senior Two spent modeling may have been better spent in other steps where he may have been lacking such as gathering information and generating ideas. A more iterative design process may have led to more time in these earlier steps perhaps resulting in a higher quality solution. The stacked bar charts show the difference in time spent modeling by the two subjects and the abundance of time spent modeling by Senior Two. An investigation of some more specific data suggests that too much time spent in this step may constrain quality.

### Three Dimensional Bar Charts

The effects of modeling and other process steps on design are further explored using Figure 5. The three dimensional bar chart represents a detailed matrix of design process variables. Here, episodes of each step in the process used is shown divided between “activity codes.” These codes describe the following design actions or activities: 1) when a designer is reading either the problem statement or information that has been gathered, 2) identifying, dealing with or meeting problem constraints, 3) making implicit or explicit assumptions, 4) making calculations, 5) “other” which includes mostly requests for information that is unavailable. Analysis using these charts is a natural progression from that using stacked bar charts, as one can make more detailed comparisons between design processes in terms of time spent in design steps.

For example, Figure 5 clearly presents more information regarding the difference in modeling behavior between Seniors One and Two. Calculations clearly dominate the process of Senior Two. About 29% of his cells coded are calculations while modeling. The three dimensional bar charts are more evidence of Senior One’s more varied process behavior. Senior Two’s chart shows that only two areas contribute more than 10% to the student’s total design process: calculations while modeling and defining problem constraints. Senior One, the student who designed the higher quality playground, allocates more than 10% of his total design process to five different areas including reading, gathering information and generating ideas with respect to constraints. These seem to be important inclusions in a successful process. Such details about the time a student spends while designing are useful in comparisons, and they are easy to see using three dimensional bar charts.
Figure 5. Three Dimensional Bar Charts

Conclusions

Timelines (Figures 1 and 2) can show the transition behavior of a subject. They provide a detailed map of a designer’s process, what the student is doing at every point in their design. The timelines for the two seniors in this paper show the level of specificity at which objects are considered for design and how students spend time in the design process.

Cumulative time charts (Figure 3) are composed of eight different curves that describe the accumulated time spent in each design step, at points during the process. These charts show to what degree designers spend time in each of the design steps throughout their processes. They also vividly represent common behavior of designers that allows some singular step to dominate their processes. This behavior was illustrated in Senior Two whose Modeling curve “broke away” from the others and became virtually the only one increasing.
Stacked bar charts (Figure 4) are a more traditional representation of how each design step contributes to the total time spent on a design. Also, stacked bar charts provide a good method for comparing not only the total time different students spend on their designs, but the time they spend in each individual design step. Senior Two (compared to Senior One) dedicated more than twice the amount of time modeling for time spent defining the problem, gathering information and generating ideas. Given Senior One’s higher quality and “better” process behavior, this dominance of modeling may have been a process handicap to Senior Two. This bar chart representation makes it easy to determine how much each step contributes to the overall process used by the designer.

Three dimensional bar charts (Figure 5) divide the time represented in the stacked charts more specifically into activities such as addressing constraints and making assumptions. The higher quality design of Senior One is further explained with more evidence of a better balanced process. One immediately notices Senior Two’s heavy reliance on calculations while modeling in contrast with Senior One’s more varied behavior.

Student design processes differ, and these differences may contribute to the differences in the quality of the designed products. A deeper understanding of the different student design processes can be gained by constructing multiple representations of verbal protocol data used to analyze process behavior. The observations made here about Seniors One and Two would not have been possible without the exploratory tool of multiple graphical representations. Different representations of student design behavior made it possible to “see” differences in the verbal protocol data that were not previously known. Such improvements in the ways researchers and educators understand student design behavior will help them to better assess and teach engineering design.

References