Investigating Engineering Design Through Model-Building

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Abstract: *This paper reports on a study utilizing Verbal Protocol Analysis (VPA) during prototype construction to investigate student's understanding of the engineering design process. Students were asked to think aloud during the design and construction of a prototype jar opener for physically challenged individuals. The results show that the inclusion of a hands-on component helped not only the researchers gauge student's understanding, but also helped the students in designing possible solutions.*

Introduction

Understanding the engineering design process is important in order to understand and implement effective teaching of design courses**.** To this end, there has been a great deal of research investigating the design processes of engineers and engineering students (e.g. (Atman, Cardella, Turns, & Adams, 2005; Atman, Chimka, Bursic, & Nachtmann, 1999; Atman & Turns, 2001; Bursic & Atman, 1997; Chirstiaans & Dorst, 1992; Cross, 2002; Ennis & Gyeszly, 1991; Krueger & Cross, 2006; Stauffer & Ullman, 1988). Although previous researchers studying the design process have utilized sketches, drawings, and written communications while collecting verbal protocols, the purpose of this research was to extend their findings by collecting verbal accounts while subjects were building a physical prototype. This research was driven by the following questions:

1. Does a model-building component enhance the assessment of engineering design understanding?
2. Does a model-building activity contribute to students' understanding of engineering design?

Theoretical Background

Kolb and Fry (1975) and Kolb (1984) described experiential learning as a process in which knowledge is created by transforming experiences. In exploring the processes associated with making sense of our experiences, they developed a 4-stage, circular model of experiential learning: Concrete Experience (dissection, reverse engineering), Observation and Reflection (discussion, identify unexpected difficulties), Forming Abstract Concepts (thinking, analysis), and Testing in New Situations (simulations and experiments). The authors suggested that learning often begins with a person carrying out a particular action in a particular setting, reflecting on the effects of this action, and then, understanding these effects. As did Dewey (1938), Piaget (1972), and Kolb and Fry stressed the role that concrete here-and-now experiences play in learning and made special note of the importance of testing ideas and receiving feedback (performing actions and examining results) to alter theories; in essence, learning by doing (Anzai & Simon, 1979).

Although experiential education can be broadly applied, this paper will focus specifically on the experience of building prototypes and models or hands-on experiential learning (McNeill, Evans, Bowers, Bellamy, & Beakley, 1990), an important component of engineering. There is much in the engineering literature supporting the learning benefits of building a hands-on model. Design assumptions, made during the preliminary design phases, come to the surface during model building and can then be either validated, or reflected upon for redesign and re-examining concepts (Helbling & Traub, 2008). Students frequently have difficulty visualizing a structure from a drawing and are tempted to blindly accept results from computer analysis without review (Schumucker, 1998). Schmucker wrote that building physical models help students investigate the differences between real behavior and the conceptual model used to predict that behavior. O'Neill *et al.* (2007) similarly wrote that building models helps students see the differences between theoretical and measured results. Model building also gives students tangible results more quickly than preliminary highly theoretical courses and offers students experience with the non-idealities of real-world engineering(Bales & Consi, 2003). In addition, all of these authors noted that students' response to model building was generally quite favorable.

Research Methods

Verbal Protocol Analysis

Since we cannot directly observe cognitive processes, we can't know what people are thinking unless we ask them. To this end, we can advance our understanding of how engineers and engineering students go about developing solutions to complex problems using Verbal Protocol Analysis (VPA). VPA is an analysis method used to probe students to provide evidence beyond what they may report spontaneously (Ericsson & Simon, 1980, 1993). In VPA, subjects are asked to think aloud while designing. Although subjects may not have a conscious awareness of their cognitive processes, they can report the contents of short-term memory, allowing insights into at least some of their cognitive activities. From this, we can gain insights into how subjects generate and transform information about problems and how they go about developing solutions. Dorst & Cross (1995) claimed that VPA is the most appropriate method to study the cognitive processes and abilities of designers and it has been used extensively in engineering since the 1980's; however, VPA is not an assessment tool appropriate for large subject populations because of the copious amount of time required (Ericsson & Smith, 1991).

Four engineering seniors were asked to participate in a design experiment. They were: a male mechanical engineering major (MME), a male general engineering major (MGE), a female civil engineering major (FCE), and a female environmental engineering major (FEE). It was a sample of convenience, as the first author knew the students. Students were tested in a small conference room within the engineering department. A small video camera was mounted on the ceiling that focused on the participants' hands (faces could not be seen). They were told the purpose of the study and given a practice think-aloud project of putting together a 24-piece puzzle. When the subjects finished the puzzle, they were given an information sheet that explained the design task, which was to develop a jar opener for individuals that had the use of only one hand. Laid out on a large table were 15 sets of cards (each set made up of between 5 and 12 additional cards) that offered various snippets of information. The information sheet explained that they could choose whichever information cards they thought might help them formulate a solution. Some information was based on the Massachusetts Department of Education Science and Technology/Engineering framework engineering design process model (Massachusetts Department of Education, 2001/2006). Some information was totally irrelevant. The cards were titled: *Talk to Jim (an amputee), Speak with Mary (a stroke victim), Learn about Amputees, Learn about Stroke Victims, Review First Principles of Physics, Talk to Jar Manufacturers, Examine Elementary Mechanics, Read Technical Descriptions of Prototype Jar Openers, Build a Prototype, Look at Jar Variables, Look at Other Models, View Available Materials, Investigate Aesthetic Options, View Unnecessary Nonsense, and Plan/Draw/Sketch.*

LEGO® pieces were the medium used for building the prototype (see Figure 1 for sample prototypes). When subjects chose the *Build* card, they were handed a kit of LEGO parts and were advised to use the pieces simply to get their idea across, and to not be concerned with the limitations of the LEGO pieces. While the functionality of the pieces did not allow heavy force to be used to open a jar, the fact that they could be assembled, taken apart, and reassembled quickly and easily outweighed this disadvantage. In addition, most students are at least somewhat familiar with LEGO pieces. Students had two hours to complete the task.

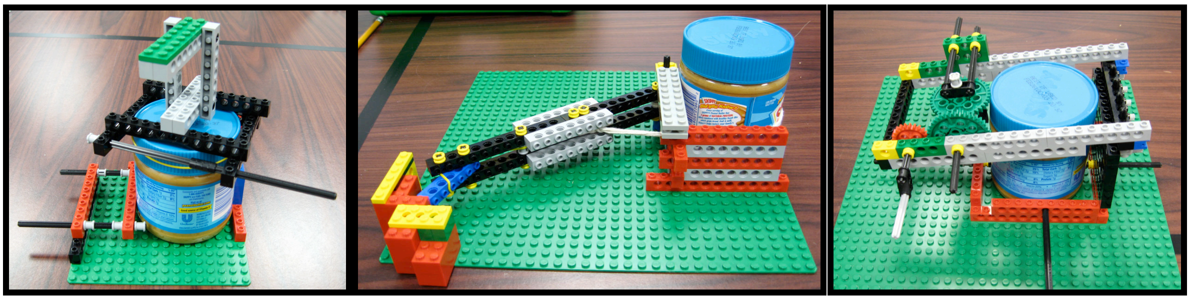

Figure 1: Sample LEGO jar opening prototypes

Data Analysis

Content analysis was employed (Creswell, 1997; Patton, 2002). This involves searching through text for recurring patterns, words, or themes; creating groups of words and phrases; developing a coding or classification system; and determining each category's significance. Once groups of categories were created, constant comparison (Patton) was used to assure internal homogeneity (cohesiveness) and external heterogeneity (independence) of the categories. However, more important than individual categories were the trends or pathways in engineering design that emerged.

Since the analyst is the research instrument, there is an element of subjectivity when interpreting other people's thoughts. Two researchers checked category entries for internal homogeneity and external heterogeneity. Some items within the categories were questioned. After a brief discussion, some items were deleted, some items remained, or a new category was generated to reach a consensus.

Results & Discussion

The number of students in this sample was too small for statistical analysis, but from the data collected, there does appear to be some consistency. Model building can help students clarify ideas. While sketching out his idea, the MME student said, "You have to somehow clamp this top part in" and it wasn't until he actually started building that he found a solution. Although he did not incorporate gears into his drawing, when building he said, "There'll be something here like a crank. I can use like, a gear and have the gear do it." The FEE said, while drawing, "My issue is still how I want to clamp onto the lid" and when building said, "We're gonna start with what I want it to be like and then go backwards and make sure that they [the clients] can do it."

Model building can help students when they have difficulty visualizing. When asked how he would make the device adjustable, MME answered, "I'm not exactly sure what I'm envisioning" but after beginning to build, constructed a hinge that worked very well. The FEE student, while sketching said, "I can't really see while I'm drawing" and added, "It's easier to touch things and hold things."

Model building can expose flaws in preliminary sketches. While building, MME said, "The way I have it now is like horizontal and then it'll go down . . . but I want it to go up this way. So it would have to be like this." Also while building, FEE commented, "We're just seeing how this works . . . Definitely coming across um, things that I want to change." As Kolb's theory suggests, there was a constant process of testing ideas, receiving feedback, and making modifications to the prototype. MME was constantly evaluating his work and at one point said, "What we want to have, is to go from vertical up this way to horizontal instead of horizontal to vertical downwards. And so we have to switch the blocks." FEE said, "What a nice long axle. But then it's harder to do with one hand."

Model building pushes limits and tests knowledge. MME commented how difficult the task was, that gear trains could be such "a beast," but succeeded in creating a very elegant model using gears. FEE, frustrated at one point said, "Right now, I'd like to just open the jar for them." This was not an easy process for any of the students. All experienced periods of frustration, creative blocks, and obstructed progress. When this happened they tended to go back to the cards again, either re-reading cards they looked at earlier, or trying to cultivate ideas from looking at cards they had previously ignored. What was important is that they all persevered and produced a functional prototype. As Manzini (2009) wrote, “Being a designer means being an optimist . . . We presume that we can solve problems because we have no alternative” (p.4).

What have we learned about the design processes of engineering students? What we found was that how students framed the problem dictated how they formulated a solution. MGE framed the problem as, “How do you produce enough force with one hand?” and came up with a ratchet device similar to an oil filter wrench. MME said, “The things we need are some sort of base to stabilize the jar . . . some way to lock it in, and then a third component to, to turn the lid” and his model clearly reflected those three components.

Bursic and Atman (1997) noted that in general, students did not ask for enough information. In this project there was a range of skill level in how students perceived information. While some were very skilled in weeding out information of no value (e.g. MGE noted, “Couldn’t do math well, that doesn’t really pertain to this”), others tried to find meaning and application to worthless snippets (e.g., FCE read, “Bones fracture under torsional loading” and theororized, “So if you’re dealing with someone who’s been injured already, you wouldn’t want that person doing their own twisting.”)

In looking at design processes, Stauffer and Ullman (1988) concluded that designers do not follow any set procedures. This was the case with our sample where students took various routes to their solution. Some of the students created a more circular path by testing out many ideas before making a decision. FCE thought about using a cone, a ratchet wrench, gears, and rubber tires before making a decision based on opportunistic behavior, while FEE incorporated more of a linear process, designing a prototype with ideas gathered from the pictures, and did not stray from that idea. Some students organized the cards first before sketching and some students stopped reading after a couple of card choices, sketched briefly, then started building. Designing is a subjective activity filled with qualitative reasoning and influenced by personality and personal knowledge.

One final note about the students is that they were all skilled at evaluating and critiquing components of other models. They continually assessed their own models throughout the building process as well, averaging 48 evaluative comments within about 90 minutes (although given 2 hours to complete the task, most were done much sooner).

Conclusions & Future Work

The purpose of the present research was to utilize a hands-on, model-building component to assess the design process of engineering students. Model building, paired with VPA, has proven to be a viable method of collecting data pertaining to the engineering design process. In addition, it has demonstrated to be a beneficial learning tool that accommodates different learning styles.

More hands-on VPAs need to be conducted before broad generalization can be made about student engineering design processes. The future for the study will be to expand the population to include engineering students at all levels as well as professional engineers to obtain a full grasp of the breadth of possible design pathways.

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