AC 2010-1972: METHODS FOR EXPLORING ENGINEERING DESIGN THINKING IN HIGH SCHOOL STUDENT TEAMS

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A better understanding of engineering and its relationship to society is critical for all Americans even though few will pursue engineering as a career [1]. At the heart of engineering is design and therefore developing an understanding of the engineering design process is essential for all students to be literate citizens [2]. Design thinking is fundamental in understanding the technologically dependent nature of our society because design represents a decision making process for converting resources optimally to meet our needs [3]. This study was developed in an effort to gain a better understanding of how to administer and measure design thinking of high school students. Using a modified protocol analysis, this study focused on the design thinking of engineering design teams. As proffered by Roberts et al. [4], "The development of design, problem solving, and communications skills within a team setting is a crucial component of the education of a globally competitive engineer" (p. 2). This research will serve to inform developers of team design thinking measurements.

Curricular and pedagogical efforts are currently in place to develop an understanding of engineering design among high school students through formal and informal experiences. *Engineering in K-12 Education* [5] presented discussion of a variety of curricular efforts. Included in these are The Academy of Engineering, Engineering: *An Introduction for High School, Engineering by Design, Engineering Your Future: A Project-Based Introduction to Engineering, Engineers of the Future, The Infinity Project, INSPIRES, Learning by Design, Principles of Engineering, TeachEngineering.org, TECH-Know, A World in Motion, Engineering the Future, Ford Partnership for Advanced Studies, Full Option Science System, The Infinity Project,* *Materials World Modules,* and *Project Lead the Way.* The sample for this study was drawn proximal to Utah State University which resulted in the inclusion of students from Project Lead the Way (PLTW) programs. The National Academy of Engineering highlighted three significant benefits of improving the public understanding of engineering:

1. **Sustaining the U.S. capacity for technological innovation**. A better understanding of engineering would educate policy makers and the public as to how engineering contributes to economic development, quality of life, national security, and health.
2. **Attracting young people to careers in engineering**. A better understanding of engineering should encourage students to take higher level math and science courses in middle school, thus enabling them to pursue engineering education in the future. This is especially important for girls and underrepresented minorities, who have not historically been attracted to technical careers in large numbers.
3. **Improving technological literacy**. To be capable, confident participants in our technology-dependent society, citizens must know something about how engineering and science, among other factors, lead to new technologies [1].

Goals and Purpose Statement

This case study was designed with the intention of piloting techniques used for measuring design thinking of high school engineering teams. The research question for this study was: How do high school teams exhibit engineering design thinking? Four cases were chosen to comprise this case study as suggested by Creswell [6]. Three of the four cases involved pairs of students, while the fourth case involved only one student due to scheduling and participant availability. The purpose of this case study was to pilot a method of inquiry to understand high school students' use and application of design thinking. The guiding questions for this case study were:

1. How do high school student teams exhibit design thinking during a three hour design challenge?
2. What additional understanding can be gained about the study's methodology and its capacity to measure engineering design thinking from conducting reflective interviews?

Literature Foundation

The methods and design thinking constructs measured in this study were built on a foundation of previous work which emerged from the University of Washington led by Cindy Atman. This study is differentiated from the Washington work in two distinct ways. First, this work extended the continuum of novice to expert to include high school students whereas previous work employing these methods focused specifically on college students and practicing experts. Second, our study attempted to explore design thinking in dyads using a modified verbal protocol approach in which the unit of study was the pair of students rather than individual students.

Significant discoveries with implications for design education have been made in the past decade which has provided a foundation for changes in undergraduate education. It was our hope that this methodology and these findings will contribute to the research foundation of secondary education design thinking which may lead to pedagogical improvements. Fundamental to educational philosophy is the requisite potential to improve students' critical thinking abilities. Through a study of freshmen and senior engineering majors, Atman and colleagues [7] concluded that the students' ability to generate quality designs improved. This improvement suggested that design thinking can be learned and improved through education and practice.

Previous studies have demonstrated the value in design iteration. Atman and colleagues provided evidence through measuring transitions that more advanced students create more frequent transitions while designing. Atman's 1999 study also considered problem scoping and discovered that seniors gathered more information covering more categories than did freshmen. Atman and colleagues [8] extended their comparison to include expert designers with the previous study on undergraduate engineering majors. This comparison was significant as practicing experts represent the goal of undergraduate education in terms of providing an education that leads novices toward the behaviors that demonstrate expertise. Experts allocated more of their time in the design to problem definition and information gathering than seniors engaged in design. Experts spent more time making decisions than seniors engaged in design. Experts also considered more alternative design elements than did seniors. Overall, experts had a greater number of transitions between steps in the design process which was attributed with their increased total time rather than transitions per minute differences.

The practice of engineering design is commonly a team enterprise [9-12]. Diversity of thought, skill and experience extends team performance beyond the individual capabilities of team members. This synergy is recognized by industry and education in organizing design teams who can work together successfully. "Engineers don't just sit in a cubicle and solve mathematical equations; they work in teams to solve challenging engineering problems to make life safer, easier, and more efficient for the world we live in" [13].

Research Design

This case study gathered multiple forms of data and utilized qualitative analysis strategies. Case studies are characterized by the study of an issue explored through one or more cases bounded by time and/or place [14]. Data collection in case study research relies on multiple forms of information, including: observations, interviews, documents, and audiovisual data [14]. As researchers, we endeavored to provide a substantive case report detailing, (1) an explication of the problem; (2) a description of the context and/or setting; (3) a description of the processes observed; (4) a discussion of the salient themes; and (5) a discussion of the outcomes [15].

Method/Techniques

Two data elucidation techniques were employed: the playground problem and reflective interviews. ***The playground problem*** has been used in multiple studies and can be traced to Dally and Zang [11], who identified the need for team based project driven approaches in the freshman engineering design course to increase student performance and retention and to situate student learning of abstract concepts through real world applications in an experiential activity. In this activity, students designed a swing set with slides and seesaw. Atman, Chimka, Bursic and Nachtmann [7] revised the foundational work of Dally and Zang to create a playground design problem. In this challenge, engineering students were presented with a brief playground design task and access to relevant information upon request. Participants were provided with a maximum of three-hours to develop a solution to the problem while thinking aloud. In lieu of using traditional verbal protocol to collect data, we employed a modified protocol analysis, utilizing audio and video recordings, tracked information gathering, and student generated documents.

Students participated in reflective interviews at the conclusion of the design challenge to provide insight into the cognitive processes employed as teams solved the design task and to offer reflection on the methods used by the research team. A retrospective interview using semi-structured questioning techniques provided the opportunity to gain insight regarding the cognitive processes employed as teams solved the design task. The retrospective interviews were team based, allowing researchers an opportunity to document responses and team member interactions [16]. Group interviews also provided an efficient data collection methodology allowing researchers to gather information from participants immediately following the design task before memories begin to fade [17]. Participants were asked to justify and explain their rationale for decisions made during the design process. They were also asked what they would do differently given another challenge in the future.

Student teams were observed and video recorded as they worked through a design task, consistent with prior research on team based problem solving in both collegiate and secondary classrooms [18-19]. Students communicated and interacted with each other as they progressed through the design task. To adequately document the students' thinking through verbalizations, each student team was videotaped [19]. Student teams had available a computer with internet access, except for the first case. Excluding case one, each case made use of the internet for information gathering related to their design task. Navigation and information seeking behaviors were tracked digitally [18].

Audio and video data provided behavioral evidence and verbal communications between team members, but lacked the cognitive insight of methods such as verbal protocol or thinking-aloud strategies. Thinking-aloud strategies are not well suited for environments where teams of individuals are collaborating as the verbalization "intrudes into the performance of the underlying task and changes the performance and strategy to the point where the resulting data are problematic" [20]. A modified verbal protocol was also used to alleviate inherent issues that arise when attempting to use verbal protocol to examine "team" interaction including tacit gestures not verbalized and written communication, such as notes and sketches [20].

The playground problem coding scheme was congruent with the approach used in prior studies [7, 21-22]. The data were coded into these nine categories presented below by Atman et al.[8]:

Design Activity	Example(s)	Coded Example(s)
(PD) PROBLEM DEFINITION Defining what the problem really is.	Reading, re-reading, or rehashing the problem statement Identifying criteria and constraints; also saying what they imply for the solution	"That means we'll have to rely on volunteer labor."
(GATH) GATHER INFORMATION Searching for and collecting information (i.e. facts, data) needed to solve the problem.	Asking for information from the experimenter and reading information statement from the experimenter Stating as assumption or how s/he would go about getting the information	"Um, do we have a budget?"
(GEN) GENERATE IDEAS Thinking up potential solutions (or parts of potential solutions) to the problem.	Coming up with an initial idea (or set of ideas) for a solution "Playing" with solution ideas Thinking up potential ways to get around an impasse	"I might give it a circus theme."
(MOD) MODELING Detailing how to build the solution (or parts of the solution) to the problem. Applies to initial solution concepts as well as to the final design	Estimate or calculating measurements (dimensions, costs, loads, etc) Fitting a solution element in the larger design	"So we'll need 3 bricks per square foot."
(FEAS) FEASIBILITY ANALYSIS Assessing and passing judgment on a possible or planned solution to the problem (or parts of the problem)	Verifying workability in general Determining whether a solution or solution element meets the Problem Definitions criteria or constraints	"Yeah, that's good because it's strong enough to hold an adult."

(EVAL) EVALUATION Comparing and contrasting two (or more) solutions to the problem on a particular dimension (or set of dimensions) such as strength or cost	Specifying or debating tradeoffs among alternative solutions or solution elements Devising and applying a scheme (e.g., matrix) for comparing and contrasting potential solutions on a particular dimension or set of dimensions	"Red oak is the most expensive then redwood, then spruce."
(DEC) DECISION Selecting one idea or solution to the problem (or parts of the problem) from among those considered	Selecting the type of material to use from among alternatives Selecting or specifying a solution element to include (e.g., piece of playground equipment) Specifically eliminating an option or changing one's mind about what to use/include	"We'll just have to make them out of, uh, metal then."
(COM) COMMUNICATION Communicating elements of the design in writing (e.g., sketches, diagrams, lists, and reports), or with oral reports to parties such as contractors and the community.	Sketching or diagramming Making a bill of materials Making instructions Presenting/ reporting results	"See drawing to swing three, four."
(OTH) OTHER None of the above codes apply	The participant says something not relevant to the problem being solved.	"It sure is hot in here."

In addition, coding included information requested by the participant and at what point in time. Also consistent with prior research, the following categories of information were made available for participant request [22]: budget, information about the area, material costs, neighborhood opinions, utilities, neighborhood demographics, safety, maintenance concerns, labor availability and costs, legal liability, material specification, supervision concerns, availability of materials, body dimensions, handicapped accessibility, technical references, and other information. Within these categories, specific detailed information was available, and participants' request for this information provided us with data regarding problem scoping and problem definition techniques employed. "Question asking while designing is influential to the cognition of designers. It is related to the cognitive aspects of their problem solving, creativity, decision making, and learning processes, and, consequently, to their overall performance" [23].

Participants

The sample included seven high school students who were actively engaged in the study of engineering design. The participants were recruited by advertising through their teachers in engineering and/or technology education programs. A criterion sampling strategy [6] was used which identified, (1) high schools that have an established program of study which employs a focus on engineering in a sequence of courses; and (2) students who have completed multiple courses in the sequence.

Case one consisted of two Caucasian male students who had completed their sophomore and junior years in high school. The senior in case one had completed courses in Introduction to Engineering, and Civil Engineering and Architecture as part of the PLTW course sequence. The junior in case one had completed courses in Introduction to Engineering as part of PLTW course sequence as well as a course in Physics and Technology. Case two consisted of two Caucasian males who had completed their senior and sophomore years in high school. The graduate in case two had completed courses in Introduction to Engineering, Digital Electronics, Computer Integration Manufacturing, Civil Engineering and Architecture, Principles of Engineering and a Capstone Course as part of the PLTW course sequence. The sophomore in case two had completed courses in Aerospace Engineering and Introduction to Engineering Design as part of the PLTW course sequence. Case three consisted of two Caucasian females who had completed their senior and junior year in high school. The graduate in case three had completed courses in Digital Electronics, Introduction to Engineering, Principles of Engineering, Computer Integrated Manufacturing, Civil Engineering and Architecture, and a Capstone Course. The senior in case three had completed courses in Principles of Engineering and Introduction to Engineering Design as part of the PLTW course sequence. Case four consisted of one Caucasian male who had completed his junior year in high school. The senior in this case had completed courses in Introduction of Engineering Design, and Computer Integrated Design as part of the PLTW course sequence.

Context

In the spring of 2009, researchers employed by the National Center for Engineering and Technology Education solicited four teams of high school engineering students for this pilot study. In order to recruit participants for this study, researchers identified high schools within a ninety mile radius of the researchers' institution with a high school engineering program. For high schools to be considered for the research project, the high school needed to have an established program of study that employed a focus on engineering in a sequence of courses. To participate in this design study, students had to provide their own transportation to the research site. Compensation for students' participation came in the form of breakfast, lunch and a campus tour which was provided to the student participants throughout the one day data collection. Upon completion of the participants design tasks, students were also provided with a stipend of fifty dollars.

Data collection was conducted in a conference room. All student teams were provided with paper, pencils, pens, white boards, calculator and post-it notes as resources to use during the design process. During the reflective interview with the first team, the students suggested that a laptop computer and access to the Internet would be beneficial to their ability to demonstrate design thinking. The following teams were provided with access to a computer and internet connection. One video camera was strategically placed in the conference room to capture student behavior as they engaged in an engineering design challenge. Throughout the design challenge, researchers photographed student data and other material written on the whiteboards using a digital camera. For each picture, times were written down to assist in the analysis of data.

Design Challenge

Prior to the students engaging in the design challenge, we explained the criteria and constraints of the design challenge in a one page design brief. During this process, student teams were reminded of the three hours that they had to provide a solution to the *Playground Challenge* and the fact that research facilitators held information which might inform their design. Student teams were only provided with pieces of information from the administrator when they asked for it specifically. If the administrator did not have a handout with the desired information, student teams were instructed to make an estimation or assumption. Cases two, three, and four, were provided with the opportunity to use both the internet and 3D modeling software in the design process, as well as request information from the administrator. Throughout the design challenge, the administrator reminded students of time left.

After the completion of the design solution and/or time elapsed, researchers ensured that student teams ceased working on their design solutions. At the conclusion of the design challenge, researchers collected all student design team artifacts which included any written material, digital models or drawings, information gathering, digital photographs, and video recordings. After a short break, student teams participated in post design challenge reflective interviews. The purpose of the reflective interviews were to understand the design experience, highlight why and how decisions were made and solicit feedback on improving the research methods. The interviews were also used to inquire about student perception of the appropriateness of this design challenge in demonstrating their design abilities.

Findings: Methodological Strengths and Limitations

Video Recording. In order to measure design thinking in high school students, a coding scheme was adapted from the previous work of Mosborg and colleagues [21]. The original intent of the coding scheme was to be used on transcripts of individuals in think aloud sessions. It was adapted by considering pairs of students as the unit of analysis. When elements of the coding scheme were identified as exhibited by either or both team members, the code was applied to the video timeline with NVIVO software by QSR International. When using this modified protocol and direct video coding in particular for the present study, a number of strengths and weaknesses of this methodology were perceived by the researchers.

When coding the stages of design thinking directly from video segments, in comparison to coding design thinking from written transcripts, there may be a higher degree of ecological validity of the data obtained. Specifically, the researchers of the present study were able to directly assess the actions of the students when completing a design challenge, rather than just inferring the behaviors from transcripts. Moreover, this ability to see what the actions of the students were when completing the design challenge may have provided a rich depth to the information that was gathered. For example, when coding each video segment for “generating ideas,” the researchers could ascertain not only if the students were generating ideas through brainstorming, but the manner in which the students were brainstorming (e.g., sketching versus using the internet). In addition, the use of digital tracking software allowed the researchers the added benefit of having documented data on the websites and search terms utilized. Thus, perhaps a greater quality of information can be collected when using video segments and tracking software in addition to written materials.

Not only is a high degree of ecological validity important when studying engineering design thinking, but it is also essential to be able to compare findings to those of previous studies in order to build a broader base of knowledge. Modifying the Mosborg et al. [21] coding scheme for video recordings, rather than creating a new coding scheme, allows for the creation of this knowledge base and comparisons of findings from the current study to previous studies that have used this coding scheme. Because the present study was novel in that high school students' design thinking was being assessed, it was essential to use this modified protocol in order to make a more direct comparison to other studies that have investigated design thinking in college students and expert engineers.

Although coding directly from video segments provided a number of strengths, some considerations must also be made when using this type of methodology to study design thinking. Students are allowed to move around the room and use a variety of types of materials to complete the design challenge (e.g., writing on white boards, paper, using the internet), thus it is essential to have multiple cameras in the room at different angles in order to record all behavior. Further, various microphones should also be used in order to clearly hear all verbalizations made by students when completing the design challenge. In the present study, we found that one camera with its microphone was not sufficient to capture all of the nuanced behaviors students make when transitioning through the various stages of design thinking. Along the same lines, it may be difficult to clearly see what is being written on a white board or paper from a video segment. Thus, for the present study, pictures were taken of the students' created materials when completing the design challenge, in order to supplement the video segments. If these pictures are taken, it is essential to specify at which stage in completion of the engineering challenge the picture was taken, it order to map when the students created the drawing. Researchers concerned with the negative effects of their presence in carrying out these processes may note that case one explicitly stated that researchers' presence "made it less awkward" for the students when completing their challenge.

Possibly the most substantial challenge of using the Mosborg et al. [21] coding scheme with the coding of video segments is that it was sometimes unclear what stage of design thinking the teams were using when they are working *without* verbalizing their behaviors. To illustrate, case four expounded on the difficulty of verbalizing his thoughts by stating "That (verbalizing student thoughts) probably makes it so you can see what I'm thinking, but I think it slows it (the process) down". To help counteract this challenge, case four suggested that we provide "a little bit more time" for the students to complete the design challenge. In the present study, there were times in which the students appeared to be calculating, drawing, or reading from a document silently, and without the student verbalizing their actions it was difficult to code that behavior precisely. Thus, if using this modified protocol analysis, students must be frequently encouraged by the facilitator to verbalize their behaviors, especially if they are transitioning from one behavior to another. To do this effectively, three hours may not be adequate time to measure high school students' engineering design thinking for this task. Case three stated that "To demonstrate our abilities (to perform design tasks) three hours is not enough".

Technology to Complete Design Challenge. Along with there being various strengths and weaknesses to the modified protocol analysis adopted for the present study, we also found that allowing students to use available technology, such as internet searches, presented a diversity of issues to consider when inferring the types of design thinking students use from the present methodology. To alleviate the issues of coding student information gathering behavior from the video, the researchers employed the use of tracking software for some design teams. The tracking software ran silently in the background on the laptop that the participants used. Using the tracking software, researchers were able to determine what, when and where the student teams were searching. The tracking software was not used for all design teams thus allowing the researchers to compare and contrast the benefits/hindrance of technology for high school design teams.

Specifically, in the present study, all teams with the exception of the first team were allowed to use a computer and the internet in order to complete their design challenge. Thus, we can make a rough initial comparison between the first team and all other teams in terms of the costs/benefits the use of the internet made for the completion of the design challenge. When coding the video segments, it appeared that the use of a computer and the internet could possibly allow students to create a more novel solution in a shorter amount of time. Case one, which was not allowed access to a computer or internet, stated that not having a computer was "really limiting", and that the use of a computer and internet would provide a "broader search area". In addition, case one felt that with the help of design software they "could have drawn out the playground better". In comparison, when asked about the advantages of using the computer, case two stated that "the computer could really give you a detailed view of what we were thinking". This increased efficiency could possibly be due to the fact that using the internet is like a modified type of "brainstorming," where the students would create an initial idea (e.g., using a swing set in the design challenge), and then were able to search for various options in order to improve upon that initial idea. The ability to use online resources is also more realistic, because real-world engineers completing a task would have full access to this abundant amount of information.

Although it appeared that those students in the present study which had access to the internet were able to think of solutions more efficiently, it also appeared that the use of the internet actually hindered the progress of other students. Specifically, the use of the internet appeared somewhat limiting to one case because they relied so heavily upon the internet that it slowed their progress in certain areas of design thinking, such as generating ideas. For example, this team appeared to become fixated on buying pre-made playground equipment, rather than brainstorming and developing a wider range of ideas about how to cheaply build what was needed. Case two expressed these sentiments as they reflected on the use of the internet stating "it is helpful but it is a little time consuming". When speaking about the computer aided design software (CAD) made available, case three felt that "within the (limited) time (allotted), CAD software (was) more of a hindrance". This case also did not like the idea of drafting their solutions using CAD stating "I would not put a working drawing on it (Inventor software)". In terms of coding the video when teams are allowed access to the internet, it was difficult to determine which stage of design thinking was being employed if students were using the internet did not verbalizing what they were doing or why they were using the computer/internet. Thus it is vital that facilitators encourage the students to verbalize all behavior and the motives for that behavior when using a computer or the internet to complete the design challenge.

When speaking about the authenticity of the design challenge presented, the four cases had varying views that they expressed in the reflective interviews. Case one felt that the design challenge was "something that everyone would know" thus making it an effective design challenge. Case two stated that they "really didn't like the problem". When probed further it was stated, “I don’t really like civil engineering that much”, suggesting that the problem would be more akin to something a civil engineer would solve. Case three felt that the problem was “broad enough to understand”, yet constrained “just enough to be creative”. However, it was noted that a member of case three felt that it wasn’t an engineering problem by stating, “I don’t think I would consider it an engineering problem”, and that “I don’t think you have to be an engineer to solve the problem”. Case four was a little glib in stating the he felt that the problem was “challenging, but not overwhelming”.

Implications for future research

This study focused on piloting a method of inquiry used for measuring design thinking of high school students. Findings generated by this case study have multiple implications for future research. Four implications will be discussed here.

First, engineering design thinking of high school students can be collected through audio and video segments that provide behavioral evidence and verbal communications between team members. More research is needed that clearly delineate how teachers and researchers can effectively and efficiently evaluate the performance of student teams engaged in design. The use of audio accompanied with video segments help address many issues that arise when attempting to strictly use verbal protocol to measure engineering design thinking of students. Multiple cameras at different angles in the room and various microphones might be helpful to clearly capture all behaviors and verbalizations made by students while engaging in a design challenge task.

Second, a verbal protocol can help researchers document students’ engineering design thinking through verbalizations. Students must be frequently encouraged by the facilitators to verbalize their behaviors; however, it might be a challenge not to hinder students' flow of thinking, especially in team contexts. Future research should focus on piloting alternative techniques to verbal protocol in assessing engineering design thinking for student teams. Alternative methods such as using tracking software and scanned images of student work may help portray student design thinking and could offer insight into effective methods that do not hinder student progress. Future research may probe into the correlation between process and product to establish key indicators of products that indicate expert like processes for high school students.

Third, reflective interviews can be a valuable method to understand the students' engineering design thinking and to investigate student perception of the design challenge and the methods employed by the researchers. Reflective interviews offer students the opportunity to expound on their design thinking and the strategies that they use to solve engineering design problems. These interviews offer insight into students' cognitive processes and allow students the opportunity to inform researchers and practitioners on the feasibility of design challenges and techniques employed. Future research may focus on discovering the extent to which students are capable of accurately reflecting on their processes, to uncover what (if any) design processes are subconscious.

Fourth, the use of a computer and the internet may impact the design process. More research using tracking software can allow researchers to determine what, when, and where the student teams are searching and how that impacts the design process. However, the use of internet could hinder the progress of design thinking, so careful supervision by facilitators is necessary to encourage the students to verbalize all behaviors even while using a computer. It should also be noted that the three hours allotted to high school students completing design tasks may not be adequate if researchers and practitioners allow students the use of computer-aided drafting software and internet searches. Case one in our study was the only team not to use technology and this was the only case that felt they had fully developed a solution within the time allotted.

In conclusion, the use of a modified verbal protocol to measure engineering design thinking of student teams appears to be an effective method. Many challenges still lie ahead for teachers wishing to engage students within an engineering design context. However, we feel that this study provided a framework for researchers and practitioners alike, with future research focused on addressing many of the challenges that were described in this study. This study may help future researchers design a study to measure engineering design thinking of high school student teams.

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