AC 2012-4849: HIGH SCHOOL STUDENT ENGINEERING DESIGN THINKING AND PERFORMANCE

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High School Student Engineering Design Thinking and Performance

Abstract

Our vision is to improve the STEM learning and teaching environment for high school students through their understanding of engineering design. Engineering employs principles of mathematics and science to create technologies, thus serving as a STEM integrator. Design is recognized as the critical element of engineering thinking which differentiates engineering from other problem solving approaches. The purpose of this exploratory research was to clarify engineering design as a construct and perform empirical preparatory research on engineering design as a STEM learning experience for high school students. Engineering design has the potential to integrate science, technology and mathematics concepts for students and is essential for developing technological literacy [2]. This three year project tested the reasonableness of comparing high school student engineering design thinking with that of experts, and investigates the feasibility of these research methods by addressing the following question: ***How does high school student engineering design thinking compare to that of experts in terms of engineering design performance and knowledge?***

Fifty-nine participants from four states were asked to think out loud in a three hour design challenge which was video and audio recorded. Verbal protocol analysis was conducted as the students engaged in the engineering design process. The area of focus for this paper is time allocations across essential elements of the design process. This research may help to uncover the elusive cognitive thought processes employed by students as they practice engineering design thinking and will inform curriculum developers and teachers planning classroom strategies to improve high school students' understanding of engineering.

Keywords: Engineering Design, High School, Engineering Education, Technological Literacy

Rationale

According to the National Center for Technological Literacy[1], "While most people spend 95% of their time interacting with the technologies of the human-made world, few know these products are made through engineering", or that engineering design is "the missing link that connects science and math with innovation". The National Center for Technological Literacy suggested that "The key to educating students to thrive in a competitive global economy is introducing them early to the engineering design skills and concepts that will engage them in applying their math and science knowledge to solve real problems"[1]. The engineering design process is a systematic problem solving method and is the key element of the field of engineering. Engineering design has the potential to integrate science, technology and mathematics concepts for students and is essential for developing technological literacy [2]. For over a decade now, experts have been calling for a push to increase technological literacy of our Nation's K-12 students [3-7].

While a demand for technological literacy is loud and clear, many young people are unprepared to make informed decisions in our democratic society regarding the development of new technologies and their applications. The discrepancy between our society's reliance and dependence on technology and our ability to understand various technological issues has emerged as a serious concern for educators. "Technology is the outcome of engineering; it is rare that science translates directly into technology, just as it is not true that engineering is just applied science" [8]. Specifically, "Americans are poorly equipped to recognize, let alone ponder or address, the challenges technology poses or the problems it could solve" [7]. The relationship between understanding engineering and technological literacy is of special urgency during the high school years, since "technologically literate people should also know something about the engineering design process" [7].

This paper reports the results of an NSF funded three year exploratory project focused on understanding how high school students think through the engineering design process. The research has been completed and results are presented to address one of the two research questions: **"How does high school student engineering design thinking compare to that of experts in terms of engineering design performance and knowledge?"** Results and analysis compare high school students entering the sequence of engineering design courses with those finishing the sequence, and compare these students to practicing expert engineering in the field.

Background

The University of Washington, Center for Engineering Learning and Teaching has explored the cognitive processes of college engineering students extensively [9-13]. Findings in the past decade from this work rely on a variety of studies of freshman and seniors from multiple major universities and also practicing expert engineers in the field. One conceptual theme of this work is that performance can be positioned on a continuum from novice to expert. Expert performance represents a target for novice development. One goal of education is to improve novice performance such that it resembles expert design thinking more closely.

Design thinking is a creative way of problem-solving [14]. It promotes developments of diverse ideas, which are essential for innovation [15]. Studies show that teaching design thinking helped students in learning core subjects as well as fostering social skills [16-17]. In addition, it also encourages students' metacognition [18]. Design thinking teaches students how to work in groups, as stated by Carroll, Britos, Koh, Hornstein, Goldman and Royalty:

> They (students) became more empathetic, learned how to work in a group setting with a focused goal, and struggled to figure out how to participate as a seventh-grade student in a collaborative task. Design thinking activities provided tools that helped illuminate the complex nature of collaborative efforts, and the multiple ways to develop as a successful collaborator. [18].

The Center for Engineering Learning and Teaching has provided substantial insight into the design thinking and performance of college students and experts, as well as, provided comparisons on a variety of constructs. Implications of this work provide guidance for collegiate learning and teaching environments. Our goal is to extend the continuum of novice to expert to include high school learners. By leveraging the Washington based Center's work on experts as a trajectory for high school student development, this research project will have implications for high school curriculum development, learning, and teaching methodologies.

Design problems in these previous studies are ill-structured and open-ended. These kinds of problems have many potential solution paths stemming from an ambiguous identification of a need. The Carnegie Foundation for the Advancement of Teaching has prepared a series of studies including a focus on educating engineers [19]. Sheppard's research identified reflective judgment as an appropriate framework for understanding the cognitive development of design thinking. "As individuals develop mature reflective judgment, their epistemological assumptions and *their ability* to evaluate knowledge claims *and* evidence and to justify their claims and beliefs change*"* [19].

King and Kitchener have identified seven stages of reflective thinking organized into three clusters: pre- reflective thinking, quasi- reflective thinking, and reflective thinking [20]. Results of a ten-year longitudinal study of reflective judgment suggested that juniors in high school have a cognitive development that tended to approach stage 3 while college juniors tended to be nearing stage 4 [21-23]. This indicates that, on average, high school students are in the pre-reflective thinking cluster while college students are in the quasi-reflective cluster of development. Results of design thinking studies conducted on the college level might yield different results based on the advanced cognitive development of college students. The quasi- reflective cluster of development is characterized by people recognizing that some problems are ill-structured and that uncertainty requires judgment. This quasi- reflective cluster differs from the pre-reflective thinking cluster wherein individuals perceive knowledge to be certain and its sources are that of authority or direct experience. These developmental differences in cognitive approach to ill-structured problems suggest that high school student performance may differ from college student and expertise performance. This framework for cognitive development also suggests that high school students may have a tendency to search for information about other peoples' solutions (an authority on playground design) rather than accept that they are the responsible designer of this solution.

This study identified quality high school engineering learning and teaching environments in a criterion based sampling strategy where "technology teachers with a good understanding of science and the interactions between technology, science, and society will be well prepared to work with other teachers to integrate technology with other subjects" [7].

The playground problem has been used in multiple studies and can be traced to Dally and Zang, who identified the need for project driven approaches in the freshman engineering design course to increase student performance and retention. The project driven approach helped to situate student learning of abstract concepts through authentic applications in an experiential activity [24]. In this activity, students designed a swing set with slides and seesaw. Atman, Chimka, Bursic and Nachtmann [9] revised the work of Dally and Zang to create a playground design problem. In this challenge, university engineering students were presented with a brief playground design task and access to background information upon request. Participants were provided with a maximum of three-hours to develop a solution to the problem while thinking aloud. Mosborg, Adams, Kim, Atman, Turns, and Cardella [11] applied the playground design challenge using the "think aloud" research protocol to 19 practicing engineers who were identified as experts in the field. Mosborg, Cardella, Saleem, Atman, Adams, and Turns [12] compared groups of freshman and senior engineering students with practicing engineers using data previously collected on the playground design challenge. Atman, Kilgore, and McKenna [10] analyzed data from previous studies using a lens focused on the language of design and its relationship to design thinking as a mediator and how this internalization of design thinking relates to language acquisition. This work provided a well developed design task and results for comparisons between the high school student data collected by our study with expert data analyzed previously.

The playground design task is an effective task to demonstrate design thinking by students as it is an open-ended, realistic, accessible, and complex problem [12]. The endeavor to model problem solving satisfactorily has eluded scholars across domains [25-28]. Engineering design problems in practice tend to be structurally open-ended and highly complex. An open-ended problem may have numerous solution paths and be bound by some rigid and some negotiable constraints, not always presented with the problem. Engineering design is more than the manipulation of numbers and the solving of scientific equations. The processes employed in engineering design encompass a broad variety of topics and field of study. Through the lens of an ethnographer, Bucciarelli described engineering as a social process [29]. The National Academy of Engineering suggested that engineering education was deficient if it did not include the global perspective in engineering design such as social, political, and environmental issues [8, 30]. The global perspective of engineering is synonymous with the term “systems engineering.” Systems engineering involves design from the whole systems level rather than from an isolated modular perspective.

Not only do open-ended problems more accurately reflect industry practices, they also provide students more flexibility and choice [31]. As students are given more freedom and choice, they become further engaged in their own education [32-33]. Authentic problems provide a broad impact, rich in real-world contexts. As such, open-ended problems give the student an authentic experience and greater motivation [34]. Furthermore, playgrounds are familiar to students as they are common to most neighborhoods. This design activity does not require domain-specific knowledge such as electrical, biological, or mechanical engineering and, therefore, is accessible to many student participants with a variety of backgrounds and experiences [12].

Data Collection Methods

Consistent with triangulation mixed methods research strategies, quantitative and qualitative data were collected and analyzed, concurrently, providing multiple lenses from which to understand engineering design thinking among high school students. Areas of congruence between quantitative and qualitative data enable strong conclusions regarding design thinking, while points of divergence may highlight gaps in student learning between “design knowledge and its practical application” [10]. Sheppard also addressed the gap between knowledge and application, “in addition to ‘knowing that’ – having a firm grasp of the theories and principles-students need to ‘know how’ – how, when, where, and why to use theories and principles in analyzing engineering problems or situations” [14].

The participants of the playground problem were initially given a one page design brief. The constraints were vague with the participant, acting as a local engineer, assigned to design a playground on a donated city block. The constraints include limited budget, child safety, and compliance with laws or zoning. The participant is also able to query the research administrator for additional specific information such as, for example, the lot layout, cost of materials, or neighborhood demographics. There was a three-hour time limit for completion of the design proposal. The participants were asked to generate a written proposal describing their design. This activity engaged the participants in problem framing and developing an initial solution. Limitations of this design task included the lack of opportunity for participants to investigate the need for a solution; it is directly presented to them. Students did not have an opportunity to construct physical models or prototypes. Participants were aware that implementation of the design project would not occur, and their designs would not have the potential to become realized.

Before the design task was administered, the research team would enter the room and set up equipment for the data collection. First, the research team would arrange a table to create a workspace for the student. The table was usually square in shape and had enough space to make the student comfortable while working through their design task. On the table a calculator, ruler, a small note pad, graph paper, white 8.5" x 11" paper, pencil, highlighter, sticky note, and the design task were placed before the student entered the room. Video recorders were used to capture the student's work and were placed to create a view of the students working as well as to capture the table the students were working on. The research administrator discussed the agenda for data collection and provided food for the research participant before the task was administered. During this time, the researcher made a judgment about the student's voice projection. Quieter students were asked to wear a lapel microphone. Audio/video recording was done to capture the participants as they verbally worked through the problem, as well as, to show what participants were reading, drawing, and so on. The documents used in administering the problem were colored to help the observer differentiate between information (blue), problem definition (yellow) and student work (white).

Three hours were allotted for students to complete the design task, although the average student completed the problem prior to the administrator stopping the session. During the participant's design session, a member of the research team acted as the administrator of the problem. The administrator provided the students with a physical copy of the design task and read it aloud with them [for more details on the design task refer to Atman [9-10]]. The design task included a description of the general constraints and the method students could use to access information. The administrator provided various documents containing information upon specific request. The pilot to this study included internet access, however, the main data collection for this study did not permit internet use. Use of the internet in the pilot was a variance from previous work to maintain ecological validity, but the practice was discontinued at the suggestion of the advisory group based on the validity of comparison with expert data. While students were working, administrator kept track of the information requested by the students. Using a simple chart, the administrator made a note of what information was requested by the participant, as well as the specific time the information was requested.

During the design task, the administrator was responsible for ensuring students were continually thinking aloud. It was imperative for the participant to verbalize their thoughts while simultaneously working through the problem. This was done by the administrator prompting the students, such as, "keep talking", "what are you thinking", "what are you doing", "what are you drawing". The administrator also created a list of questions that were focused on the participant's solution development to be used for a follow up interview that was conducted after within a few weeks of data collection.

The administrator would continue the problem until the participant indicated they were finished (or the three hour session had expired). Once the participant felt that they had completed a design that satisfied the problem, the administrator would thank them for participating in the study and remind them that there will be a follow up interview in a few weeks. Follow up interviews were usually conducted 2-4 weeks after the initial design task was completed. These served as a way for the research team to gain more information about what student were doing while developing their solution. Common questions asked of participants were, how did you define the problem, how did you compare ideas, why and how did you choose your final idea or plan, along with question directly related to the students work. When the follow up interviews were completed, students were compensated for their time with a 40 dollar check.

Data Analysis

The playground problem coding scheme was congruent with the approach used in prior studies [9, 11-12]. The data were coded into these nine categories presented by Mosborg et al., [12]: **Problem Definition (PD)**: Defining what the problem really is. **Gather Information (GATH)**: Searching for and collecting information needed to solve the problem. **Generating Ideas (GEN)**: Thinking up potential solutions (or parts of potential solution) to the problem. **Modeling (MOD)**: Detailing how to build the solution (or parts of the solution) to the problem. **Feasibility Analysis (FEAS):** Assessing and passing judgment on a possible or planned solution to the problem. **Evaluation (EVAL)**: Comparing and contrasting two (or more) solutions to the problem on a particular dimension (or set of dimensions) such as strength or cost. **Decision (DEC)**: Selecting one idea or solution to the problem (or parts of the problem) from among those considered. **Communication (COM)**: The participants' communicating elements of the design in writing, or with oral reports, to parties such as contractors and the community. **Other**: None of the above codes apply. See table 1.

Table 1

Coding Scheme and Description

Code	Description of Code
Problem Definition (PD)	Define what the problem really is, identify constraints, identify criteria, reread the problem statement or information sheets, question the problem statement
Gather Information (GATH)	Search for and collect information
Generating Ideas (GEN)	Develop possible ideas for a solution, brainstorm, list different Alternatives
Modeling (MOD)	Describe how to build an idea, measurements, dimensions, calculations
Feasibility Analysis (FEAS)	Determine workability, does it meet constraints, criteria, etc.
Evaluation (EVAL)	Compare alternatives, judge options, is one better, cheaper, more accurate
Decision (DEC)	Select one idea or solution among alternatives
Communication (COM)	Communicate the design to others, write down a solution, or instructions

Adopted from Atman [9]

Data analysis began with segmenting the data sets. During the pilot study, data was segmented and coded simultaneously. This practice resulted in unacceptably low Kappa values demonstrating poor inter rater reliability. The advisory group provided insights related to the research effort that suggested segmenting should be a separate activity prior to attempting to code the data set, which is consistent with previous literature on protocol analysis [35]. During the segmenting, it was important to define what constitutes the thought which was defined as a pause bound utterance as suggested by Atman [9].

Two graduate students who were involved with the pilot of this study were tasked with segmenting the data. Each was assigned one-half of the data set. To ensure quality segmenting, each graduate student segmented ¼ of a video assigned to the other student. This provided 25% overlap based on video time. Videos very divided into quarters and determining which quarter of the video to overlap was randomly done by the research leadership team. Segments generated by each graduate student were assembled into a spreadsheet and compared. The research leadership team qualitatively reviewed the discrepancies and coached the graduate students toward consensus. This process was iterative as the students would segment one video, meet, resolve differences and segment the next video. Quantitative measures of inter rater reliability on segmenting were not made. The research leadership determined the segmenting of reasonable quality by the inter rater reliability measures for coding were high. If segmenting were done successfully, coding could potentially result in high inter rater reliability. Coding served as a proxy for quality control of the segmenting process.

Two undergraduate students coded the data. They began with pilot data set and developed their technique and understanding of the codes. The coders also were assigned one-half of the data set each. The undergraduate coders used the segmented data and each coded 25% of the other student's assignment for a total overlap of 25% measured by time. Again, 25% was determined per video where 25% of each video was randomly assigned for overlap and comparison. An iterative processes was followed wherein 25% of a video was coded independently by both students. The students generated a Kappa value for each code based on the coding comparison tool in NVIVO 8 software. Coders, under the guidance of project leadership, began to resolve discrepancies prioritizing the lowest Kappa value codes and working toward agreement. At the conclusion of the discussion, the team would document their negotiations (learning from their mistakes) in a dynamic coding document and attempt 25% of the next video. This iterative process continued throughout the data set. When 25% of each video was coded, the coders began to code full videos, redoing the early comparisons with low Kappa values. Kappa values are reported as an average of all 59 comparisons done independently.

A "Dynamic" Code Book was created and maintained. This was a document with very specific examples of the different codes developed by creating a description of the code and compilation examples in context. This included adding detail and clarifying the meaning of our segmenting and coding procedures and providing examples as coders did their work. The document was updated regularly and shared via network real time. It was suggested by our advisory group that the codebook be a 'living document' and it would grow in details as the project developed. As understanding and interpretation was negotiated by the segmenters, coders and research team leaders, the codebook documents the increasingly specific definitions. Any team member could update the code book. Skype provided access for distance desktop and video media sharing by the team as they spanned three geographic locations.

Two undergraduate students were trained in the coding methodology using documents shared by the University of Washington. While the coding scheme was consistent with previous literature, the technique was slightly different. Previous work used transcriptions, segmenting and coding as three separate activities in the analysis process [9]. Inter-rater reliability was calculated on the coding to ensure reliability of the multiple coding analysts. Our project bypassed transcription using NVIVO software which presented coding analysts with synchronized video and audio feed. Codes were associated with the timeline on the video/audio tracks and inter-rater reliability was computed with Cohen's Kappa statistics. Inter-rater reliability data is presented for each code in table 2. The average inter-rater reliability of 0.91 was higher than comparable to previous work [30]. A total of 11,162 segments were coded for comparison representing 25% of the total data set among the 59 participants. These coded segments were used to generate the Kappa values shown in the table 2 along with the number of coded references for each code. The number of references includes the coding of both undergraduates and serves as a sum of the two students.

Table 2

Cohen's Kappa For Each Design Activity

Design Activity	Cohen's Kappa	References
Problem Definition activity	0.9087	730
Gathering Information activity	0.9497	1551
Generating Ideas Activity	0.8959	408
Modeling activity	0.9186	6512
Feasibility Analysis activity	0.7978	914
Evaluation activity	0.9238	49
Decision activity	0.9192	103
Communication activity	0.9427	895
Average Inter-Rater Reliability	**0.90705**	

Sample

Four schools were identified and recruited for this study representing four states, and range from urban to rural (refer to table 3 and table 4 for school and community demographic information). Utah State University, Purdue University and two other well recognized universities with strong engineering outreach programs collaborated to identify the four schools. A criterion sampling strategy [37] was used which included:

- The high schools have an established program of study which employs a focus on engineering in a sequence of courses developed in association with an engineering outreach effort as part of a university program.
- In these courses, students participated in design activities which engage their critical thinking and problem solving skills within the framework of the engineering design process.

Table 3

School Demographics

School	Enroll-ment	Female	Male	African American	**American Indian**	**Asian**	**Caucasian**	**Hispanic**
1	1136	45%	55%	2%	**1%**	**3%**	**65%**	**30%**
2	216	54%	46%	1%	**1%**	**1%**	**76%**	**20%**
3	1833	47%	53%	4%	**1%**	**1%**	**86%**	**7%**
4	874	55%	45%	96%	**0%**	**1%**	**1%**	**2%**

Source: http://nces.ed.gov/ccd/schoolsearch/index.asp

Table 4

Community Demographics by School

School	Community Population	Median Household Income	African American	American Indian	Asian	Caucasian	Hispanic
1	91,000	$45,000	1.2%	0.5%	4.0%	88.3%	8.2%
2	78,000	$34,000	2.3%	1.2%	1.4%	79%	23.6%
3	61,000	$36,000	3.2%	0.4%	1.2%	88.9%	9.1%
4	>500,000	$59,000	54.0%	0.4%	3.2%	40.6%	8.8%

Source: http://quickfacts.census.gov/qfd/index.html

Meetings were held with the engineering and technology education teachers to help create an understanding of what the overarching goals of the study were and their role providing researchers with access to the school facilities and students. Once the teacher was familiar with the study, a member of the research team made classroom visits to begin the recruitment process. The researcher explained the purpose of the study and the student's role within the study.
Two target student populations were used in this study. Thirty students were recruited who had completed most or all of the courses in the engineering sequence. Typically these were senior students, but some students took all the courses prior to their senior year. Thirty students entering the sequence were chosen, typically freshmen, if they had intentions of completing the sequence. This stratified sample permitted conclusions about differences between program starters and program finishers, referred to here as freshmen and seniors. The average student in the study reported taking 2.96 engineering related courses. Student demographic data and courses taken, as reported by students, are shown in tables 5 and 6.

Table 5

Participant Demographics

	Number of Participants	
Self reported identity	Male	Female
Asian	2	1
Black or African American	12	0
Hispanic or Latino	2	3
White	25	7
More than One Race	4	2
Other or Unknown	2	0

Table 6

Courses Taken by Participants

Courses	Number of Participants
Intro to Engineering Design	40
Principals of Engineering	23
Digital Electronics	15
EDD	21
Aeronautical/Aerospace Engineering	13
Civil Engineering/Architecture	12
Computer Integrated Manufacturing	5
Bio-Medical/Bio-Technology	0
Math	3
EPICS	3
Robotics	4
Physics	3
Metals Manuf.	3
Technology Systems	3
Plastics Manuf.	3
Extra Classes	12
Average number of courses taken by students	**2.96**

Students were provided a recruitment packet including a letter to parents which provided a description of the study, a parental consent form, participant information form, a student assent form, and a demographic data sheet. Fifteen students from each participating school were selected and times were set up for data collection. Data collection was scheduled not to interfere with students academic responsibilities. In most situations, students were able to complete the design task after school hours or on weekends. Due to the logistics of data collection, efforts spanned multiple days which presented the chance participants would talk with each other about the challenge. At the conclusion of each participant’s session, they were asked not to discuss the session with peers until all the data had been collected from that school.

Results

High school students tackled the design challenge without hesitation. Fifty-nine students participated in this study, 30 of which were finishing their sequence of engineering courses and 29 were beginning the sequence. Students spend an average of 92 minutes engaged in the design challenge as compared to 132 minutes for experts. Table 7 presents a comparison of the average high school student with expert results from previous literature while table 8 compares high school freshmen and seniors by gender.

Results indicate that students spent less time in the problem scoping stage than did experts. This was evident in the quantitative data, but also evident on a qualitative level. High school students averaged 5.6 minutes considering the problem while experts spent 8.3 minutes. Throughout the design experience, students made little effort to understand the problem. Information requested was primarily related to the solution rather than understanding the problem. This lack of problem scoping frequently resulted in design effort that was not aligned with the problem at hand. While students were obviously engaged and making substantial effort, they blatantly missed some of the constraints and did not address all aspects of the problem.

Students less than half the amount of time in the *Information Gathering* phase compared to experts. *Information Gathering* code applied when students were looking for information about their design problem or solution. Students were able to query the research administrator with specific questions to probe for information which is consistent with previous literature. The demand for information beyond the immediate identified need is substantial and ubiquitous in the design process. Ennis and Gyeszly [39] found that gathering information was an essential element of the expert designers' approach to problem solving and that generation of ideas was influenced by the information. Experts have practice accessing information and are familiar with the structure and content of databases, previous project examples and other experts with whom to collaborate. Novice students do not have these engineering domain specific information literacy skills. In a recent study comparing college student and expert engineering design behaviors, Atman et al. stated that "Results support the argument that problem scoping and information gathering are major differences between advanced engineers and students, and important competencies for engineering students to develop" [36]. These differences, according to Christiaans and Dorst, include a finding that some students get "stuck" gathering information and this fixation prevents students from making progress on their design [40].

Generating ideas was coded when students were developing possible ideas for a solution, brainstorming, or listing different alternatives. High school students in this study rarely followed a "textbook" approach to brainstorming. This classic step in the design process is characterized by creating a list of possibilities without passing judgment. All judgment should be suspended during brainstorming so that wild ideas may spark another related, but practical idea. Students in the study rarely conducted this form of brainstorming. Rather, they recalled their previous experiences and frequently stuck with the first thoughts that came to mind. Students spend less than 3 minutes engaged in brainstorming as compared to experts' average of 6.6 minutes.

Students and experts spend a good deal of time modeling. Efforts to model included determining size, position, scale, quantity needed, shape, location. Modeling was done visually (described verbally), graphically and physically. Students spent less time than did experts modeling, but did spend a higher percentage of time in this area. This time allocation might be related to the emphasis placed on drawing and sketching by many high school engineering and technology education programs. Coders often had difficulty differentiating between modeling and communication as students blurred the lines between these two activities. Conceptually they are distinct in that modeling is related to determining how to build something while communication is documenting the design for the builder. Students often began with sketches that were rough evidence of brainstorming. They modified these sketches and improved their level of detail and finally turned the sketches in to their final solution. This evolution made differentiating between modeling and communicating difficult for the researchers as the differentiation was not clear to the students. The result was poor communication in that drawings were messy and incomplete, often looking more like notes and sketches than a final plan for their design.

Students spent very little time determining the feasibility of their ideas and little time evaluating alternative designs. Feasibility was coded when students attempted to determine if a solution was viable and practical. Evaluation In the *Evaluation* activity, we looked for students to compare alternatives and prepare to make judgments. When students did compare alternatives, they did so in a very clear overt way. Interestingly, all comparisons (though there were very few) were done verbally. None of the students created a decision matrix or anything that even resembled a matrix to compare alternatives. The senior students, all having taken a capstone course, it seemed reasonable to assume they would spend more time making decisions and have a systematic method for comparing alternatives. This was not the case.

Students spent very little time in the decision making process. They frequently took the first idea that came to mind and implement that in their design. They seldom compared alternative solutions in evaluation and made very few decisions. Decisions were coded when students specifically choose between two or more alternatives. In many cases, a student would specify some element of their design without considering alternatives. As an example, typically students would include a swing set in their design and may specify a color, material, height and other details. This was not coded decision unless they were considering two or more alternatives. With students' habits of accepting the first idea that comes to mind, few decisions were made.

Students spent more time than did experts in communication. Communication was coded when students made explicit reference to documenting their design so that it could be built or they provided evidence that the documentation was for someone else. Evidence included attempts to scale the drawing, annotations, detailed drawings and use of rulers and straight lines. The difference between developing their idea (modeling) and documenting their idea (communication) was difficult which may be related to students thinking graphically and using drawing as a mental tool to represent data which they discover is incomplete when shown on paper. This incomplete representation of the design is developed further on paper and eventually becomes their final design.

Comparison between novice high school students and experts suggest substantial differences. Table 7 provides the average time and standard deviation represented by minutes spent and percentage of total time. Expert data are presented from Atman [36] for comparison. Atman identified eight elements of the design process grouped into three stages. We choose to display "other" which represents time in the design process not coded in the other eight elements.

Table 7

Mean and Standard Deviation Summary Statistics for High School Students and Experts

Design Process Measures	**High School Students (n=59)**		**Experts (n=19)**	
	Minutes (SD)	Percent of time (SD)	Minutes (SD)	Percent of time (SD)
Total Time	91.7 (47.4)		131.9 (20.3)	
Problem Scoping stage	15.5	18.0	31.3 (16.2)	24.4 (12.5)
Problem Definition	5.6 (3.1)	7.7(4.9)	8.3 (2.8)	6.3 (2.0)
Gathering Information	9.9 (13.3)	10.3(11.7)	23.0 (16.3)	18.0 (12.5)
Developing Alternative Solutions stage	63.2	70.5	93.3 (25.3)	70.2 (12.1)
Generating Ideas	2.9(6.6)	3.9(10.5)	6.6 (5.8)	5.0 (4.5)
Modeling	54.4 (35.4)	60.2 (17.4)	73.2 (24.6)	55.1 (13.6)
Feasibility Analysis	4.4 (4.1)	5.4 (4.5)	11.6 (6.5)	8.8 (4.4)
Evaluation	1.1 (3.5)	1.0 (3.0)	1.9 (2.3)	1.4 (1.7)
Project Realization stage	8.2	7.6	7.3 (5.4)	5.5 (3.7)
Decision	0.4 (0.7)	0.4 (0.6)	2.4 (1.8)	1.8 (1.2)
Communication	7.8 (13.0)	7.2 (11.1)	4.9 (5. 0)	3.7 (3.5)
Other	3.1	3.8	0.0	0.0

Data suggested that high school students spent more time in the project realization phase, while experts spend considerable time in problem scoping and developing alternative solutions. Figure 1 graphically represents the average time in each phase. Figure 2 provides graphical representation breaking each stage into an element of the design process. This detail suggested that experts spent nearly twice the amount of time gathering information as did students. Experts were substantially more involved with modeling, feasibility, and evaluation than were high school students. High school students spent much time communicating their results, though researchers noticed their documentation was generally of very poor quality. Quality was not objectively measured in this study, but without exception, a contractor would not be able to build the playground from the design documentation as presented. In most cases, the documents were very disorganized, messy, and incomplete.

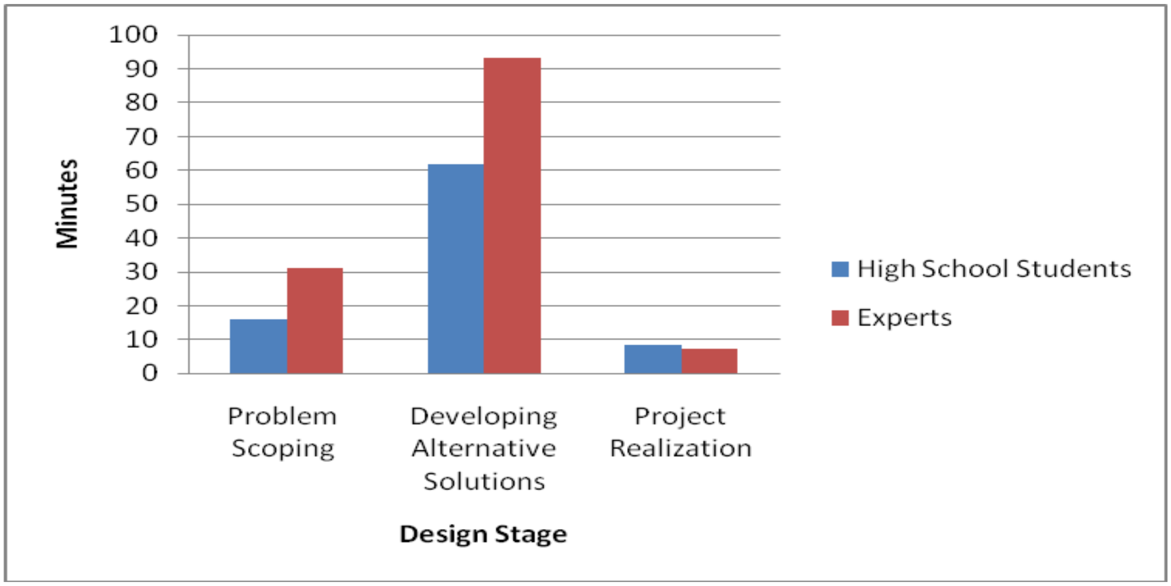

Figure 1. Mean time expressed in minutes each group spent in playground design stages.

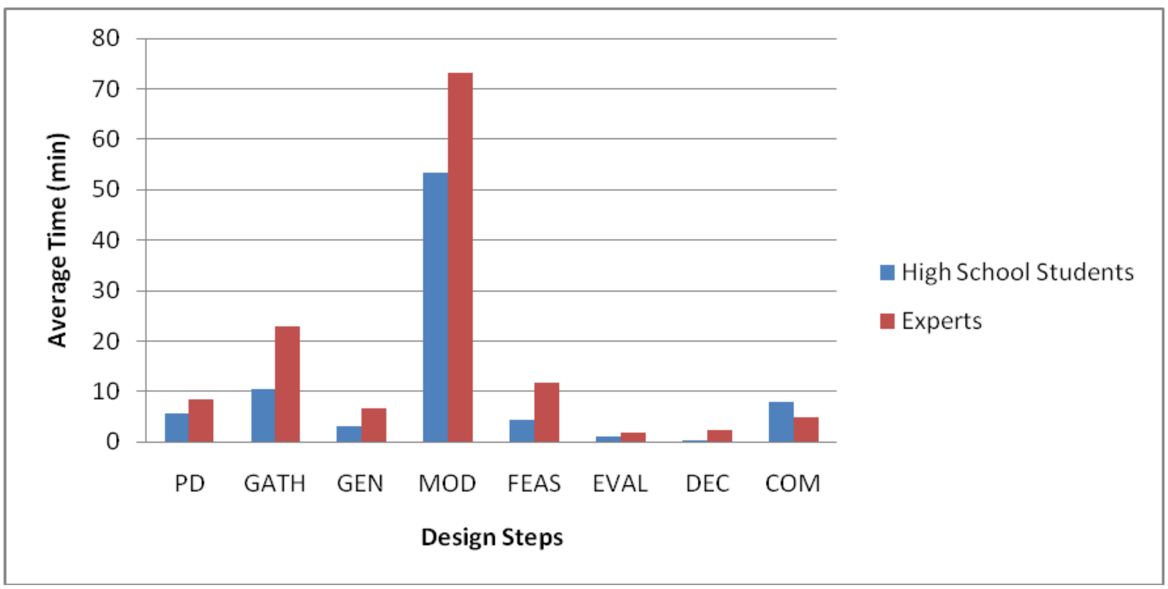

Figure 2. Average time spent in each design step for high school students and experts.

Gender differences were noticed across the student groups (refer to Table 8). Freshmen spent more time than did seniors on the problem while freshmen females and senior males spent more time than their counterparts. Freshmen females spent more time gathering information (17 minutes) than did freshmen males and seniors (11, 7 and 8 minutes). Senior females spent a considerable amount of time generating ideas as compared to the other groups (8 minutes as compared to 1 and 3 minutes). Senior females modeled much less than did senior males and freshmen with 30 minutes as compared to 58, 55 and 66 minutes. Female freshmen spent more time communicating and no time making decisions as compared to their counterparts.

Table 8

Mean and Standard Deviation Summary Statistics for High School Students

Design Process Measures	Freshmen High School Students Minutes (SD)		Senior High School Students Minutes (SD)	
	Females (n=6)	Males (n=24)	Females (n=7)	Males (n=23)
Total Time	111.0 (51.8)	89.9 (45.3)	57.6 (47.6)	100.0 (45.8)
Problem Scoping stage	22.2	16.3	9.9	14.6
Problem Definition	5.0 (2.8)	5.5 (2.6)	3.5 (1.1)	6.5 (3.7)
Gathering Information	17.2 (15.7)	10.8 (15.0)	6.5 (8.4)	8.0 (12.1)
Developing Alternative Solutions stage	70.1	61.1	40.6	69.6
Generating Ideas	1.1(1.6)	1.4(2.2)	8.3 (18.4)	3.2 (2.5)
Modeling	66.0 (46.4)	55.2 (35.3)	30.0 (32.2)	58.0 (32.4)
Feasibility Analysis	2.8 (2.0)	3.7 (3.5)	2.1 (1.5)	6.3 (5.0)
Evaluation	0.1 (0.2)	0.7 (2.0)	0.2 (0.4)	2.1 (5.2)
Project Realization stage	15.6	3.4	7.3	11.5
Decision	0.0 (0.0)	0.1 (0.3)	0.2 (0.3)	0.7 (0.9)
Communication	15.6 (15.4)	3.3 (7.2)	5.6 (10.4)	10.8 (16.0)
Other	2.0	3.0	1.1	4.1

Implications

Teachers may take note of the results and consider a few aspects of this research: information gathering, modeling, and decision making. Students in this study spent very little time brainstorming. While students may memorize the purpose and procedure of brainstorming, few students in this study had internalized the method. Further research should investigate the impacts of information access on solution quality for younger learners. The balance between becoming fixated on finding information related to the problem and using that information to make decisions is delicate and may be difficult for novice learners.

Teachers may consider the general lack of modeling and decision making from these results as an area to strengthen in their classrooms. How can modeling be taught? Curriculum and teaching methods should be reviewed for their treatment of analysis [see Katehi, Pearson, and Feder 2009 for a discussion of existing curriculum]. Teachers need to emphasize the role of analysis such that students can apply these techniques in the context of the problem at hand. Analogical reasoning is often used in engineering design and should be included in engineering design curriculum and instruction [41]. Decision making should be based on data derived from analysis and information gathered. Textbook examples guiding decision making include use of the decision matrix, but not one student demonstrated this technique. While students may be able to use a matrix when asked, they are not choosing to do so when provided with an opportunity. Quality decision making is essential to the engineering design process and data suggested that students are making very few thoughtful decisions. Research team member reflection on the pilot student performance suggested that high school students are rarely considering alternatives.

Next Steps

Problem definition is a critical step in design thinking. It is the first stage of engineering design and it sets the foundation for developing solutions. Atman et al. believed that experts tended to spend more time on this stage. Jain and Sobek [42] found the more time students spent on problem definition, the more satisfied clients would be. "Research has uncovered differences in the breadth of problem-scoping exhibited by "novice" student engineers and "expert" designers, who are typically advanced professionals with significant work experience" [43]. Christiaans and Dorst [44] suggested novices looked for less information and demonstrated less thorough problem scoping in comparison to expert designers. Bogusch, Turns and Atman [45] concluded freshmen considered fewer aspects of the design problem than did seniors in a college level study of engineering design thinking. Comparable to collegiate level studies, this study investigated the design thinking of high school students. The most substantial problem discovered in this research was that high school students spent very little time on problem definition. High school students in this study (freshmen and senior alike) were inclined to spend insufficient time (as compared to the work of experts in previous studies) on problem definition and jump to the phase of finding solutions. Students seldom revisited the problem during the process of design. From a qualitative perspective, student designers did not understand the problem at hand. They also did not make substantial efforts to understand the problem; rather, they were quick to engage in the solution space with results that failed to align with the problem. Students demonstrated capacity for asking questions, but their efforts focused on questions about the solution, including cost of materials they wished to use. Few asked about location, use, users, clients, goals or objectives of the stakeholders. Even constraints presented in the problem were often unconsidered.

The National Academy of Engineering Committee on K-12 Engineering Education reviewed curricula in 2008. This review included more than 10,000 pages of materials and suggested there is little unified definition of engineering education for pre-college students. The existing curricular efforts serve a variety of purposes and present different points of view regarding engineering as a profession and a way of thinking. Fifteen formalized high school curriculums were reviewed, five of which were considered in depth. Reviews were organized into threads which included Science, Mathematics, Technology and Design. Design was noted to be a strong thread, with almost all curricula presenting design as a cyclical process. "In most of the curricula, the first step in a design activity is to pose a problem or define a test. [Yet] …few curricula engaged students in a robust analysis to identify and define the problem" [2].

The concurrent lack of problem scoping efforts noted by college level and high school level engineering design research studies and weak treatment in high school engineering curricula present a gap that this project will address. Research studies show that design can be taught and problem scoping is both a learnable skill and consistently weak in novice designers.

As a next step for future research would be to develop, test and disseminate learning experiences to support student and teacher learning of engineering design processes. By developing resources for, and affording teachers' opportunities to develop ways of integrating engineering design thinking into engineering rich programs, our vision is to add capacity to these programs.

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