

Engineering Design Thinking

Engineering design thinking is a topic of interest to STEM practitioners and researchers alike. Engineering design thinking is “a complex cognitive process” including divergence–convergence, a systems perspective, ambiguity, and collaboration (Dym, Agogino, Eris, Frey, & Leifer, 2005, p. 104). Design is often complex, involving multiple levels of interacting components within a system that may be nested within or connected to other systems. Systems thinking is an essential facet of engineering design cognition (Accreditation Board for Engineering and Technology, 2007; Dym et al., 2005; Katehi, Pearson, & Feder, 2009; Ottino, 2004; Schunn, 2008).

Although systems thinking has not previously played a prominent role in engineering education research, it is becoming recognized as an important engineering trait (Dym & Little, 2009; Katehi et al., 2009). Due to the nascency of systems thinking research in engineering education, there are few studies that have investigated systems thinking and its impact on engineering design, particularly with K–12 students. As a result, how high school students employ systems thinking processes and strategies is not adequately understood or identified.

This research examined high school students’ systems cognitive issues, processes, and themes while they engaged in a collaborative engineering design challenge. Cognitive issues are mental activities used during a design challenge, while the processes are the ways in which the issues are approached or sequenced (Gero, 1990). Using exploratory triangulation mixed method research, the systems cognitive issues and processes were analyzed through the Function-Behavior-Structure (FBS) cognitive analysis framework. Additionally, emerging systems thinking themes and phenomena in engineering design were analyzed thematically outside of the FBS framework. Data from the different sources (verbal, video, computer movements, and sketches) were coded, organized, categorized, and synthesized for themes and patterns. Each data analysis technique yielded useful results on their own, but they were also used together to produce a broader understanding of systems thinking. The research was guided by two questions:

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1. What are the cognitive issues and processes used by high school students when attempting an engineering design challenge analyzed through the FBS framework?
2. Are there emerging qualitative themes and phenomena as they relate to systems thinking in engineering design? If there are themes or phenomena, how can these themes and phenomena be analyzed and interpreted—essentially repeatedly reviewing and analyzing the data sources outside of the FBS framework looking for themes, patterns, and phenomena?

Background

Engineering design is a process that has no agreed upon definition. Nevertheless, there are multiple K–12 programs and curricula that purport to teach engineering design (Katehi et al., 2009). Although the design definitions vary, studies have shown that high school students can engage in engineering design (Apedoe, Reynolds, Ellefson, & Schunn, 2008; Brophy, Klein, Portsmouth, & Rogers, 2008; Dally & Zhang, 1993; Eisenkraft, 2011; Hmelo-Silver, Holton, & Kolodner, 2000; Kolodner, 2002).

Complexity is another ambiguous term, (Davis & Sumara, 2006) yet complexity typically involves systems and their interacting phenomena. Systems thinking is a concept found in complexity, but it is also a term that has different meanings for different fields and disciplines. Engineering design often includes systems thinking facets and operations including: multiple interconnected variables, non-linearity, open-endedness, emergence, optimization, and graphical visualizations.

Complexity and Systems Thinking in Engineering Design

As the name suggests, complex systems are not easily defined and have given way to various precepts and constructs. Systems are dynamic with respect to time, with distinct variables varying along unique time scales. Complex systems have multiple interconnected variables with emerging interactions that cannot be viewed in isolation in order to understand the aggregate system (Hmelo-Silver & Azavedo, 2006). Complex systems are non-linear and unbounded (Davis & Sumara, 2006; Foster, Kay, & Roe, 2001). Most physical and social phenomena at the systems level do not follow a simple cause-effect relationship. Schunn (2008) defined optimization in complexity as balancing constraints, trade-offs, and requirements. In summary, complex systems are dynamic, adaptive, emergent, non-linear, and iterative. These systems are also influenced by multiple time scales, contain interconnected variables, and often include human activity as another variable.

Dym, Agogino, Eris, Frey, and Leifer (2005) unambiguously stated that design thinking is complex and offered the following definition of engineering design:

Engineering design is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints. (p. 104)

Dym et al. (2005) further stated, "A hallmark of good systems designers is that they can anticipate the unintended consequences emerging from interactions among multiple parts of a system" (p. 106). The American Society for Engineering Education's seminal report in the 1950s on engineering education, commonly referred to as the Grinter Report, advocates as one of their primary tenets "an integrated study of engineering analysis, design, and engineering systems" (Grinter, 1956, p. 74). The National Academy of Engineering (NAE) and Accreditation Board for Engineering and Technology (ABET) both promote systems thinking for engineers. ABET (2007) defined engineering design as follows, "Engineering design is the process of devising a system, component, or process to meet desired needs" (p. 3). NAE (2005) called for the next generation of engineers to be global, (or systems), in their thinking and practice. Support for systems thinking in engineering comes from researchers, practitioners, and preeminent national organizations alike. Katehi et al. (2009) in their work on K-12 engineering education stated, "one crucial idea that appears regularly... is the concept of *systems*" (p. 42).

Katehi and colleagues (2009) explained that a system "is any organized collection of discrete elements designed to work together in interdependent ways to fulfill one or more functions" (p. 5) and that systems thinking "equips students to recognize essential interconnections in the technological world and to appreciate that systems may have unexpected effects that cannot be predicted from the behavior of individual systems" (p. 91). Systems thinking was defined in this study as the ability to understand the components of a system and their interactions and resulting outputs.

Not all engineering requires systems thinking because not all engineering problems are complex. Structured problems and Newtonian principles are not only present in engineering practice but are also helpful in engineering education pedagogy and content. Furthermore, complex problems may be broken down into subsystems and subproblems for a more simple understanding (Schunn, 2008).

Facets of Complexity and Systems in Engineering Design

Many of the facets of complexity science are found in engineering design. Engineering designers must often consider interconnected, wide-ranging, and non-linear variables. Interconnected variables may be complicated and complex. Complicated systems are elaborate and have multiple variables. Complex

systems may be complicated, but they may also have variables that interact non-linearly and yield emergent properties.

Jonassen (2000) describes design as a form of problem solving that is open-ended and complex. Engineering designs generally have multiple solutions and varying solution paths (Brophy et al., 2008; Eide, Jenison, Mashaw, & Northrup, 2002; Foster et al., 2001). In addition to containing multiple variables, the variables often vary non-linearly along unique time scales. Katehi et al. (2009) stated that aggregate behavior is qualitatively distinct from the sum of behaviors of individual components and indicates a complex engineered system, such as highways, the Internet, the power grid, physical locations of companies in a city, and many others, which are all around us.

Systems Operations Within Engineering Design

Engineering requires that the designer meet multiple, possibly conflicting, requirements or constraints through optimization (Brophy et al., 2008; Cross, 2002; Katehi et al., 2009; Silk & Schunn, 2008). Optimization is generally an iterative process that balances trade-offs. These trade-offs may include the competition of performance versus cost, robustness versus social constraints, and time versus environmental impacts. Iteration is an integral component of optimization and may occur at any point in the design process (Hailey, Erekson, Becker, & Thomas, 2005). Iteration may be understood as the process of revisiting a design for continuous improvement while balancing constraints. Although optimizing trade-offs may impose a substantial cognitive load, the concept of trade-offs can be learned through improved pedagogical and curricular strategies. These strategies may include mathematical modeling and iteration (Silk & Schunn, 2008).

Katehi et al. (2009) suggested the use of graphical visualizations can help students improve systems thinking. Sketching can be used for representation and generation of ideas (MacDonald, Gustafson, & Gentilini, 2007). Anning (1997) stated, "Drawing and the processes by which they are made give us a window on children's cognitive processing which can be as informative as studying their language" (p. 237). Sketching can reduce the designer's cognitive load, "The sketch serves as a cognitive support tool during the design process; it compensates for human short-term memory limitations and at the same time supplements cognitive effort by depicting the mental imagery in a concrete form" (Plimmer & Apperley, 2002, p. 9).

Methods

The Function-Behavior-Structure (FBS) framework was used in this research for representing a design process. It should be noted that Function-Behavior-Structure is also represented in literatures as SBF with different meanings and nuances. As design often involves systems or components that are

part of a system, the FBS framework may be used to elucidate systems thinking. Gero and Kannengiesser (2004) offered a definition of FBS.

1. Function variables describe the teleology of the object, i.e. what it is for.
2. Behavior variables describe the attributes that are derived or expected to be derived from the structure variables of the object, i.e., what it does.
3. Structure variables describe the components of the object and their relationship, i.e. what it is (p. 374).

Kathehi et al. (2009) proffered another definition: “FBS relates the components (structures) in a system to their purpose (function) in the system and the mechanisms that enable them to perform their functions (behavior)” (p. 123).

Kathehi et al. (2009) further stated that the FBS framework is well suited for describing systems thinking this way: “Systems thinking involves identifying parts [Structures], determining their function [Function], uncovering relationships, discovering how they work together as a system [Behavior], and identifying ways to improve their performance” (p. 91).

FBS was first introduced by Chandrasekaran and Milne (1985) in artificial intelligence (AI) design. Gero (1990) further developed the FBS framework. Recently, Gero has applied the FBS framework to engineering students and software developers. Other researchers have expanded the FBS framework to K–12 to understand cognition within complex systems (Goel, 1997; Hmelo-Silver, 2004; Hmelo-Silver et al., 2000). “The SBF framework allows effective reasoning about the functional and causal roles played by structural elements in a system by describing a system’s subcomponents, their purpose in the system, and the mechanisms that enable their functions” (Hmelo-Silver, 2004, p. 130). FBS is not a complete theory for describing the design of systems but rather a framework that aids in the understanding of human cognition in complex systems.

Setting and Data Collection

The students and high school were selected through criterion purposeful sampling. This study included 12 student participants drawn from a high school in the Intermountain West. The high school was selected because it had a reputation for having an exemplary pre-engineering program in the region. The high school recommendation was derived from high school teachers, state administrators, and university faculty from across the region. The students were high school upperclassmen and had taken at least two pre-engineering courses. These students were chosen based on their previous coursework in pre-engineering and their interest in engineering.

Participating students were paired to perform a design challenge. The team size was chosen to maximize verbalization from the students. The engineering design challenge in this study was a double-hung window opener that assists the

elderly with raising and lowering windows. This challenge has been used by Gero (2010) and other researchers to study engineering design. Double-hung windows are commonly used and most students are familiar with window operation and function, so they do not need advanced engineering knowledge or background to complete the design challenge. Additionally, the design encompasses a variety of constraints: technical, ergonomic, financial, and social. The students had access to materials to aid in their design such as a desktop computer with Internet access, engineering graphing paper, and pencils. Similar to Atman's (1998) work, the students were given a time frame, in this case one hour, to complete the design proposal. They did not completely finish the design challenge due to the limitation of time. Instead of presenting practical products by the end of design, participants only submitted design proposals as their final outcomes. There were not instructions about the form or the content of the proposals they submitted. They did not build, test, and analyze their design because of the time constraint.

While working in teams, the students communicated their thought processes through verbal and nonverbal interactions. To augment the collection of students' cognition, audio was supplemented with video (Derry, 2007; Gero & Kan, 2009). While the participants were either analyzing or gathering information independently, or even gesturing, the video helped fill potential data gaps in the audio. The study collected data mainly through protocol analysis. In the process of collaborative engineering design, the conversation naturally occurred and the participants did not need prompting or coaching to verbalize. Researchers recorded participants' conversations by audio and nonverbal interactions by video without asking questions or answering participants' questions. The audio and video data complement each other to provide richer information about the conversations and actions in the engineering design process. The computer tracking data and the participants' sketches also supplemented the protocol data. The participants would often visit a website for information gathering or point to a drawing to communicate to their team member. These non-verbal artifacts were useful for helping bridge gaps in the verbal protocol data.

Post-hoc focus group reflective interviews were administered following the challenge (Zachary, Ryder, & Hicinbothom, 2000). The verbal data from the design challenge and interview were transcribed, segmented, and coded. Additionally, the students produced a design artifact, sketches and notes, from the design challenge that was also included in the analysis. The artifact was not evaluated, but rather used as another source for data corroboration. There was also tracking software that followed and collected the students' movements while on the computer.

Data Analysis

Analysis of the quantitative and qualitative data for this mixed method triangulation research study was performed concurrently. After the audio from the design challenge and the interview was transcribed, the data were segmented and coded by two separate analysts, solicited graduate students (Chi, 1997). The video, computer movements, and sketches were also used to help the analysts reproduce the students' design process in order to segment and code the verbalizations more effectively.

The transcribed student verbalizations from the design challenge were broken down into segments. The segments were then coded using the FBS codes: requirements, function, expected behavior, structure, derived behavior, and description. Excerpts from a design challenge will serve as an illustration of the issues in Table 1.

Table 1
Examples of Design Issues from the Design Challenge

| Utterance | Issue |
|---|------------------------|
| <i>How much do you think fishing line could hold?</i> | Expected Behavior (Be) |
| <i>The crank would raise the window by pushing it up probably</i> | Derived Behavior (Bs) |
| <i>Let's write that negative one down</i> | Documentation (D) |
| <i>That would spread the work out, make it easier</i> | Function (F) |
| <i>Get the window to go up, that's the um bottom line</i> | Requirements (R) |
| <i>Now we got to do the position of the crank and everything</i> | Structure (S) |

Within the FBS framework, the coded segments were termed design issues, and the transition from one design issue to another was termed processes. Table 2 is excerpt from Dyad B during the design challenge that demonstrates various design processes.

Table 2
Excerpt from Dyad B Design Challenge Showing Design Processes

| Student | Utterance | Issue | Process |
|---------|--|-------|------------------|
| 1 | <i>You'd have to have it down at an easy to reach level</i> | Be | - |
| 1 | <i>So you could find where the hooks are</i> | S | Reformulation II |
| 1 | <i>But then you'd have to go um over so you have like a little crank</i> | Bs | Analysis |
| 1 | <i>Like you'd have something.</i> | Be | Evaluation |
| 2 | <i>Then you'd have somebody come up over with like a pulley</i> | S | - |
| 1 | <i>Down on the hook</i> | S | Reformulation I |

To ensure inter-rater reliability, the coding analysts received over 30 hours of training on segmenting and coding in the FBS framework. After the final training, the analysts were able to individually code segments with a percent agreement of 93.2%. Cohen's Kappa was calculated between the coders to be 0.89, exceeding an accepted reliability coefficient of 0.7 in the social sciences (Schloss & Smith, 1999).

Frequency counts and distribution of codes over time for both the issues and processes were analyzed descriptively. The processes were also analyzed using measures of centrality. The measures of centrality used were betweenness, closeness, and degree. Analysis was performed to aid in understanding the relative significance of the issues and processes.

The audio and video data from the design challenge, audio and video data from the post-hoc interview, the tracking data, and the design artifact were analyzed as a whole for evidence of systems thinking. Additional unanticipated themes or phenomena also surfaced during this process. Hmelo-Silver et al. (2000) used a similar methodology in their study. This research was also open to and sought new themes by poring over the data outside of the FBS framework and the resulting segmenting and coding. Deductive themes were derived from the literature in systems thinking. These themes included multiple interconnected variables, emergence, open-endedness, and optimization (Brophy et al., 2008; Eide et al., 2002; Katehi et al., 2009; Schunn, 2008). Inductive themes emerged from the data including graphical visualizations and analogical reasoning. These qualitative themes are discussed later in this paper.

Results

FBS Issues and Processes

The first research question of this study sought to understand cognitive issues and processes used by high school students in an engineering design problem through the FBS framework. There were 1,917 segments coded. Of these coded segments, 1,012 (52.8%) fell within the range and were coded using the FBS framework. The total FBS codes are found in Table 3 with their mean, standard error of the mean, and percentage. The percentages were calculated from the total number of FBS coded segments.

Table 3

Descriptive Statistics for Function-Behavior-Structure Coding

| Code | <i>M</i> | <i>SEM</i> | % |
|------------------------|----------|------------|-------|
| Expected Behavior (Be) | 44.83 | 3.63 | 26.6% |
| Derived Behavior (Bs) | 28.00 | 8.62 | 16.6% |
| Documentation (D) | 15.67 | 3.23 | 9.3% |
| Function (F) | 2.33 | 0.42 | 1.4% |
| Requirements (R) | 4.00 | 0.93 | 2.4% |
| Structure (S) | 73.83 | 9.40 | 43.8% |

Structure (S) was the most prevalent code at 43.8% with the lowest being Function (F) at 1.4%. Nearly one-tenth of the coding was given to the teams documenting (D) their design. This was done through sketching and list making. Note that only utterances that pertained to documentation were coded with (D). There were many instances when the students were “documenting” but they did not verbalize it. Therefore, without an utterance there was no coding attached. The processes were operationally defined as transitions from one FBS code to another. The code transitions were analyzed using descriptive statistics and measures of centrality: degree, betweenness, and closeness. The total FBS transitions are found in Table 4 (next page) with their mean, standard error of the mean, and percentage.

Table 4
Function-Behavior-Structure Transitions for All Dyads Combined

| | <i>M</i> | <i>SEM</i> | % |
|-------------------------|----------|------------|--------|
| Reformulation I (S→S) | 37.00 | 4.73 | 36.69% |
| Reformulation II (S→Be) | 17.50 | 1.95 | 17.36% |
| Synthesis (Be→S) | 16.00 | 1.83 | 15.87% |
| Evaluation (Be↔Bs) | 14.00 | 2.92 | 13.88% |
| Analysis (S→Bs) | 11.33 | 4.70 | 11.24% |
| Documentation (S→D) | 3.83 | 1.92 | 3.80% |
| Reformulation III (S→F) | 0.50 | 0.34 | 0.50% |
| Formulation (F→Be) | 0.50 | 0.34 | 0.50% |

The number of design processes was highest for structures, with the majority being reformulation. Reformulation is a modification or an addition to a design based on the surface characteristics or structure. The participants synthesized their ideas transitioning from expected behavior to structure. The results from the design processes are congruent with the findings from design issues; the participants concentrated on structures and expected behaviors. The participants were able to create ideas, expected behaviors, and synthesize them into structures. However, the amount of analysis (structure to derived behavior) was low (11.24%) when compared to reformulation and synthesis.

Table 5 (next page) displays the results for all measures of centrality for all dyads. Expected behavior (Be) and structure (S) had the highest results for all measures of centrality. Although structure (S) had the highest frequency count, expected behavior (Be) had the highest degree, which is a measure of the number of links or connections to other codes.

Table 5
Mean Centrality Values for All Dyads Combined

| FBS Code | Degree | | Betweenness | | Closeness | |
|----------|----------|------------|-------------|------------|-----------|------------|
| | <i>M</i> | <i>SEM</i> | <i>M</i> | <i>SEM</i> | <i>M</i> | <i>SEM</i> |
| Be | 5.33 | 0.33 | 3.53 | 0.97 | 0.16 | 0.01 |
| S | 4.50 | 0.34 | 3.58 | 0.88 | 0.17 | 0.01 |
| Bs | 4.17 | 0.31 | 1.28 | 0.63 | 0.15 | 0.01 |
| D | 4.00 | 0.37 | 1.64 | 0.66 | 0.15 | 0.01 |
| R | 2.67 | 0.42 | 1.14 | 0.85 | 0.12 | 0.01 |
| F | 1.50 | 0.22 | 0.17 | 0.17 | 0.12 | 0.01 |

Systems and Design Themes

The second research question sought to understand any qualitative themes and phenomena related to the students' systems thinking in engineering design. The qualitative analysis was performed by repeatedly reviewing and analyzing the data sources outside of the FBS framework looking for themes, patterns, and phenomena (Glesne, 2006). The researchers reviewed the data looking for themes. For example, one of the common practices in which the students engaged was using analogies to further understand the problem and communicate ideas to teammates. FBS was not used as a frame of reference for this analysis. Undoubtedly, the FBS framework had influenced the researcher's thinking. However, the FBS framework was not intentionally used or referenced in the qualitative analysis.

The qualitative analysis involved looking at all data sources in tandem. All of the videos were viewed to get a feel for the study. Following the viewing, the videos were analyzed along with the transcripts, the computer movements, and the corresponding sketches by dyad. The results of this analysis yielded three new inductive themes: sketching, analogous reasoning, and design challenge relevance. These themes were then identified and situated in complexity and engineering design literature. Deductive themes were also derived from the literature including: multiple interconnected variables, emergence, non-linearity, optimization, and open-endedness (Davis & Sumara, 2006; Dym et al., 2005; Schunn, 2009). With the themes identified, the data sources from all dyads were analyzed against themes listed above. This section will discuss and attempt to interpret these themes.

Multiple interconnected variables. The students considered multiple variables related to their designs. Not only was each dyad's design solution complicated with multiple interacting parts, they were complex. They were

complex in that the designs included variables outside the technical design solutions. The primary non-technical variable referenced by the students was accessibility. This was followed by aesthetics, physical placement of the design solution, cost, maintenance, and manufacturability. Accessibility was frequently referenced as a design constraint among all dyads. Perhaps the students were able to relate to nursing homes and other facilities and had an idea of the end user. One of the students, Byron, even remarked how his design “would have helped her [his deceased great grandmother] out a lot” in her later years. The students not only made general mention of assistive constraints, they specifically considered arthritis, wheelchairs, and other ergonomic factors. Furthermore, the students in this study belonged to the generation raised while the Americans with Disabilities Act (ADA) was effected and implemented. Although the impact cannot be easily measured, the ADA has had at least indirect, if not direct, impacts on the students’ ways of thinking.

The students also mentioned physical placement of their design solution. Some dyads considered aesthetics and the solution’s placement in the design. Again, aesthetics could be considered another constraint in reference to the nursing home tenants. There were other variables that were only briefly mentioned. These included costs, manufacturability, and maintenance. The latter two were only mentioned once. Perhaps this is due largely to the scope of the design challenge. If the design challenge had actually included production and testing of a prototype, the students would have more likely considered a wider spectrum of variables. The students’ limited references of these diverse constraints does not imply that they were incapable of balancing them in their designs, as they were able to successfully recognize and design to the nursing home tenants’ needs and constraints.

Open-endedness. Engineering designs may be approached through multiple solution paths with varying end products (Asunda & Hill, 2007; Sneider, 2011). The students in this research investigated multiple alternatives and variations on their final design. Altogether, the students generated 14 possible design solutions. Not every dyad contributed an equal amount. Dyad F generated six unique ideas, while Dyad D produced two. Interestingly, these same dyads represented the top and bottom of the range for analogies generated, 17 and one respectively.

All of the dyads considered a pulley system in their design, with four dyads using pulleys as part of their final design solution. It is not certain why pulleys were so prevalent in their designs. Their instructor was consulted on this finding. He stated that pulleys did not receive more attention than other topics in the curriculum. Even though the students’ designs converged on pulleys, the students considered other design alternatives and compared them to each other. Eric and Eddie were a prime example as they wrestled back and forth with which of their four main ideas they would use. They finally decided upon a solution that blended their distinct ideas. Other dyads combined the ideas they

generated to produce a final solution. These students demonstrated that they can generate and compare alternative ideas.

Optimization. The students optimized their designs seeking to balance competing constraints. The students had to make trade-offs between technical functionality and either costs or aesthetics. What appeared to be trade-offs often led to an improved design. Examples included a rope being traded for a transparent high strength cord or the ergonomic placement of a manual crank by Dyad B. From the data, it may be deduced that the students were continually reevaluating and improving their designs.

Within the dyads, the students had to balance the competing ideas among themselves. Each dyad had positive conflict resolution. The conflict often led to better or improved ideas. Dyad A consisted of a boisterous, outspoken senior, Anthony, and a reserved junior, Andrew. There were many instances when Andrew's suggestions appeared to be ignored. However, Andrew persisted and was eventually able to implement his ideas in the design. For example, early in the design challenge Andrew suggested the idea of a large push button. It was not until much later in the design that Andrew was able to have his idea considered. Eventually, Dyad A was able to implement the push button into their final design. This small conflict did not create contention. As a matter of fact, when the design challenge began to wind down, the one turned to the other and said, "We're a great team dude!"

All the dyads in this research study iteratively optimized their design solutions. This was evident throughout the design challenge. If the students had further personal experiences with a sash window and its construction, perhaps they would have worked with a deeper level of comprehension with the competing constraints inherent in this design challenge.

Graphical visualization. Sketching and annotation were used by all students throughout the engineering design challenge. Sketching is helpful when understanding and analyzing a system (Katehi et al., 2009; MacDonald et al., 2007). For example, Brody suggested the idea of a crank, but he recognized that there was a challenge in using a crank to move the window up and down. So, his teammate Byron attempted to tackle the problem.

Byron: Well, what I was thinking... [pause] you could... [pause] and this is a little complicated.

Brody: Okay, we just have to draw it out.

After Byron struggled to articulate his ideas, Brody realized that sketching their design would be helpful.

Sketching was not just limited to offloading cognitive effort, it was used to generate, develop, and communicate designs. Dyad C applied sketches and list making to brainstorm their ideas, see Figure 2 (page 69). Sketching was also applied to develop and optimize the students' designs. Sketching was further employed to communicate ideas and designs to each other and the "client." Sketching was the primary tool, physically and cognitively, exploited by the

students. Albeit, the computer was used for information gathering and concept verification, the depth and breadth of the use of sketching was vast in the students' design process. The results of this study are congruent with the literature in that graphical visualization plays an important role in engineering design (Anning, 1997; Katehi et al., 2009; MacDonald et al., 2007). Therefore, educators might do well to use sketching and other graphical visualizations more effectively in their curriculum.

Analogical reasoning. The students used analogies to help themselves and others understand their ideas. Analogies were also used in design development. The total number of analogies used by all the students was 38. Without much technical experience with windows or assistive design, the students drew upon their experiences through analogies. In the post-hoc focus group, the students were asked how they generated different ideas.

Fred: We tried finding examples. We used a screw driver, a crane, blinds, car jack. [We] just tried finding things that we already used.

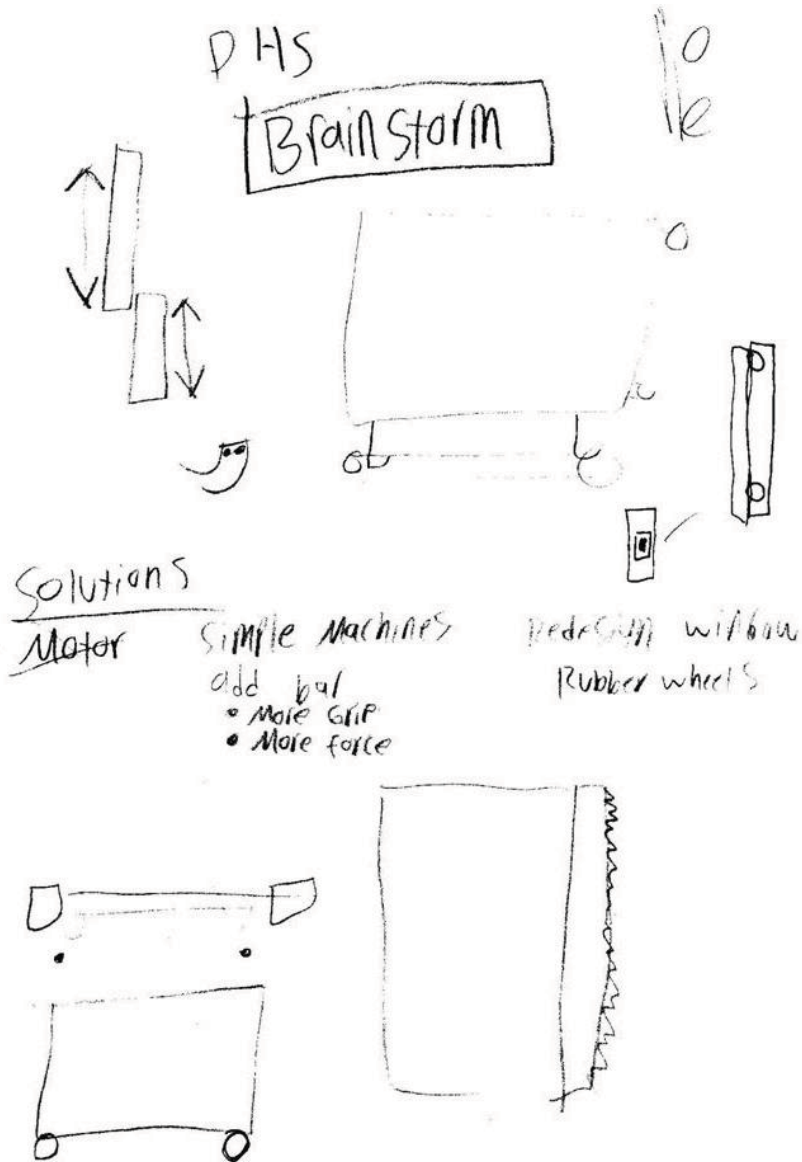
Forrest: Me and my dad go around the house—projects—we mess with stuff like that. [We] never had to mess with windows, though we have sliding windows that push up. I also got my ideas from a snow boarder binding system.

These students were explicit about drawing from their episodic memory. However, analogies do have limitations. It is possible that a fallacious analogy could be used incorrectly and in turn propagates misconceptions. Additionally, not all students have the same background or experience. Hence, an analogy that works for one student may be completely irrelevant to another. In spite of the limitations analogies pose, their use with students should be capitalized on.

Relevance. Students, particularly K–12 students, tend to be more engaged in a design activity if it is perceived to be relevant and pertains to the student's everyday life (Brophy et al., 2008; Sadler, Coyle, & Schwartz, 2000; Svensson & Ingerman, 2010). Overall, the students favorably spoke of the design challenge's relevance. Their comments included, "cool", "fun", and "interesting." The design challenge also "had real life application" that pertained to the students. Some of the students took ownership of their designs by spontaneously naming them. Furthermore, the design challenge scope was not overly restraining and was simple enough for the students to understand (Sadler et al., 2000).

Figure 2

First page of sketching by Dyad C. The figure shows the students' sketches, brainstorming, and development of ideas, such as pulleys and rack gears



Implications for Engineering and Technology Educators

This study is limited in that the participants were students from one pre-engineering program. Therefore, the reader is encouraged to reflect on how the findings from this study may be applicable to their unique situation through naturalistic generalization. From the results of this study, engineering and technology teachers may infer that systems thinking can be learned by students as it relates to the FBS framework and other phenomena. That is not to say that the instructors and students alike have to be trained in all of the details and nuances of Gero's FBS framework. Although the nomenclature of FBS may not need to be taught, the underlying concepts and thinking of the FBS framework could lend to enhanced systems thinking (Katehi et al., 2009). Hmelo-Silver and colleagues found that sixth grade students were capable of systems thinking, albeit, quite limited (2000).

Structures constituted the dominant cognitive activity in this study. Expert designers have also relied heavily on structures in previous studies (Gero & Kan, 2009; Kan & Gero, 2008). Experts often considered and employed functions and behaviors to create their designs as well. Therefore, students should be encouraged to go beyond the structures of a device or system while designing. The students did not receive explicit training in systems thinking, let alone in the FBS framework. Nevertheless, the students in this study were also able to consider behaviors, particularly when transitioning from one thought to another.

Expected behavior was pivotal in the students' cognitive processes. The participants in this study relied heavily on expected behaviors when transitioning to other FBS codes. In the FBS framework, *expected behavior* is defined as the designer's expectations for the structure; in other words, what the solution does, or what it could do. Examples of expected behavior from this study included,

(Be) So it will slide up easier

(Be) Yeah, so it's like, does it like lock and you open the window halfway or some way

(Be) Crank that one over and it will roll down

Expected behavior often includes idea generation. The students in this study often used expected behavior, suggesting that high school students from similar backgrounds might also be able to exploit this ability.

Curriculum and pedagogy with systems thinking could help the students discover the purposes (function) of a device and explore how those purposes are achieved (behavior). For example, when investigating and learning about pulleys, the teleological aspects could be addressed. The teleology may include mechanical advantage, hoisting, or rappelling. The purposes could also be made contextual, ranging from an assistive window opener to cranes or even mountaineering. Relevant behaviors, such as securing a load, reducing friction,

and providing an ergonomic feel, may be examined as well. However, curricula with a systems focus are not widespread in K–12.

In addition to discussing and teaching functions and behaviors, interconnectedness of variables can be explored. The students from this study were able to consider multiple variables and also noted that these variables interacted within the design. For example, one dyad realized that a manual crank was not aesthetically attractive below the window. Moving the crank to the side of the window not only created a more attractive design, but also allowed for one less pulley and easier access for the tenants. The results of this study do not suggest that students will address all germane variables, as maintenance and manufacturability were only addressed by two separate students. Recently graduated engineers moving into industry are not expected to know every aspect and variable about their new responsibilities (Lang, Cruse, McVey, & McMasters, 1999). Even an experienced and expert engineer has to frame the problem. What then is to be expected of a high school student in engineering design with regard to multiple interconnected variables? Clearly, students will not be able to identify and design for all variables. However, the students should be taught that there are multiple factors in a design that likely interact. Furthermore, instructors could instruct the students that among all the variables there are those which are salient and those which are not.

Quite noteworthy was the finding that all students consistently recognized the human variable in their designs. Perhaps the design problem was sufficiently pertinent such that the students could relate to and visualize it. Many of the students commented on how interesting the design challenge was to them. These students had no experience with window design or maintenance and were only vaguely familiar with the intricacies involved. Yet, the students have all used a window before; albeit, not sash windows. Considering these points, the students were able to some degree relate to or imagine the end user's perspective. After Dyad A had decided on an initial design, they began to further visualize their design.

- Andrew: If they're too old to even push down on it, they can just lean on it.
- Anthony: Yeah.
- Andrew: And if they get bored...
- Anthony: Lean on it.
- Andrew: If they fall asleep, guess what? They'll open the window a little bit too.
- Anthony: Okay. I want to take this a little bit further. This window is not safe for elderly use.

The students are not only capable of including the human factor in their design, but they should be encouraged to extend to other non-technical variables as well (NAE, 2004).

The students engaged in sketching throughout the entire design process, with an increase toward the end of the design challenge. Students should consider the use of sketching to not only communicate ideas but to generate, develop, and optimize ideas and designs as well. The sketching does not have to be precise or expert. As Byron stated, "it's not the ability, just get the idea across." Too often, sketching is merely used to communicate ideas (MacDonald et al., 2007), yet research has shown that drawing is integral in engineering design (Bucciarelli, 1994). Not all educational activities need a formal assessment. Sketches to aid in design could be assessed formatively without a grade assigned. Teachers may also want to increase how often sketching is performed.

Sketching is not only helpful in design; it likewise assists the students in systems thinking. The abstractness and looseness of sketching allows for adaptation and divergence. Furthermore, the sketch can offload the cognitive stresses related to complexity. Sketching is not limited to a pencil and paper drawings. There is an array of multimedia tools available to students in design; however, this research did not allow students to use computer aided drafting tools. Results from previous research were mixed in regard to the use of computer aided drafting (Denson, Lammi, Park, & Dansie, 2010).

All of the students in this study considered multiple alternatives in the design challenge. The curriculum in the pre-engineering program included the use of decision matrices; however, not one team used an annotated decision matrix in their analysis. Educators should carefully consider how to instruct students on developing design alternatives and how to make informed decisions regarding such. Perhaps the underlying principle is continuous improvement. Optimization, iteration, and evaluation of competing constraints have the end of an optimal design. There are many models of continuous improvement in industry such as Total Quality Management and Six Sigma from which instructors may draw.

Educators should help students draw from their own experience when designing. Analogous reasoning can help the students understand the many abstract science and math concepts in engineering. Analogous reasoning is often used in engineering design and should be included in engineering design curriculum and instruction (Christensen & Schunn, 2007).

Systems thinking is an important concept in engineering design (Asunda & Hill, 2007; Brophy et al., 2008; Dym et al., 2005; Katehi et al., 2009; Mehalik & Schunn, 2006). The implications for systems thinking are expansive and broad. This study was able to focus on a portion of systems thinking, particularly through the lens of the FBS framework. The implications for educators include focusing on deeper concepts and behaviors, multiple variables and their interactions, optimization, sketching, and analogous reasoning. Most salient is the finding that students in this study were capable of thinking in terms of systems.

Conclusions and Recommendations

This triangulated mixed methods research study is a viable approach for studying student thinking in terms of systems. Although there were limitations with this study, all of the data sources combined to recreate the students' design process and shed light on the students' system thinking. Hence, qualitative and quantitative themes emerged through the use of triangulated data coupled with analysis in the FBS framework.

This research attempted to collect data in an environment close to the students' everyday classroom settings. The students worked with peers in their engineering classroom while working at their computer workstations. The students were aware that they were being audio and video recorded along with their computer movements. However, when asked in the interview, the students stated that the recording equipment was not imposing or distracting. Additionally, the researcher in this study did not hover over the students. The students were accustomed to working in teams and rarely sought help. The researcher was always present for any questions, yet the researcher purposefully moved to the other end of the room from the students. The students were aware and took advantage of the freedom to move about the room. The environment where data is collected is important as it affects the students' context and attitudes as well as research validity. As a researcher, small efforts to accommodate the study participants may yield more trustworthy and valid results.

The findings from this study demonstrated that high school students are capable of systems thinking in an engineering design challenge. The students' systems thinking was demonstrated through FBS analysis and complexity themes alike. Although the high school students focused primarily on structures, they also referenced behaviors. From the analysis of the measures of centrality, it was found that expected behavior played a pivotal role in the students' cognitive transitions. These results suggest that the students looked beyond the façade of their design and delved into its anatomy and operation.

Engineering design is by definition rarely performed in isolation, i.e., isolation from other designs, networks, systems, or humans. Dym (2005) goes so far as to say that all design is systems design. If systems are so pervasive in engineering design, then what is to be taught that is unique to systems thinking and how will it be delivered? Foster et al. (2001) have been able to successfully include complexity thinking in their undergraduate engineering curriculum. However, can systems thinking be taught to high school, or even K–8 students? Jacobson and Wilensky (2006) claimed that students can learn to think in terms of complexity at some level. The findings from this research study have shown that high school students can think in terms of systems. However, this study does not claim to know how this capability was developed. This research could

not only provide insight to researchers in engineering and technology education but to educational practitioners as well.

This research could provide a springboard to additional research studies, including a larger sample of students from diverse schools using distinct engineering curriculum. Qualitatively, different schools and different pre-engineering programs could be included. Undoubtedly, students from other pre-engineering curricula would have unique language, techniques, and themes. Quantitatively, a larger sample size would yield a higher statistical power. Additionally, a larger sample size would also allow for inferential statistics to be computed and analyzed. The range of students studied could also be stratified by year in school and academic performance. Questions to be answered could include: How do seniors in high school differ from freshman? How do non-engineering students in high school compare to pre-engineering students? This study could also inform experimental research that investigates system thinking interventions. Systems thinking is not unique to engineering design. Other studies outside of engineering might also benefit from the FBS framework and other systems perspectives.

Other perspectives and frameworks of engineering design could be investigated, such as collaboration, creativity, and the use of the computer for sketching and information gathering. The scope of the design challenge could also be expanded by allowing the students to build, test, evaluate, and redesign.

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