AC 2011-1808: THINKING IN TERMS OF SYSTEMS THROUGH ENGINEERING DESIGN

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Thinking in Terms of Systems through Engineering Design

Abstract

The essence of engineering is design. Design may yield an artifact, system, or process to realize an opportunity or to satisfy a problem. Engineering design is complex and typically set within a system that may be interwoven into other systems. Furthermore, engineering designs are often non-linear, iterative, and contain multiple interconnected variables. Therefore, thinking in terms of systems in engineering design is a required skill for the successful engineer's tool box. The aim of this research study was to understand high school students' systems thinking when engaged in an engineering design challenge. Specifically, emerging qualitative themes and phenomena related to systems thinking in engineering design were explored and analyzed.

This study included 12 high school students. The students were paired into teams of two to work through an engineering design challenge. These dyads were given one hour in their classrooms with access to a computer and engineering sketching paper to complete the design. Immediately following the design challenge, the students participated in a post hoc reflective group interview.

The methodology of this study was informed and derived from cognitive science's verbal protocol analysis. In this research study we gathered multiple forms of data and triangulated these data in our analysis. These forms included audio and video recordings of both the design challenge and the interview, computer tracking, and student generated sketches. Additionally, qualitative analysis techniques were used to understand and interpret systems and engineering design themes and findings.

Through the qualitative analysis, it was shown that the students demonstrated thinking in terms of systems. The results imply that systems thinking can be part of a high school engineering curriculum. The students considered and explored multiple interconnected variables that were technical as well as non-technical in nature. The students showed further systems thinking by optimizing their design through balancing trade-offs of non-linear interconnected variables. Sketching played an integral part in the students' design process as it was used to generate, develop, and communicate their designs. Although many of the students recognized their own lack of drawing abilities, they understood the role sketching played in engineering design. Therefore, graphical visualization through sketching is a skill that educators may want to include in their curricula. The qualitative analysis also shed light on analogous reasoning. The students drew from their personal experience in lieu of professional expertise to better understand and expand their designs. Hence, the implication for educators is to aid the students in using their knowledge, experience, and pre-existing schemata to work through an engineering design.

Introduction

Engineering design thinking is a topic of interest to engineering education practitioners and researchers alike[1-4]. Engineering design is a complex process that often requires systems thinking. Systems thinking, for the purposes of this paper, is the ability to understand the components of a system, their relationships to each other, and their interactions.

Due to the nascency of systems thinking in engineering education research there are few studies that have investigated systems thinking in engineering design; especially in the K-12 context. Therefore, how high school students employ systems thinking processes and strategies is not adequately understood or identified. Hence, there is a need for research in systems thinking within engineering design at the K-12 level[5].

Literature Foundations

Engineering Design

Engineering design contains multiple systems themes: optimization, global perspective, and complex variables, such as social, political, environmental, and economic factors. Design is also dynamic and iterative, therefore, it is not easily represented by simplistic linear models[6]. Jonassen[7] designates design as a distinct type in his “problem type taxonomy.” Design is not only listed as complex and ill-structured, but it also requires higher order problem solving skills.

There are diverse models of design varying in complexity and scope[8-14]. One simple perspective asserts that design has a problem and a solution space[8]. Design typically commences with defining the problem space[14]. The purpose of defining the problem space is to gather pertinent data, delineate the overall goal, and create an initial plan or “next steps.” The designer then moves from the problem space to the solution space[8]. However, the process may move back and forth between the problem and solution spaces iteratively as new insights or constraints are gained. Engineering design typically entails the resolution (trade-off) of the designer's goal, natural and physical laws, and the criteria set forth by clients or other external parties[15]. The external criteria are often constrained and associated with resources, such as capital or time[9].

Jonassen[16] further asserts that as a problem type, design skills are influenced by domain knowledge, cognitive skills, and affective traits. This is supported by Ericsson[17] who states that the affective traits, focus, and commitment are also factors in design. Through the lens of an ethnographer, Bucciarelli[18, 19] described engineering design as a social process. The National Academy of Engineering (NAE) clearly stated that engineering education was deficient if it did not include the global perspective in engineering design such as social, political, and environmental issues[20, 21]. The global perspective of engineering involves viewing design from the whole systems level rather than from an isolated modular perspective.

Facets of Systems Thinking

Systems thinking is a part of engineering design [5, 22]. Systems thinking has multiple facets, a few of which are described below: complexity, multiple interconnected variables, open-ended, and emergence. Engineering is moving from immediate problems such as structural integrity to broader interconnected issues of environmental impact, political implications, and aesthetics[23]. The National Academies have echoed similar sentiments regarding engineering[21]. When science education as a formal subject in US public schools was beginning to take root, John Dewey[24] stated that the curriculum should "arouse interest in the discovery of causes, dynamic processes, [and] operating forces." These dynamic processes could be explored through a systems perspective.

Complexity. As the name suggests, complex systems are not easily defined and have given way to various precepts and constructs. Sweeney and Sterman[25] assert that,

> There are as many lists of systems thinking skills as there are schools of systems thinking… [yet] most advocates of systems thinking agree that much of the art of systems thinking involves the ability to represent and assess dynamic complexity. (p. 250)

Davis and Sumara[26] further concur that complex systems are dynamic and adaptive. Systems are dynamic with respect to time, and these distinct variables may differ 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[27]. Complexity in systems is generally non-linear and unbounded[23, 26]. Most physical and social phenomena at the systems level do not follow a simple cause-effect relationship. Schuun[28] also defines 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 humans as another variable.

Multiple interconnected variables. Many of the ideas and concepts of complexity are found in engineering design. Engineering design encompasses multiple interconnected variables. In addition to the technical variables, such as temperature, load, or electrical current, there are non-technical variables as well. Wulf and Fisher[29] offered a few of the many possible non-technical variables encountered in engineering design: concerns for safety, environmental impact, ergonomics, nature, cost, reliability, manufacturability, and maintainability. It is also worth noting separately that within this class of problems is the human variable[20, 21, 30]. In an engineering problem, the designer has to decide which variables are germane and which are not. Furthermore, the relevant variables might also be analyzed for interactions. Engineering designers must often consider interconnected, wide-ranging, and non-linear variables.

Interconnected variables may be complicated and they may be 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. Furthermore, engineering design is a complex process in itself.

Open-ended. Jonassen[7] describes design as a form of problem solving that is open-ended and complex. Engineering designs generally have multiple solutions and varying solution paths[10, 23, 30]. There is not typically one right answer. Although distinct designs might approach convergence, the process of arriving at the final design could have been sought through drastically unique paths. Ottino[31] stated, “Most design processes are far from linear, with multiple decision points and ideas evolving before the final design emerges.”

Emergence. The behaviors resulting from the interaction of components in a system is termed emergence in engineering design[5]. In addition to containing multiple variables, the variables often vary non-linearly along unique time scales. Katehi, et al.[5] further state, “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, and many others, which are all around us.” An example would be an aerospace launch vehicle with multiple stages. The launch vehicle will experience dynamic temperatures, pressures, and gravitational effects while traveling through distinct settings in the atmosphere into space.

Systems Processes within Engineering Design

Optimization. Engineering requires that the designer meet multiple, possibly conflicting, requirements or constraints through optimization[5, 15, 30, 32]. 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. Although the components in trade-offs may be considered individually to help understand the system, the components often interact with each other, thus, cannot be evaluated independently.

Iteration is an integral component of optimization and may occur at any point in the design process[12]. Iteration may be understood as the process of revisiting a design with the intent of 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 include mathematical modeling and purposeful iteration[32].

Sketching. Katehi, et al.[5] suggest sketching can help students improve systems thinking. Sketching can be used for representation and generation of ideas[33]. Research suggests that the role of representation dominates the role of idea generation in classrooms[33-35]. Garner claims that most drawings are not seen by others; rather, the drawings aid the designer in ideation and idea development. Anning[34] states, “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.” 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.”[36].

Complex Systems in Engineering Education Rationale

Dym, et al.[9] unambiguously state that design thinking is complex and offer 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.[9] further state, “A hallmark of good systems designers is that they can anticipate the unintended consequences emerging from interactions among multiple parts of a system.” 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"[37]. The national organizations ABET, Inc. and the NAE both promote systems thinking for engineers. ABET, Inc[38] defines engineering design as follows, "Engineering design is the process of devising a *system*, component, or process to meet desired needs." As mentioned previously, NAE[21] calls 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 and colleagues[5] explained that a system, "is any organized collection of discrete elements designed to work together in interdependent ways to fulfill one or more functions" 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 form the behavior of individual systems."

Not all engineering requires systems thinking for 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. Additionally, complex problems may be broken down into subsystems for a more simple understanding[28].

Purpose of the Study

The purpose of this research study was to understand high school students' systems thinking when engaged in an engineering design challenge. Specifically, emerging qualitative themes and phenomena related to systems thinking in engineering design were explored and analyzed.

Methods

Twelve high school students were paired into dyads while attempting an engineering design challenge. Verbal reports, as well as raw video were collected to capture the students' cognitive processes and strategies[39]. Additionally, software tracked the students' activity on a desktop computer. Post-hoc focus group reflective interviews immediately followed the design challenge[40]. The audio and video data from the design challenge, audio and video data from the post-hoc interview, the computer tracking data, and the design artifact were triangulated for evidence of emerging themes or phenomena in systems thinking.

Participants

School selection. A high school pre-engineering program was chosen that had open-ended authentic engineering design as part of the curriculum. Authentic was defined as a challenge that was similar to what was experienced in industry: open-ended, realistic constraints, collaborative, and includes an artifact or artifact design. The high school program was chosen through chain sampling[41]. Chain sampling for this research involved asking those "in the know" (teacher educators, graduate students as practitioners, the state office of education) to recommend high school programs. The school was chosen from the Mountain West Region.

The High School had predominantly White students. The school has a certified pre-engineering program using Project Lead the Way curriculum. There are six courses offered that become available to the students starting their sophomore year: Introduction to Engineering, Digital Electronics, Civil and Architectural Engineering, Computer Integration and Manufacturing, Principles of Engineering, and Engineering Design and Development. The instructor was a retired mechanical engineer who had worked for large and small engineering companies.

Participant selection. The participants were chosen through purposeful sampling[42]. The purpose was to work with students who had successfully taken at least two pre-engineering courses. As engineering courses are elective in this region, the students had taken more than one course by choice. The engineering high school students were recruited with assistance from their high school pre-engineering instructor. The instructor began recruitment with the senior level design course and then opened up the study to juniors. Students with the highest number of engineering courses were given priority. The majority of the students selected for this study were upper classmen. Additionally, students were selected for interest and availability as this study was performed during non-school hours. The students were randomly paired from the pool of available students. The students received an honorarium and an additional amount was donated to their pre-engineering program. The money given to the engineering program helped with the procurement of new equipment, materials, and class fees for low socio-economic students.

Context

This study included 12 students, grouped in pairs or dyads. The group size was chosen to maximize verbalization of the participants. "In comparison to quantitative studies, with their emphasis on large, representative samples, qualitative research focuses on smaller groups [samples] in order to examine a particular context in great detail"[43]. Conducting the design challenge at the respective high school accommodated the study participants. The participants attempted the design challenge in a classroom with minimal distractions. The data collection took place outside of the regular school hours, such as after school and on the weekend. Furthermore, the room was arranged to collect audio, video, and computer software movements (keystrokes, web pages visited, and internet searches).

Engineering Design Challenge

The window design challenge has been used by Gero and colleagues with undergraduate engineering students. The window design was chosen because it can be attempted by participants without specific engineering training. Additionally, the design encompassed a variety of constraints; technical, ergonomic, and social alike. The challenge was only complete if the students submitted a design proposal. The design proposal was not specific in how it was to be submitted. The students used the resources available to them: paper and/or computer software. However, the entire design process was not evaluated because the proposal was not built and tested. The design brief was distinct from that used in other engineering design thinking studies, as the participants were not engineers, nor were they college engineering students. Therefore, the participants were asked specifically to produce an engineering design and analysis to provide an engineering context.

The student were given one hour to complete the design challenge. The students attempted the challenge in their pre-engineering classroom during after school hours. The students were given a sheet of paper with links to the related web sites the following text.

> Your design team has been approached by a local nursing home to design a new product to assist its elderly residents.
>
> The nursing home administrators have noticed that changes in humidity during the summer months cause the windows of the 65-year old building to "stick," thus requiring significant amounts of force to raise and lower the window panes. The force required to adjust the windows is often much too large for the nursing home tenants, making it very difficult for them to regulate their room temperature.
>
> Your team has been tasked with designing a device that will assist the elderly tenants with raising and lowering the building's windows. Since each window is not guaranteed to be located near an electrical socket, this device should not rely on electric power.

The related websites included a video on how sash windows function and a link to the Americans with Disabilities Act.

Data Collection and Analysis

“Qualitative research is characterized by the collection and analysis of textual data (surveys, interview, focus groups, conversational analysis, observation, ethnographies), and by its emphasis on the context within which the study occurs” [43]. While working in teams the students communicated their thought processes verbally and through nonverbal interactions. To augment the collection of data to understand the students’ cognition, audio was supplemented with video,[44, 45] computer movements, and sketches. While the participants were independently analyzing, gathering information, or even gesturing, the additional data sources helped fill data gaps in the audio. These data sources used together provided a rich information source from which multiple data were extracted.

The following excerpt shows how the additional data sources helped recreate a portion of one dyad’s design challenge. The *italicized words* represent data from sources other than the audio.

Eugene	Put a pulley here [sketches a pulley on top left of window] so it will go down through there [sketches a pulley on bottom left of window] and another over to the wall [sketches pulley below window] so there's two of them there. So [the cord] runs underneath both of them [glances over to Skylar for affirmation].
Skylar	Yeah.
Eugene	And it goes up to one on the ceiling and over to another one so when they pull it down [motions pulling down a cord], they pull it [the window] down.
Skylar	Yeah and looks like that's a lot of… [turns from sketch to look over at the window diagram displayed on the computer monitor].
Eugene	'Cause if you were to just put one on the floor like this [sketches another pulley], then you have to [gestures two hands lifting together].
Eugene	[We’ll] figure something else for the bottom. [Both students turn to the computer and look up Americans with Disabilities act on wikipedia.com].

Qualitative analysis was performed by repeatedly poring over the data outside of any particular framework. Nevertheless, the analysis was informed by literature in complexity as well as literature in engineering design. The 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. With this step completed, all dyads were analyzed looking for the common themes listed above. As an idea or pattern evolved, all the data sources were analyzed to further understand the phenomenon. This research study was also open to and sought for new themes during the data analysis. Hence, additional unanticipated themes or phenomena surfaced during this process[46].

Findings

The following themes were identified and explored: multiple interconnected variables, optimization, and unboundedness. The results of the analysis yielded new additional themes: sketching and analogical reasoning. The phenomena found in this study will be described below.

Systems Themes

Interconnected variables. Engineering design is a complex process with multiple interconnected variables that are technical and non-technical alike. The human component as designer and client are critical[20, 21, 30]. To understand design, one should not merely focus on the finished product, but should also include the coming together of designers and other key players, the constraints of manufacturing, maintenance of the designed object, and role of the end user[19].

Towards the beginning of one design session, a dyad commented about the complexity of the challenge. All names are pseudonyms.

Eddie	I thought we were only trying to overcome gravity here.
Eric	We are trying to do lots of stuff.

The students in this design challenge considered interconnected variables with a primary focus on the unique end users: tenants of a nursing home with various limited physical abilities. Every dyad was cognizant of the nursing home tenants and made multiple references to their limited abilities during their design. One dyad focused on possible tenants with arthritis.

Anthony	Then we'll have a safe, arthritis–friendly lever.
Andrew	Or if they are too old to even like push down on it, they can just lean on it.

Subsequently, this dyad generated a solution allowing the tenants to lean against a large button on the wall to activate their system. Another dyad took the idea of ergonomics further by considering access by those in a wheelchair. The students were discussing a hand crank as part of their design:

Chuck	Freaky, I think that [a crank] would be too little. I mean, we have like a huge one for the grandmas. A steering wheel even.
Carlos	Yeah, we could even put it at the bottom, so like if they're in a wheelchair too.

When the students made references to the tenants, they most often mentioned terms such as "wheelchair" and "arthritis." All dyads made considerations for the disabled.

In addition to concerns for physical limitations, the students considered aesthetics, physical placement of their design, costs, and manufacturability. These constraints both guided and limited their designs. One student, Byron, commented, "Now, we want to make it aesthetically attractive." All of the dyads discussed placement of their design solution relative to the nursing home facility. Some of the students were also aware of costs and verbalized it. However, costs were not brought up until after the students were further into the design process. Forrest mentioned, "I mean, it doesn't say, but we could probably also think about cost, because they're going to want to go for the price that is not going to break the bank." The students used terms that were common among all dyads, such as "costs" and "expensive." Two of the students also mentioned the manufacturability, "it just seems easier to manufacture to me" and maintenance of their designs, “As long as we got the right tension, you can put it [belt] back on pretty easily.” Although the students mentioned multiple interconnected variables, with the exception of the tenants’ physical disabilities, the students did not make frequent references to these variables.

Multiple solution paths. Engineering design does not have a canned solution or a singular solution path. Rather engineering designs generally have multiple solutions and varying solution paths[10, 23, 30]. There is not typically one best answer. Although distinct designs may approach convergence, the process of arriving at the final design may have been sought through unique paths. The students were not asked to brainstorm or develop multiple solutions. Yet, all of the dyads considered multiple distinct solutions. Most of the solution generation took place as brainstorming towards the beginning of the design process. However, some of the dyads considered divergent solutions as their ideas developed later in the process.

There were a total of 14 distinct design solution ideas among all dyads with (M=4.17, SEM=0.54) and ranging from two to six ideas per dyad. All dyads considered a pulley system in their design. Four of the dyads implemented pulleys in their final design. At least two dyads considered each of the following ideas: pump, lever, lubricant, wedge, jack, and ratcheting system. Within the pulley system, Dyad B investigated and elaborated on multiple other items, such as the cord used to connect the system, Ultra High Molecular Weight Polyethelyne, the crank, gear, and the connection of the system to the window rail. Although each dyad was unique in their solution and solution path, each dyad developed a final solution through iteratively analyzing and evaluating.

Systems Processes

Optimization. Optimization is the iterative balancing of trade-offs to meet multiple conflicting requirements or constraints through optimization[15, 30, 32]. These trade-offs may include the competition of performance versus cost, robustness versus social constraints, and time versus environmental impacts. All dyads acknowledged the trade-offs they encountered in the design challenge. The only explicit constraint for the window design challenge was the inability to use an electrical outlet. Hence, two of the dyads mentioned other sources of electrical energy, solar and battery. However, the one dyad decided against solar energy due to costs. The other dyad implemented battery power without a solution for recharging them. Three of the dyads mentioned the trade-off between technical functionality and costs.

Forrest	They're going to want to go for the price that is not going to break the bank.
Fred	Yeah.
Forrest	[Our idea] defeats the purpose.
Fred	But they last forever. So we need something that lasts more than [we need] something that saves costs.

The students also attempted to balance functionality with aesthetics. Another dyad of students was sketching their design on engineering paper and realized the design was going to obstruct the window:

Byron	We could put a pulley here. There could be a hook in the wall and just have the pulley up there; then we could do the crank down here.
Brody	Yeah.
Byron	The question is, just how to fit that in without blocking the window to much?
Brody	See the crank doesn't actually have to go [on the bottom].
Byron	Put it to the side that's true.
Brody	To the side would probably be better than [the bottom]. [The bottom] would probably be too low.
Byron	That's true and you don't want a rope going across the window.
Brody	Yeah as much as you can avoid, because you kind of, it has to be pulled upward. There are things like see-through fishing line that you don't notice. Is there stuff like that?
Byron	Yeah that's true. That wouldn't be strong enough though.

Brody No, I mean there are things like that. I don't know what might be strong enough.
Byron Oh, yeah. It makes sense.

After this dyad decided to go with a transparent cord, it eventually became part of their final design. All of the students recognized the need to optimize their design through optimization and it usually came through iteratively revisiting their design.

Sketching. Katehi, et al.[5] suggest sketching can help students improve systems thinking. Sketching was the primary activity in which the students of this study engaged. Every dyad spent the majority of their design time sketching. The students were provided with engineering paper, pencils, pens, and erasers. However, the students did not have access to drafting software for this design challenge. Figure 1 is a sample of the students' sketches.

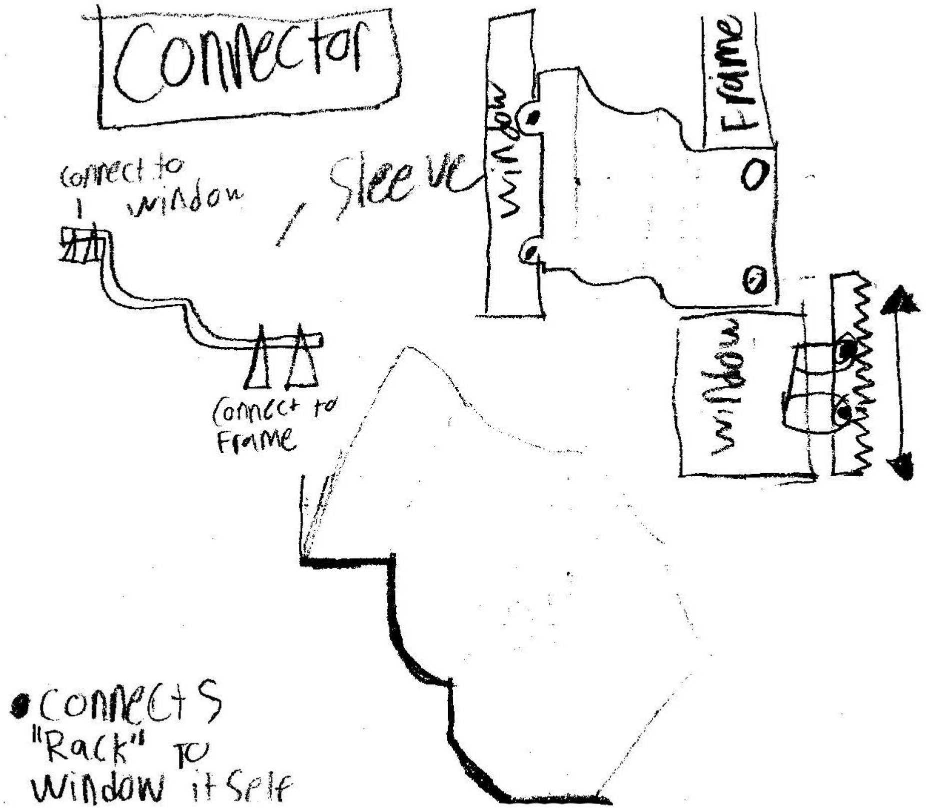

Figure 1. Sketch generated by a dyad of students showing rack and pinion ideas.

The students in this research used sketching in a multiplicity of ways; such as developing a visual dialogue or to communicate ideas among one another.

Derek I just had a thought about what we could have done to make it better. [moves toward drawing] You could have put two of these [pointing to the pulleys on the sketch] and make this [gesturing the crank expanding] wider and put one of them there and one of them there [points to drawing where pulleys will be placed] so that we need only one of the cranks. But... it doesn't matter 'cause we're done. [Pause] Let's see if we can sketch that in.
Dave So you're saying…
Derek So, just make this [crank] a little wider. Draw another piece onto it like that [sketches addition to the crank] for the other ropes so that we only have to have one crank. See what I mean there?
Dave So we only need one?
Derek No, so when we twist it this way [gestures hand turning a crank] it opens up.
Dave Oh yeah.
Derek And then we twist it back the other way.
Dave I like it. I like it a lot!

Derek attempted to explain his new idea through gesture and references to the sketch. However, it was not until Derek actually sketched his idea that he was able to elaborate and communicate it to Dave.

The students also used sketching to present their final design.

Brody Okay, so I would say draw that [crank].
Byron That's about all of my sketching ability.
Brody As you can see, I'm not doing much better.
Byron Well, it's not the ability, just get the idea across.
Brody Yeah okay.

The students' primary use of sketching was to generate, develop (See Figure 1), and optimize their designs. The earlier sketches were more fluid and open to change as it served the purpose of generating and developing ideas[33]. The final sketches were generally meant to describe final designs. Although sketching was not anticipated to play a prominent role in the students' systems thinking, it was evident through each dyad's design process.

Analogical Reasoning

Expert designers draw heavily from episodic memory and experience[8]. Fleer[47] found that children ages three to five used their prior experience to design when they had no familiarity with the challenge. Analogical reasoning occurs when, "problems are solved by reference to previously-experienced situations and the lessons learned from them."[48] Likewise, the students in this study drew from their experiences to aid in their design. However, the students did not have a depth of experience in window design or maintenance as would an expert. Therefore, the students used analogical reasoning to communicate among each other and develop their design. The dyads used a total of 38 analogies, of which 36 were unique. Dyad F contributed 45% (n=17) of the analogies, while Dyad D only drew upon one analogy. One student, Forrest, was cognizant of analogical reasoning and stated, "I can only put a simile to it like, uh, a windmill." Analogies were used in brainstorming and developing ideas as well.

Significance of Findings

Clearly, the students did not have expertise in window design and engineering. This was reflected in their lack of depth and evaluation. However, the students were able to engage in the engineering design process and demonstrated that they were able to think in terms of systems. Therefore, 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.

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. 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[49].

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 the 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.

When persons engage in design, they draw from their previous experiences [50]. Educators could help students draw from their own experience when designing. Perhaps analogical reasoning can help the students understand the many abstract science and math concepts in engineering. Analogical reasoning is often used in engineering design and should be included in engineering design curriculum and instruction[51].

Foundations for Future Research

Although there were limitations with this study, such as the students coming from one high school, all of the data sources combined to recreate the students' design process and shed light on the students' system thinking. Hence, qualitative themes and phenomena emerged through the use of triangulated data.

As this research is emerging, it could provide a spring board to additional research studies. The research could include a larger sample of students from diverse schools using distinct engineering curriculum. Different schools and different pre-engineering programs could be included. Undoubtedly, students from other pre-engineering curricula would have unique language, techniques, and themes. The results from this research provide a foundation for new research that would further elucidate students' habits of mind and action.

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