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Modeling as an Engineering Habit of Mind and Practice

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ABSTRACT

In this paper we examine a case study of a pedagogical strategy that focuses on the teaching of modeling as a habit of mind and practice for novice designers engaged in engineering design challenges. In an engineering design course, pre-service teachers created modeling artifacts in the form of conceptual models, graphical models, mathematical models and finally working models. Data also came from the students' work in the form of student-generated mind maps, design journals, final design products and their accompanying documentation, as well as peer checking procedures. The results suggest that a focus on modeling in an engineering design challenge can be beneficial to both student and instructor. Modeling not only served as a vehicle for representation, but also as an aid in assessment and documentation of students' cognitive processes.

Key words: Modeling, engineering design, pre-college

INTRODUCTION

There are many who advocate for infusing engineering design into pre-college education (Wicklein 2006, Householder 2011, Katehi, Pearson, and Feder 2009). Engineering design is not only embedded in national standards for Technology Education, but it is also found in Science Education with the Next Generation Science Standards (NGSS Lead States 2013, International Technology and Engineering Education Association 2000). Engineering design promises to engage learners in critical thinking and problem solving, promote relevance, and integrate the STEM education disciplines (Wicklein 2006, Brophy et al. 2008, Schunn 2011). However, there are questions on how to successfully integrate engineering design into k-12 learning experiences. This is further confirmed by the fact that there are no nationally established standards for pre-college engineering design. Nevertheless, there is a handful of common themes and concepts in engineering design including: trade-offs, constraints, systems thinking, and modeling (Honey, Pearson, and Schweingruber 2014). In addition to defining and providing pre-college engineering design content, there are also pedagogical issues to be addressed: how to engage students, train teachers, and provide valid and feasible assessments.

In this paper we will explore and demonstrate the utility of a pedagogical focus on modeling and the accompanying artifacts generated in engineering design. The aim of this study was to understand how pre-service teachers reason and work through engineering design with a focus on modeling artifacts. We collected artifacts through an instrumental case study approach of pre-service teachers as student-designers in a second level engineering design thinking course. The student-designers engaged in a service-learning engineering design challenge over the course of a semester. The student-designers produced artifacts in the form of conceptual models, graphical models, mathematical models, and working models. We thematically analyzed and triangulated student-generated mind maps, design journals, final design products, and their final documentation. We additionally employed peer-checking procedures to further triangulate our results. This analysis yielded an approach for engaging in and assessing engineering design challenges for students and instructors respectively. We also provide working definitions and student-generated examples of the four modeling artifacts.

LITERATURE BACKGROUND

Engineering Design

Engineering design has been championed as a pedagogical approach in pre-college education (International Technology and Engineering Education Association 2000, Lewis 2007, Schunn 2008, Wicklein 2006) and has the promise of subject integration, higher order thinking skills, academic rigor, experiential learning, and systems thinking (Hmelo-Silver, Holton, and Kolodner 2000, Jonassen 2011, Katehi, Pearson, and Feder 2009, Lammi 2011, Lewis 2004). Design is a nebulous process that may be perceived from either a scientific or an artistic viewpoint (Cross 2001). Design is dynamic and iterative; therefore it is not easily represented by simple linear models (Mawson 2003). The body of literature on engineering design suggests that engineering is feasible in K-12 education, but it does not provide much insight on novice designers' experiences.

Jonassen (2000) placed design in its own problem type in his taxonomy of problem solving. The processes employed in engineering design encompass a broad variety of topics and fields of study. Bucciarelli (1988), an ethnographer, described engineering as a social process. The global perspective in engineering is part of systems engineering. Systems engineering involves viewing design from the whole-systems level rather than from an isolated modular perspective. Engineering design typically entails resolving the designer's goal and the criteria set forth by clients or other external parties (Cross 2002). Very often the external criteria are associated with resources, such as capital or time. Jonassen and Tessmer (1996) further asserted that as a problem type, design skills are influenced by domain knowledge, cognitive skills, as well as affective traits. Ericsson (2001) specifically pointed out that the soft skills, focus and commitment, were also factors in developing expertise.

MODELING

Modeling is an essential habit of mind and practice for engineering design in the classroom, as well as in the profession (Moore et al. 2013, Carberry and McKenna 2014). The term "habit of mind" refers to a way of thinking, a range of general heuristics and approaches applicable in various situations (American Association for the Advancement of Science 1990, Cuoco, Godenburg, and Mark 1996). Modeling in engineering design is more than the production of a physical representation alone, but more broadly includes the "embodiments of thought processes, insights, and discoveries" (Katehi, Pearson, and Feder 2009, 88). A focus on modeling in engineering education not only helps the student designer but also aids the instructor pedagogically. Focusing on modeling and the accompanying artifacts is a beneficial tool for students to demonstrate their engineering design thinking while developing an essential engineering habit of mind and practice. Lehrer and Schauble (2000, 39) stated, "Models have the fortuitous feature of making forms of student reasoning public and inspectable—not only among the community of modelers, but also to teachers."

Modeling provides an enhanced understanding of engineering and engineering design concepts and processes. This is particularly beneficial when working with complex processes such as understanding systems, a key habit of mind in engineering (Hamilton et al. 2008). Research has shown that engaging students in modeling is an effective approach to advancing their understanding of engineering systems (Katehi, Pearson, and Feder 2009). It is clear that the development of models through engineering activities provides a framework for assessing student performance, but more importantly for the learner it provides a pragmatic approach to representing their design thinking, thought processes, and advancing certain knowledge acquisition.

In creating environments that promote engineering design habits of mind and practice, it is essential to have valid assessment measures of student learning (Bailey and Szabo 2005). When the goal is to observe the process of thinking or the actual behavior of a performance task, authentic assessment is the key. To achieve this, students demonstrate knowledge and skills that closely resemble those required in real life in the form of authentic, real-world problem solving (Bailey and

Szabo 2005). When creating an authentic, real-world client driven problem it is imperative that instructors introduce activities that produce models (Diefes-Dux et al. 2004).

With a focus on modeling in teaching engineering design there are deliverable milestones that facilitate learning, project management, and assessment. Using modeling artifacts allows the instructor and student-designers to successfully navigate open-ended problems systematically. Modeling artifacts provide a practical approach for students to demonstrate their design thinking and decision making processes.

Katehi et al. (2009, 141) state that "iterative, purposeful modeling appears to be central to helping students to a more sophisticated understanding of the salient idea or skill" and this helps students "understand in deeper ways" as "modeling is the most prevalent and challenging form of an activity." From a review of the literature there are four primary modeling artifacts generated in engineering design: conceptual, graphical, mathematical, and working. It should be noted that the generation of an artifact is not the sole purpose or end being advocated in this paper. The process of generating artifacts and the interactions between them is equally if not more important than the product. To facilitate a shift from product assessment to process assessment it is important that student-designers communicate their thought process throughout the engineering design problem. Wicklein (2006) asserts that in order to achieve the goal of assessing student-designers' thought processes through authentic engineering design problems, they should be able to demonstrate the requirements of design producing (1) narrative discussion/description, (2) graphical explanation, (3) analytical calculations, and (4) physical creation. Although semantically varying, Wicklein's assertion proffers that students should be able to demonstrate their understanding of engineering design through the four aforementioned models: conceptual, graphical, mathematical, and working. In order to gain a better understanding of conceptual knowledge and student cognitive abilities, behavior can be demonstrated through the creation of modeling artifacts. According to Jonassen (2000) modeling as a tool is very effective in that it helps learners to represent what they know or what they are learning.

Through a phenomenological study with engineering educators, Asunda and Hill (2007) were able to generate themes or categories of engineering design. All four of the modeling artifacts were mentioned in the thematic analysis. The terms used were: conceptualizing solutions, graphical output, predictive model, and prototype or working model. However, all four of the models were not put together in one idea or process in the literature. Katehi, et al. (2009, 149) also mentioned the four models but added an additional model, "Modeling can take the form of a physical design or a conceptual, graphical, mathematical, or diagrammatic design."

Modeling Artifacts in Engineering Education

The engineering design process usually results in an artifact. The artifact may be a device, system, or a process (ABET 2016). Students most often encounter modeling in engineering design challenges through hands-on experiences. Often, this end product is modeled before final production for testing and evaluation. A model can be a tangible prototype, simulation, or procedure. Roth (1996) stated,

> The construction of artifacts is far more important to learning than simply to motivate students. Materials, tools, and artifacts serve in important ways as structuring resources to design and make sense of the learning environment and as backdrop against and with which students can construct individual understandings and negotiate shared meanings. (p. 163)

Hands-on learning is an important concept in engineering design and is often realized through modeling artifacts. The learning that occurs from hands-on activities is more than just procedural knowledge; the students may also engage in experiential learning (Kolb 1984). Crismond (2001, 193) further states, “Hands-on activities can help students build or reconnect with substance schemas that may be important to doing design and can activate device knowledge and mechanism schemas that naïve designers understand only poorly.”

Pedagogical Focus on Modeling Artifacts

Engineering design is a complex process that does not lend to linear and procedural teaching (Householder and Hailey 2012). The different models do not have to be completed in any specific order. Many of the models are overlapping, such as using mathematical models during ideation to get a sense if an idea will work. Various software programs facilitate mathematical analysis of graphical models. Although the different modeling types are listed in a consistent order for readability in this paper, it should not be assumed that using modeling artifacts to teach engineering design must follow the same linear order. Table 1 is a summary of the different modeling artifacts with common associated terms.

Table 1. Description of Modeling Artifacts

Artifact	Descriptors
Conceptual Model	Ideation, brainstorming, flexible, sketches with annotations, alternatives are discussed, emergence of constraints, specifications, and assumptions
Graphical Model	Representational, feasibility fleshed out, communicates design, dimensions, can support computer simulations
Mathematical Model	Describes how design will work, analysis, testing, informs design, predictive analysis
Working Model	Physical prototype, proof of concept, hands-on, can be a virtual model e.g. software program

Conceptual Model

The germination and expression of a designer's initial ideas and thoughts can be represented as a conceptual model. Although the term "conceptual model" has distinct definitions, this paper draws a consensus from the STEM education literature (American Association for the Advancement of Science 1990, Asunda and Hill 2007, Katehi, Pearson, and Feder 2009). The development of a conceptual model is an exploratory exercise characterized by spontaneity and fluid thinking (MacDonald, Gustafson, and Gentilini 2007). Specific details generally do not emerge from this model. This is the artifact of the ideation phase. The artifact is generally a sketch or other loose visualization. There may be multiple concepts generated to compare one to the other. Examples include sketches, block diagrams, concept maps, and circuit layouts and conceptual models may be produced by various media types such as white boards, napkins, and computer software. Although decisions are made at this juncture, a final decision is generally held for a later period. There is also great flexibility in working with a conceptual model, as decisions have not been made that greatly constrain the design.

Graphical Model

A graphical model is principally representational. This model is usually shared among the design team in order to solidify the details of the design. The design will take on dimensions and interfaces will be defined. At this point in the design process feasibility is often determined. Therefore, this model contains dimensions, clear specifications, and more accuracy. This model may be termed hard-lined, as it is more concrete in its form (MacDonald, Gustafson, and Gentilini 2007). A graphical model is one that is typically – not always – generated with some form of software on a computer. This allows for simulation and testing transitioning into the mathematical model.

Mathematical Model

One of the principal differences between technological design and engineering design is the generation and analysis of a mathematical model (Hailey et al. 2005). The mathematical model may be represented early in the design process in tandem with the conceptual model. However, the accuracy, detail, and rigor of the mathematical model will typically improve over time in the design process. "Mathematical modeling and analysis are essential to engineering design" yet, mathematical modeling is often treated as an afterthought or ignored in K-12 education (Katehi, Pearson, and Feder 2009, 157). A landscape study of K-12 engineering curricula "did not find any projects or units in which students were instructed to develop and use mathematical models to assist them in designing solutions to problems." (Katehi, Pearson, and Feder 2009, 80).

Working Model

Design is a hands-on process that necessitates the use of materials for prototyping and working models (Apedoe et al. 2008). When the design comes to fruition as a "palpable" artifact, it is a working model. However, the artifact might not be physical or materially tangible, it is nonetheless a working model in that it functions according to the design. This model is also known as a physical model, hands-on, prototype, etc. The term working model is used because an engineer does not always produce a palpable artifact, such as a system or process (ABET 2016).

ASSESSMENT

The rigorous assessment of students' design processes is paramount to understanding how to best create an effective learning environment. According to the literature, authentic assessment is identified as the process of assessment when the researcher's goal is to observe the process of thinking (Bailey & Szabo, 2005). A primary goal of the case study was to provide observable evidence of the students' design thinking using models as a representation of their design thinking and decision making. Modeling artifacts may help address the lack of assessment tools capable of measuring the design process (Bailey & Szabo, 2005).

Although it may appear to be counterintuitive, employing a primary focus on modeling artifacts promotes assessments on the process, while also affording assessment on the final product. The key is to not confuse the means for the end; as modeling artifacts are tremendous physical traces of student thinking and learning. The end is not to produce modeling artifacts, but rather have the student-designers gain new habits of mind through immersion in the engineering design process.

Using modeling artifacts allows the instructor to work with students who are dealing with open-ended problems in a systematic fashion. Engineering design is an abstract process that can be messy, but the modeling artifacts give the instructors something to focus on for assessment and project management. One of the most contentious areas of concern for engineering design in high school settings is the issue of assessment. Without developing adequate measures to assess students' design experiences it would prove to be an arduous task to introduce authentic real-world problems to high school students. Modeling artifacts address many of these issues by providing a practical approach for students to demonstrate their design thinking and decision making processes.

A focus on artifacts lends to formative assessments as milestones to be met. Thus, instructor feedback can be given regularly. The student-designers in this study were given a weekly assessment on their design without an associated grade. This was a combination of sending the instructor a project update and face-to-face meetings.

Although modeling artifacts allow for formative assessment, they are also important for summative assessment. The student-designers can submit a final reflection and description of their design process. These final reflection pieces can be framed around the different models produced.

Modeling Artifacts as a Pedagogical Approach

The novel pedagogical approach presented in this paper is the focus on modeling artifacts – as design milestones and assessment touchpoints – to learn and teach the engineering design process. The focus on modeling is not a tangential exercise of design, but an existing, integral part of engineering design. Rather than compelling students through a step-by-step process that is typically linear, the students are given a design challenge requiring them to produce and deliver each one of the modeling artifacts. Producing a modeling artifact serves as a design milestone for the student. Furthermore, the artifact is an embodiment of the student's design thinking and practice. Habits of mind are gained over time and through authentic, immersive effort and experiences (Kolodner 2002). This approach encourages a process that minimizes contrivance.

The instructor informs the student-designers that there will be at least four milestones for the project; each of the modeling artifacts. The instructor typically leads ongoing discussions throughout the project surrounding each type of modeling artifact through prompts. These prompts might include:

- *What is the problem or opportunity you are trying to solve?*
- *Have you considered alternatives for your solution?*
- *What are the potential assumptions, specifications, and constraints for this problem?*
- *What are the details or dimensions of your solution?*
- *How are you going to represent or show your idea?*
- *How are you going to test out your idea? How do you know if your idea is going to work?*

Furthermore, these touchpoints with the student are ripe opportunities for formative assessment. These touchpoints not only facilitate instructor-student interaction, they can also become peer assessments through presentations, discussion, or gallery-walks. The modeling artifacts may likewise serve as framework for a student-designer's design process documentation.

There are challenges associated with a focus on modeling artifacts. First, the pedagogy and instructor mindset must be flexible and adaptable as students may complete the models in no particular order and on their own schedule. A focus on modeling artifacts works best with open ended projects, but may also be used with well defined projects. However, the end goal is engineering design and model based reasoning within that process, not the design artifacts themselves. Additionally, modeling artifacts are great measures of what a student did, but do not inherently include decisions and their accompanying justifications. Reflection in practice is still paramount in engineering design pedagogy (Schön 1983).

DESCRIPTION OF CASE STUDY

Participants and Data Collection Methods

Data were collected in this study in an effort to provide evidence of student design thinking and practices throughout the engineering design process. An instrumental case study approach was chosen to provide insight into the general experiences of model-based reasoning of pre-service teachers in engineering design. In this section we discuss the study participants and the data collection methods.

This study is framed by case study methodology and included the collection of multiple forms of data and the use of qualitative analysis strategies. Case studies are characterized by the study of an issue explored through one or more cases bounded by time and/or place. Data collection in case study research relies on multiple forms of information including: observations, interviews, documents, and audiovisual data (Creswell 2007). The results of this research include a substantial case report detailing, (1) an explication of the problem; (2) a description of the context and/or setting; (3) a description of the processes observed; (4) a discussion of the salient themes; and (5) a discussion of the outcomes (Lincoln 1985). Methods used in this study are consistent with case study methodology and guided the researchers' investigation of students' design thinking while engaged in an engineering design problem.

The study participants for this innovation were pre-service teachers in technology and engineering education working in teams on an authentic engineering design problem. There were 11 student-designers included in this study working in teams of two or three. The primary focus included the student-designers' experiences and understanding of the engineering design process. The challenge required the student-designers to discover, define, and solve a problem for a disability that could be approached through engineering design.

As part of their major course of study, the student-designers participated in two engineering design courses. The purpose of these courses was to prepare pre-service teachers (student-designers) to develop and deliver engineering in and outside their future classrooms. The courses introduced not only basic engineering concepts, but the engineering design process as well. The student-designers participated in engineering educational activities such as designing, building, and analyzing bioreactors, dragsters, model rockets, and assistive technologies. An emphasis was also placed on documenting and justifying their design decisions. Previous to this design challenge, the pre-service teachers were able to learn and engage in an abbreviated engineering design project using a modeling artifact approach. As such, the pedagogical focus on modeling artifacts was previously taught to the pre-service teachers.

The focus of the student-designers' experiences was a cornerstone design of an assistive technology. The student-designers were tasked with discovering and defining a problem for a disability that could be solved by engineering design. Furthermore, they were to design, build, evaluate, and explain their engineering solution for the assistive technology problem. The student-designers typically worked in groups of three. There was one group of two, but we found through previous experience with this population that the student-designers were most successful in teams of three as it allowed them to accomplish the task by spreading out the work without allowing a group member to coast by.

Student Evidence

The student-designers were familiar with the idea of engineering design, but had not been afforded the opportunity to engage in a complete engineering design activity prior to the cornerstone design project. Figure 1 contains two concept maps of engineering design generated by two separate student-designers at the start of the course.

These concept maps suggest that many of the student-designers misunderstood the engineering design process to be linear, with steps to be followed from start to finish. It is worth noting that there were common concepts generated by most of the student-designers including: problem definition, brainstorming, research, testing, and analysis.

CASE STUDY RESULTS

The four design groups were all given the same problem below:

> Discover and define a problem for a disability that can be solved by engineering design. Design, build, evaluate, and explain your engineering solution for the assistive technology problem. Prepare justification and documentation for your project. The design can either be completely novel or build upon existing technologies. You will produce a problem statement and four modeling artifacts: conceptual, graphical, mathematical, and working.

The student-designers were instructed to discover and formulate a problem on their own. The process of formulating a problem is a noteworthy topic that deserves a separate study. After delivering a problem statement, the student-designers were instructed to produce four modeling artifacts and to keep detailed documentation of their processes.

The instructor gave feedback to the student-designers from their weekly project updates and meetings. The student-designers were to share and reflect on three items in their updates: what they did, what they learned, and any questions they might have from that week. The feedback came in

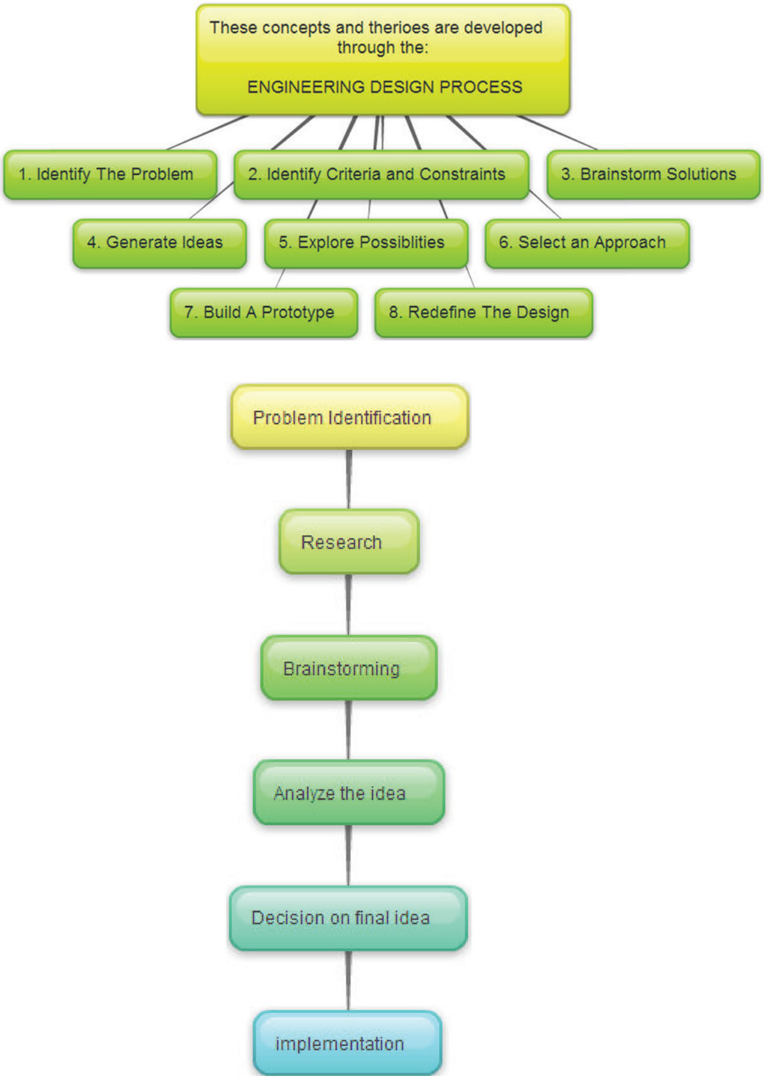

Figure 1. Student-designers' Initial Concept Maps of Engineering Design.

the form of the instructor meeting with each team during the class period. The instructor was able to tailor the feedback based on project updates. However, not all design teams required the same amount of attention. Furthermore, if the instructor came across common themes that needed to be addressed with the student-designers, all teams could be brought together for a whole class discussion.

The weekly updates helped the design teams to develop ongoing documentation of their process. As each group was tasked with developing final documentation, the weekly updates contributed to their final documentation upon completing the project. The final documentation was graded according to a rubric shared with the student-designers at the start of the project. The rubric had six categories – justification, replication, modeling, evaluation, analysis, and format – each with a weighted coefficient descending from 0.35 to 0.05 respectively.

Each modeling artifact will be discussed separately below.

Conceptual Model

Although the student-designers were not familiar with the term conceptual model, they easily went about producing them. The majority of the student-designers produced a conceptual model as a sketch, with some of the artifacts containing annotations. A conceptual model is not limited to a sketch or a series of sketches from a brainstorm. Yet, there were student-designers who presented their conceptual models with minimal effort, compromising a simple sketch or two. Often, there was a lack of detail and justification in the conceptual models. Although a conceptual model does not require exact specifications and high detail, small notes and explanations can aid in the design process by spurring creativity and facilitating communication.

As student-designers' ideas were undergoing frequent change, the conceptual models allowed for flexibility. A team developing a grip-assist technology (Team Grip-assist) began by investigating the needs of disabled children playing on a baseball team. One of the student-designers was a mentor for these children and saw a potential opportunity in developing a design for them. The student mentor initially stated that the disabled children primarily struggled with holding a bat in the upright swinging position. They brainstormed solutions on how they could assist the children maintain a grip on the bat or even redesigning the bat itself. The student-designers then proceeded to observe, work, and talk with the special needs children. The student-designers discovered that most of the children primarily struggled with cognitive and behavioral challenges that would not be easily addressed by engineering design.

The group moved on to a family member's lack of strength in gripping a golf club. Through further research they found an adequate commercial solution had already been developed and marketed. The design group then moved on to helping those with deficit manual ability in carrying heavy objects. After further refining, the student-designers honed in on a specific problem: "We want to create an improved gripping aid in a hook fashion which aids these people in carrying multiple grocery bags without the worry of the hook unclasping." The final conceptual model is seen in Figure 2. The fluid nature of the conceptual model allowed the student-designers to adapt not only the model, but their ideas as well.

Conceptual models often involve more than one solution or alternative. All of the student-designers in this study came up with more than one solution. Not all of the alternatives considered were

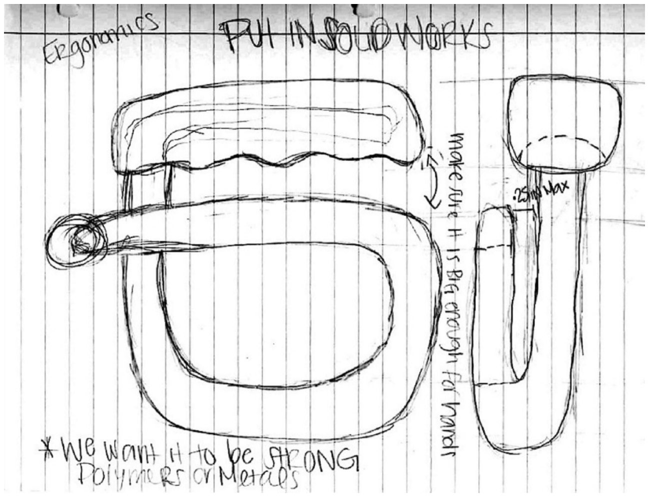

Figure 2. Conceptual Model of an Ergonomic Grip Assist

discussed and analyzed while producing the conceptual model. There were many changes that took place as the design process progressed. Yet, most of the alternatives were developed within the conceptual models. Another team (Team Chair-lift) was seeking to help those with limited strength in exiting a chair. They came up with four variations of an air bladder to lift a seat, see Figure 3. However, further into the design process they came across what they termed a roadblock.

> We found out that we would need a very expensive and industrial-sized pump to produce the required pressure that we need in order for the device to function as expected. So, using a foot pump is out of the question. We started thinking of alternatives to using a pump and air bladder. We focused on using hydraulics just like the other device, just in a more effective way.

As design is an iterative process, the student-designers returned to developing a concept with pneumatics versus hydraulics. The design evolved further to the use of metal springs only. Both of these groups had to produce more than one concept and often returned to the "drawing board" when they came across perceived roadblocks. The conceptual model helped the student-designers to further formulate the problem. By the time the conceptual model was to be developed, the student-designers were to identify the problem, but not completely formulate it. It is here that student-designers listed assumptions, specifications, and identified constraints at a deeper level. These were almost always expressed as simple annotations as previously seen in Figures 2 and 3. The grip assist design group listed out their constraints (limiting factors) and specifications, Table 2.

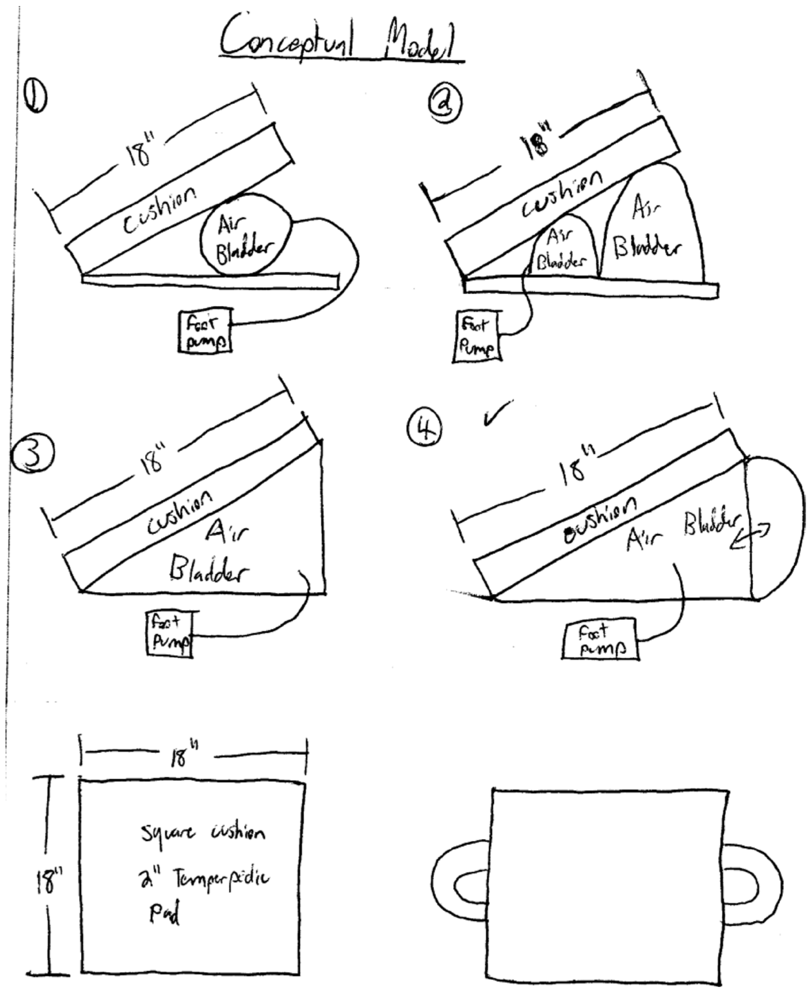

Figure 3. Conceptual Model of an Assisted Chair-lift

Table 2. List of Ergonomic Grocery Bag Carrier Constraints and Specifications

1. Hold the weight of several grocery bags (estimated at 10 kg)
2. Lifespan of at least 5 years
3. Enough room between handle and hook for one's hand
4. Enough room between point and hook to easily slip bags without allowing them to escape
5. Comfortable to hold for extended periods of time
6. Lightweight (Roughly the weight of a cell phone, 145g)
7. Durable
8. Potential unit cost must be low
9. Must have a second life option
10. Must allow those disabled to carry more weight with less pain

One of the greatest frustrations that student-designers experienced was realizing their idea had already been developed. Generally the design groups brainstormed solutions to the identified problem. After generating alternative ideas, either on their own or being prompted from the instructor, they verified and refined their solutions from a web search. The team designing a jar opener (Team Jar-opener) stated,

> From our research on shopping websites such as Amazon.com, we found that there seemed to be numerous other products that had the same basic idea as what we were going for. In the end, we decided to move away from the multi-tool idea all together.

Student-designers had a decision to make, develop a whole new idea or make improvements to an existing product. The instructor had to help the student-designers not become overwhelmed and discouraged as many of the solutions created by the student-designers were creative and they had taken ownership of their idea. It was no longer just a solution but *their* solution. Sometimes they would mentally and conceptually develop their idea and communicate it with their group. One of the constraints of the project is that it had to be original – otherwise it was not considered design, but rather a reverse engineering project. As student-designers began to find problems and solutions they took ownership of their ideas and the design. This presents both positive and negative challenges. The benefits of ownership are understood, but as students become fixed on a solution or even a perceived problem, they may have to emotionally detach from a flawed or infeasible idea.

Sketching is an important part of engineering design, especially in the development of a conceptual model (Yang 2003). Although there was a disparity in drawing ability, each student-design group produced multiple drawings. A similar finding was found with novice high school student-designer as well (Lammi and Branoff 2012).

Graphical Model

One of the roles of the graphical model was to encourage the student-designers to flesh out and refine their conceptual design. Further design details, specifications, and constraints emerged; as well as any obstacles or necessary changes. Team Chair-lift reflected on their project and stated, “Teaching your students that your design is not going to come out exactly the way you planned is crucial. Major design changes are necessary most of the time and more than likely you will have to make them.” Student-designers who allowed for flexibility in their design process developed the most successful projects; as they did not become fixated and limited to one idea only.

Team Grip-assist had to design an ergonomic handle to fit a specified range of hand spans while accounting for those who had deficit manual ability. They considered grips from workout equipment,

Figure 4. Team Grip-assist Measuring Bike Handles with Calipers

looked up dimensions on the Internet, and eventually took a pair of calipers to the bike racks to find standard sized bike handles, Figure 4.

Putting the specifications into a graphical form helped the student-designers to refine their design. It was during the generation of the graphical model that student-designers started to realize that the concept actually had to be built and tested. Team Jar-opener developed a conceptual model of a fully automated jar opener employing two microcontrollers, dc motors, and sensors. The group quickly realized it was overly complex, well beyond their capabilities, and the concept lacked elegance. The group eventually learned from their design's shortcomings stating, "We came to the consensus that there were simply too many potential points of failure associated with our design and moved on to our next idea." Their final design ended up being one simple device completely free of moving parts. As the student-designers had to justify each design decision, balancing the trade-offs between functionality and simplicity, they exercised deeper metacognition.

The graphical model also helped in communicating ideas throughout the overall design – especially when the design was put into a solid modeling program. Furthermore, computer-aided drafting supported multiple views, lending a perspective that might not have been considered before. Another team, Team Golf-assist, was designing a device that would place a golf ball and tee into the ground without bending over. The concept had interactive moving parts to function properly. The student-designers learned while making the graphical model how challenging it was to design a device that would firmly hold the ball and tee in place while being inserted into the ground and then release them without falling over. Figure 5 shows how the level of complexity increased over the design.

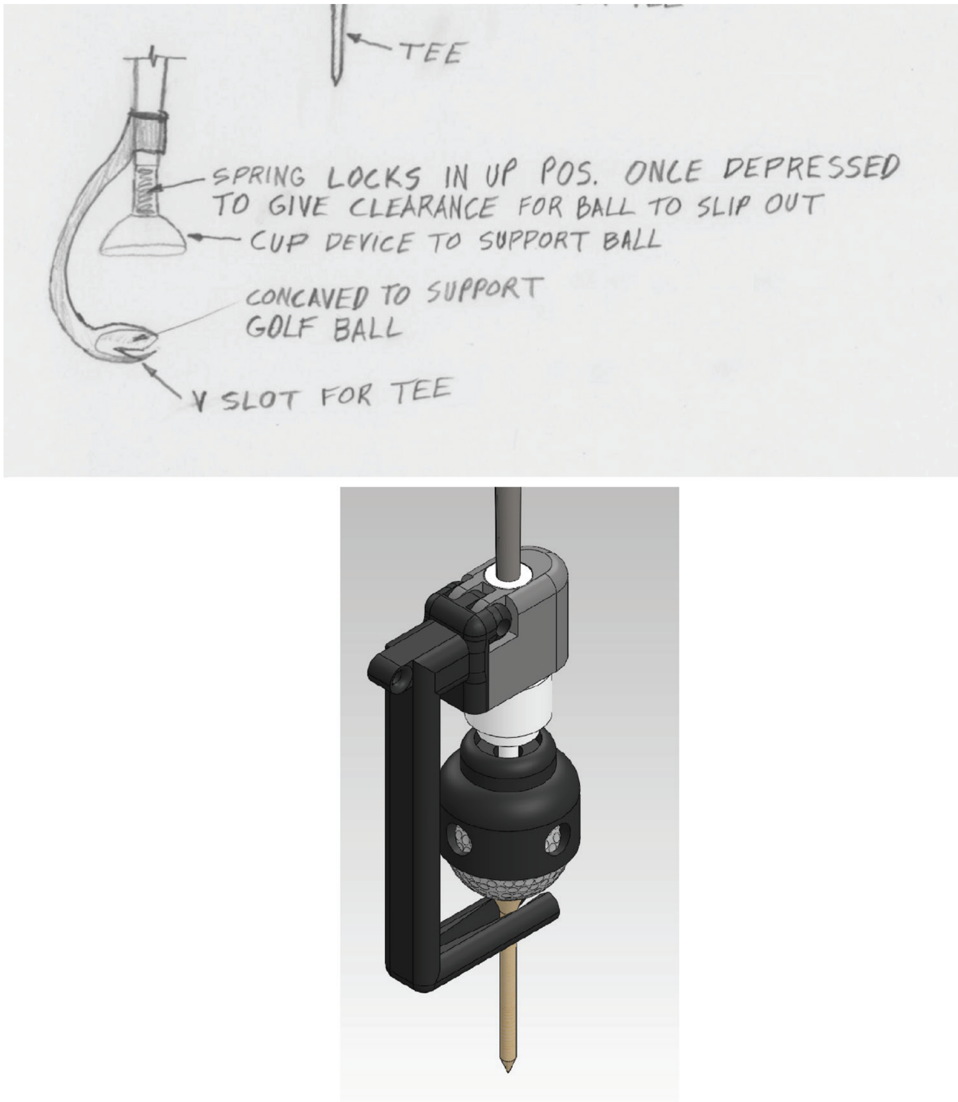

Figure 5. Conceptual and Graphical Models of Golf Ball and Tee Placer

Mathematical Model

A mathematical model can be viewed as a mathematical construct that helps us understand behaviors of interest and real world systems. Mathematical models should be viewed as an idealization of the real world and though they help predict behavior they should not be viewed as completely accurate (Giordano et al. 2009). The mathematical models were the most difficult models for the student-designers to produce. Instead, many of the student-designers wanted to jump straight to a working model. There was already a high comfort level in producing something tangible as all of the student-designers had multiple courses where they developed and produced working models and prototypes. However, creating and applying an abstract mathematical model to their designs was a relatively new practice.

The student-designers had done math in their previous projects, but had not thoroughly applied it. Furthermore, many of them did not see how a mathematical model could be used to improve a design. If they did see how it could help, they often felt that they were not capable of applying math to their design. One of the failed perspectives of the student-designers was viewing math as computations, rather than as a form of problem solving. In lieu of using the mathematical model to make a better design, most student-designers were not able to grasp the purpose of a mathematical model at first. Accordingly, the student-design groups wanted to move forward with a design decision without giving justification for their designs and decisions. An unjustified design often resulted in a flawed or failed design.

Team Golf-assist was creating a tool to be used on the golf course that would allow the golfer to place a ball and tee into the ground without having to bend over. There were three weeks allocated

Figure 6. Graphical Model of Second Golf Ball and Tee Holder

to formulating a problem, but this group came up with a solution by the second class meeting. One student-designer insisted that the problem was understood and that a prototype had to be built to take the design further. His group mates were not settled on the idea, but they moved forward with building the working model. They quickly realized that the initial design had many flaws that were not fleshed out. The device used a string to actuate a lever that held the ball and tee. Once the tee was set, the lever was supposed to leave the ball and tee in place. See Figure 5 above. However,

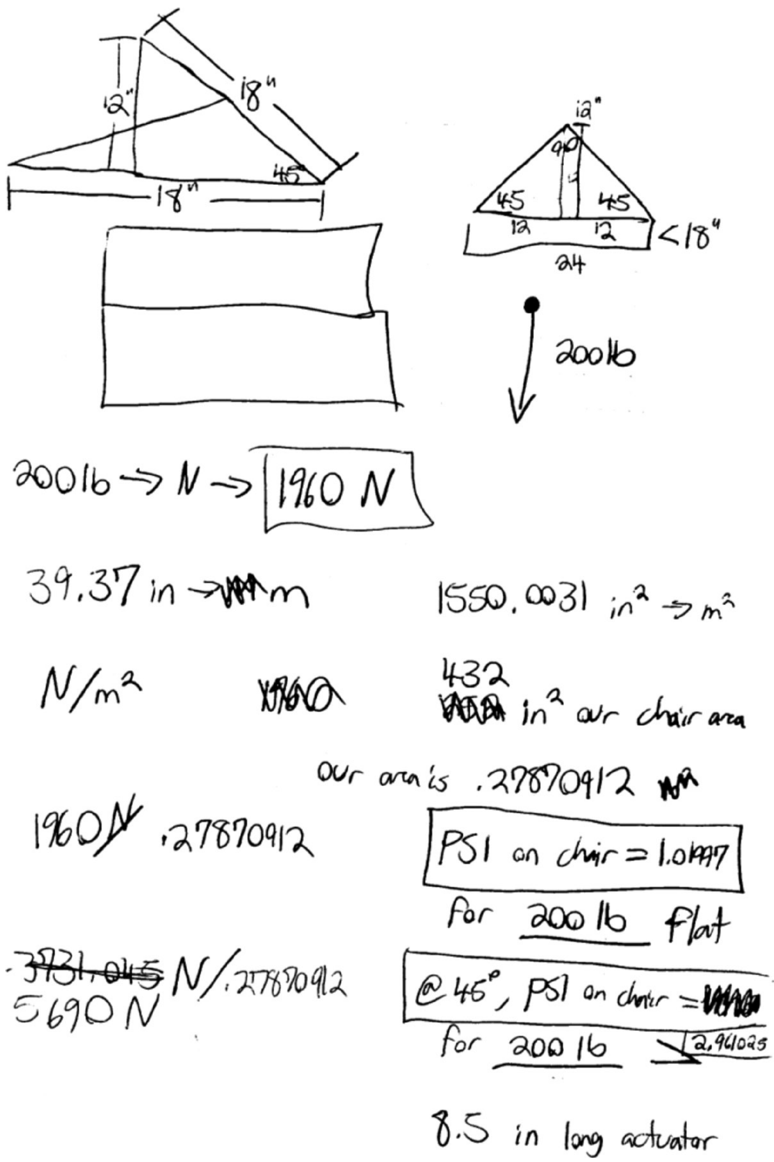

Figure 7. Mathematical Model of Actuators in the Assisted Chair Lift

TERMS
τ = 2.3 Newton*meters (Nm)
r = (6.4/2) + 26.3 = 29.5 centimeters = .295 meters
F = ?
Θ = 90°

$$\tau = rF\sin(\Theta)$$

$$2.3\ \text{Nm} = .295\ \text{m} * F * \sin(90)$$

$$2.3\ \text{Nm} = .295\ \text{m} * F$$

$$\frac{2.3\ \text{Nm}}{.295\ \text{m}} = F$$

$$\boxed{F = 7.797\ \text{Newtons}}$$

Figure 8. Geometric Torque Calculations of One-handed Jar Opener

the lever either did not release the tee or it knocked over the ball when being removed. The group built another prototype, but found "several more issues with getting the golf tee to stay straight and go into the ground."

The other group members insisted that they "should do a second design because of its simplicity of no moving parts. It was a half egg shaped cup that holds the ball and tee." Figure 6. As the group developed another concept, they eventually ran up against the deadline. If this group had not been so hasty in building prototypes, but rather spent more effort in understanding and modeling their concept, they felt "that with a bit more time and engineering [they could have] fixed the issue of the ball falling out."

Although the student-designers struggled with mathematical modeling at first, they were able to successfully incorporate them into their designs. Team Chair-lift's first conceptual design was to use an air bladder to lift a seat. They calculated the size of the seat, position of the air bladder as a wedge, and the amount of air pressure required to lift a 90-kilogram person, Figure 7. While doing

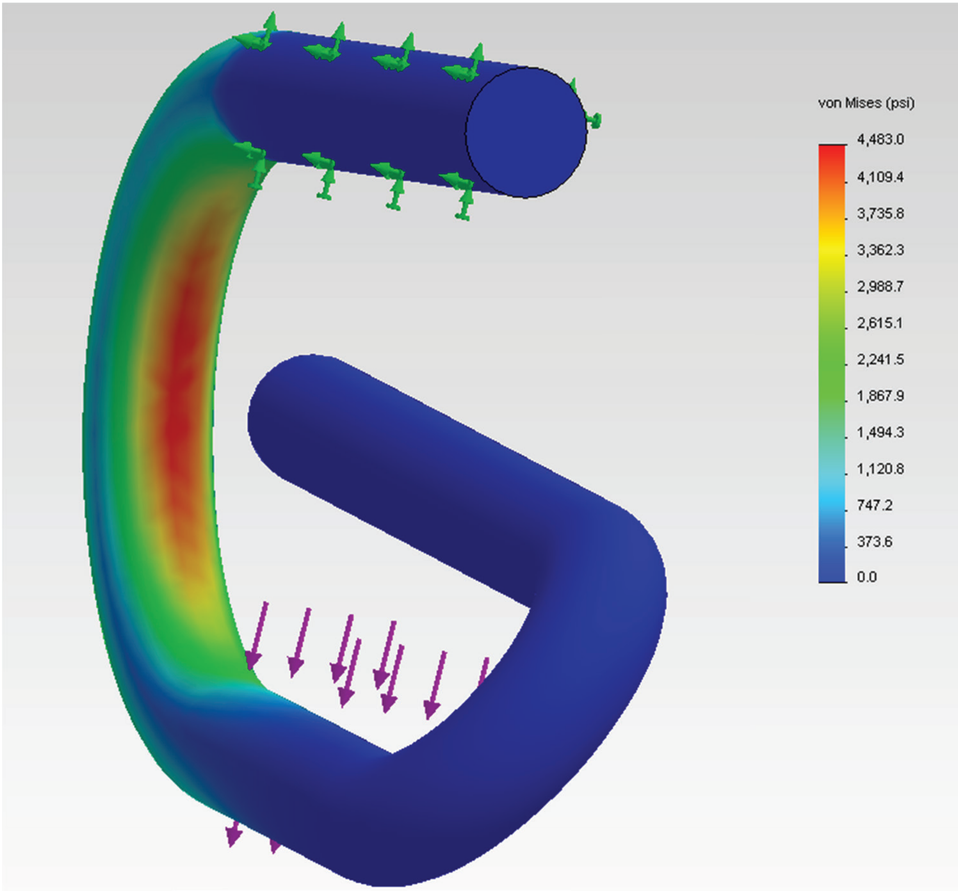

Figure 9. Simulated Stress Test in Solid Modeling Program of Grocery Bag Carrier

these calculations and mathematical modeling they realized they would "need a very expensive and industrial-sized pump to produce the required pressure that we need in order for the device to function as expected."

Moving to their second concept, pneumatic actuators, they began to work another mathematical model. This model looked into the length and position of the actuators and loads on the device.

Team Jar-opener had to keep the device stationary while one hand was removing the lid. Therefore, they realized that they needed to know what forces were acting on the device. The student-designers figured that they needed to create enough friction to counter the torque being generated by the twisting off of the cap. The design group had to make some assumptions as to how much force was needed to remove a typical lid. Through testing and researching other engineering sources, they were able to find the torque and static coefficient of friction between the device and a glass jar and the surface upon which the device rested, such as a countertop or table. These student-designers did not have experience in dynamics beyond their physics course, but they persisted and were able to make a basic mathematical model informing their design, Figure 8.

The results of the student-designers' mathematical modeling helped optimize the device's dimensions, type of material used, and mitigate points of failure. Testing, simulations, and analysis were also facilitated with the mathematical model. The graphical model produced digitally lent to simulations that were already resident on the program. These included deflection, stress, and mass properties analyses, Figure 9.

Working Model

A working model is defined as a realization of a design, whether physical like a prototyped device or a non-tangible system expressed in software. The student-designers were encouraged to produce

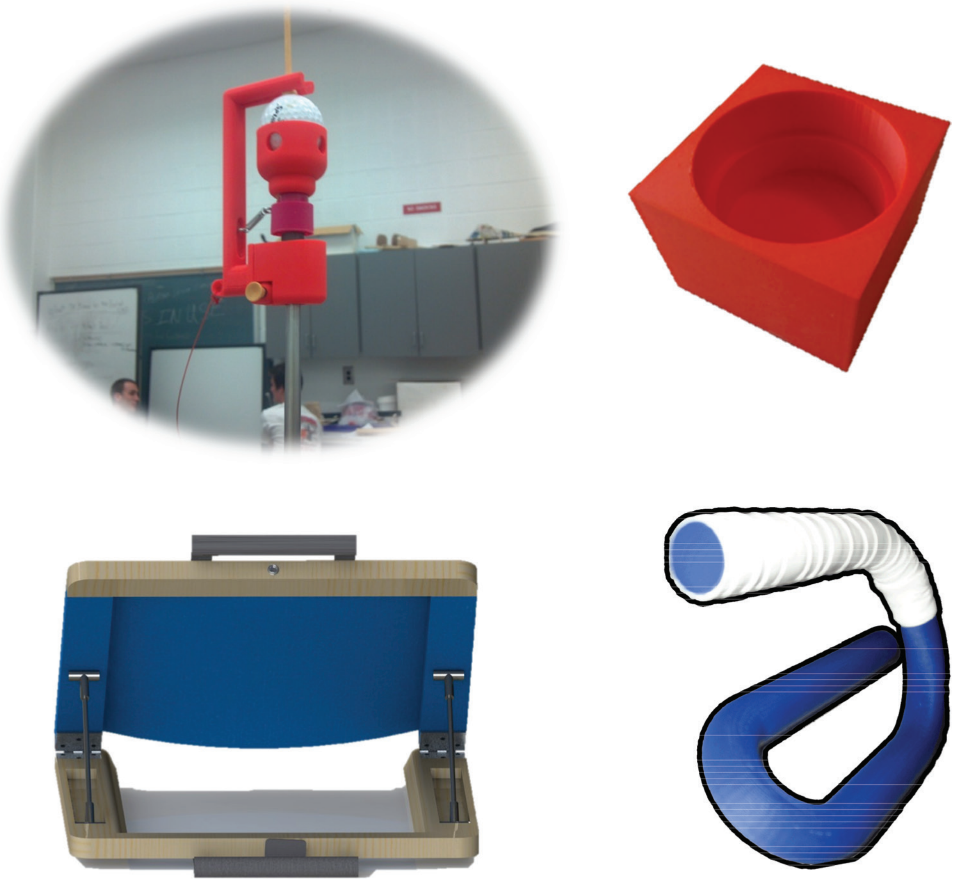

Figure 10. Working Models of Golf Ball and Tee Holder, One Hand Jar Opener, Assisted Chair Lift, and Ergonomic Grocery Bag Carrie

a working model that could take the form of a process, prototype, or a system. All of the student-designers opted to quickly fabricate physical models. The working model allowed for testing and feasibility, Figure 10. Sometimes the testing resulted in failure and others in success.

Most of the design groups expressed a desire to make improvements on their designs after producing a working model through a second iteration. The affordances provided by producing a working model were essential. The student-designers felt a sense of accomplishment as they saw connections between the previous models, especially the mathematical and working models. The design was no longer abstract but now became a reality. Additionally, they took ownership of the project they designed and fabricated. Many of the frustrations experienced while producing the mathematical model were allayed when a better working model was produced.

CONCLUSIONS AND IMPLICATIONS

The researchers developed a concept map of the student-designers' use of modeling artifacts. This was developed while analyzing and writing up the data. Around each modeling artifact are ideas and themes that became salient, Figure 11.

When student-designers are given the opportunity to design towards intermediate milestones, such as modeling artifacts, it helps demystify the engineering design process without implying a linear procedure. In this study student-designers were able to learn modeling ways of thinking, as modeling was a primary activity and supported the literature in that it was representative of what the novice designers knew (Jonassen 2000). Producing an actual client and providing modeling as an activity allowed the student-designers the opportunity to engage in real-world problem solving which is key to effectively introducing student-designers to the engineering design process (Bailey and Szabo 2005). Rather than leading the student-designers down a fixed and linear process, approaching engineering design through modeling artifacts gave student-designers direction and guidance. This revelation is vital in advancing the new phenomena of teaching engineering design at the secondary level and allows teachers the ability to engage student-designers through an approach that furthers their understanding (Katehi, Pearson, and Feder 2009). We assert that the process of engineering design can be taught through a focus on modeling artifacts.

The focus on modeling artifacts provided a setting for formative assessments. This occurred throughout the design process, especially in the preparation of the artifacts. However, the instructor must be careful in not leading the students towards an output that is artificial; a case of students turning something in only because the teacher requires it. Rather, the artifacts are to approach a

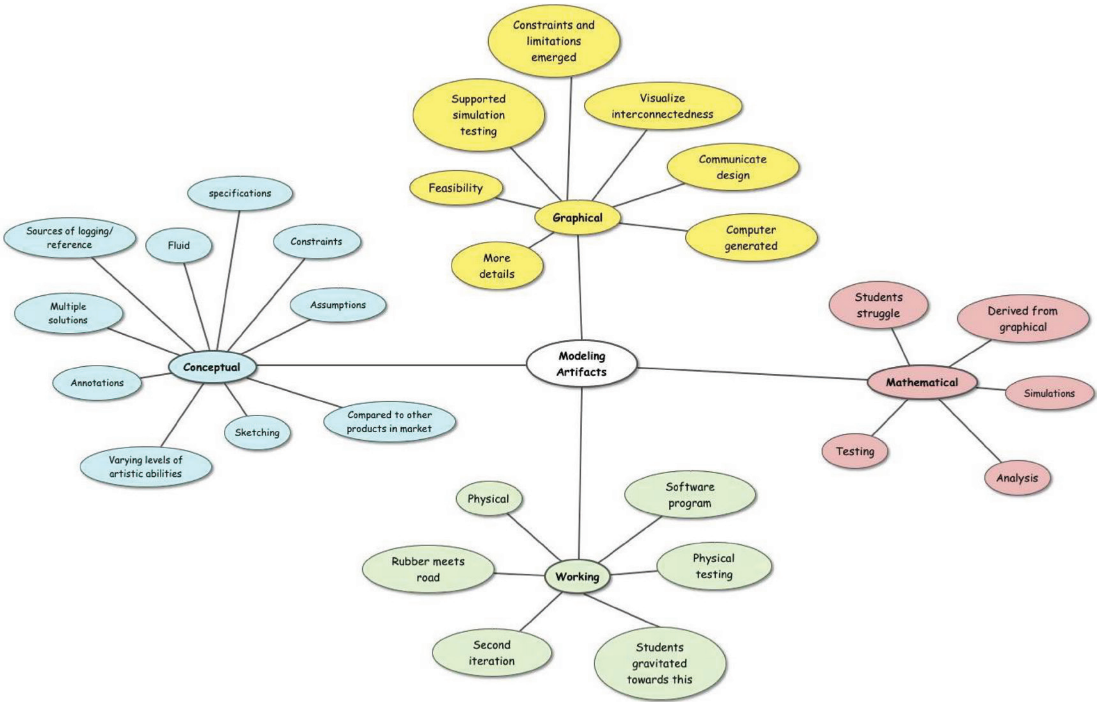

Figure 11. Modeling Artifacts Concept Map Generated by Researchers

natural output for the student-designers as they go about design. Prompts then, become a powerful tool for the instructor in engineering design (Martinez and Stager 2013).

Although, many student-designers struggled with the concept of mathematical modeling, their experiences provided evidence that modeling artifacts as deliverables helped student-designers understand difficult concepts and yielded tangibles for assessment. One pedagogical advantage of modeling artifacts is that they provide concrete examples of a very abstract process. The student-designers learned engineering design habits of mind on some level, yet it is not expected that the lessons learned became habit through a semester long design. However, the student-designers moved away from thinking that engineering design was a linear process. A habit or changing thinking takes time, not only on the part of the students but also the instructor (Cuoco, Godenburg, and Mark 1996).

In summary, the four artifacts that the student-designers developed; conceptual, graphical, mathematical and working, demonstrated their design thinking and provided evidence of decisions made throughout the design process. Further research is needed to understand this pedagogical model in various settings: pre-college learners, undergraduate students, and in-service teachers. Additionally, modeling as a habit of mind in any engineering setting warrants its own definition and studies.

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