All artifacts, from pencil holders to power plants, are influenced by designers. Although the problems encountered by different engineering disciplines may vary, design is central to all types of engineering and is recognized as such by the United States’ Accreditation Board for Engineering and Technology (ABET) which states that all engineering graduates should have the ability to develop and evaluate the design of a system, component, or process that meets some desired need.

Understanding the engineering design process is important in order to understand and implement effective teaching of design courses. To this end, there has been a great deal of research investigating the design processes of engineers and engineering students (e.g., Atman, Cardella, Turns, & Adams, 2005; Atman, Chimka, Bursic, & Nachtmann, 1999; Atman & Turns, 2001; Bursic & Atman, 1997; Christiaans & Dorst, 1992; Cross, 2001; Ennis & Gyeszly, 1991; Kruger & Cross, 2006; Pahl, 1999; Radcliffe & Lee, 1989; Stauffer & Ullman, 1988). One element of the design process on which researchers generally agree is that designing is not an algorithmic activity. When developing
a design, engineers are dependent on the situation at hand so that goals, problems, and constraints are often ill defined and may change as the problem space is unpacked. Engineers select features and identify areas of the problem they will attend to and explore, so design solutions may be influenced by elements of subjective, qualitative, and intuitive reasoning. Although engineers may have general guidelines for the design process, there is no consensus regarding one correct procedure to follow in order to reach a solution (Cross, 2001; Stauffer & Ullman, 1988; Zimring & Craig, 2001).

That ambiguity is embedded in design problems was the impetus for our investigation of model building as an instructional strategy to aid engineering students when confronted with complex design tasks. In addition, although previous researchers studying the design process have utilized sketches, drawings, verbal accounts, and written communications, there is less in the literature investigating whether hands-on model building can contribute to a better understanding of the engineering design process. This research project was designed to investigate whether a hands-on, model-building activity can contribute to students’ understanding of the engineering design process. Utilizing Verbal Protocol Analysis, we collected data from eight engineering students during an open-ended, model-building design task. This paper reports the results of that research.

1 Background

We looked at model building as an aid to the engineering design process for a number of reasons. First, students frequently have difficulty visualizing a structure from a drawing and are tempted to blindly accept results from computer analysis without review (Schumucker, 1998). Second, building a physical model presents students with the non-idealities of real-world engineering, and offers them the opportunity to investigate the differences between real behavior and the conceptual model used to predict that behavior. Design assumptions that are often made during the preliminary design phases can come to the surface during model building and can then be either validated, or reflected upon for redesign and re-examining concepts (Helbling & Traub, 2008; O’Neill, Geiger, Csavina, & Orndoff, 2007; Schumucker, 1998). Third, model building can give students tangible results quicker than preliminary, highly theoretical courses (Bales & Consi, 2003). Finally, all of the researchers cited in this paragraph have noted that most students rated model building quite favorably. That model building might be a useful tool in helping students during the engineering design process might be explained, to some extent, by experiential learning theory.

1.1 Theoretical background

Kolb and Fry (1975) and later Kolb (1984) described their experiential learning theory (ELT) as a process in which knowledge is created by transforming experiences. In exploring the processes associated with making sense of our experiences, they developed a 4-stage, circular model of experiential learning:
concrete experience (direct, practical experience), observation and reflection (discussion and identification of unexpected difficulties arising from those experiences), forming abstract concepts (critical thinking and analysis of what was observed), and active experimentation (testing the analysis in new situations).

The theory suggests that learning often begins with a person carrying out a particular action in a particular setting, reflecting on the effects of that action, attempting to understand those effects, and then modifying actions to accommodate new ideas. Influenced by Dewey (1938) and Piaget (1972), Kolb and Fry (1975) stressed not only the role that concrete here-and-now experiences have in learning, but the importance of testing ideas and receiving feedback (performing actions and examining results) to alter ideas and construct knowledge.

Model building aligns well with ELT. There are hands-on concrete experiences during model construction, observation and reflection through testing and evaluation, and the opportunity to form abstract concepts from which new analysis and implications can be drawn. During model building the learner is encouraged to reflect on his or her actions and the results of those actions in order to validate their solution or formulate a better one. The effects of similar actions can then be anticipated in future similar situations. Excluding the concrete experience or direct involvement may lead to mechanical or sterile concepts. Missed observations can result in a hasty construction of faulty conceptual frameworks, and omitting active experimentation may cause the individual to remain dormant in a conceptual rut (Zerbe Enns, 1993). Considering the potential advantages of hands-on learning, we wanted to investigate the possible benefits of including a model-building activity for engineering students during a design task.

2 Methodology

We wanted to investigate the cognitive processes of engineering students during an open-ended, model-building design task. Because we cannot view cognitive processes, one way to know what people are thinking during a design task, is to simply ask them. One method used to advance our understanding of how engineering students go about developing solutions to complex problems is Verbal Protocol Analysis (VPA). During VPA data collection, subjects are asked to think aloud while performing a task (Ericsson & Simon, 1980, 1993). We are not assuming that subjects have access to their cognitive processes, but they are able to report the contents of short-term memory. From these verbal reports, we can gain insights into how subjects generate and transform information about the problem, and how they go about developing a solution. Verbal Protocol Analysis has been used extensively since the 1970s to study the cognitive processes of engineering students (Atman & Bursic, 1998; Atman et al., 2005; Bursic & Atman, 1997; Mullins, Atman, & Shuman, 1999; Radcliffe & Lee, 1989) as well as experienced designers.
(Christiaans & Dorst, 1992; Cross, 2001; Ennis & Gyeszly, 1991). Although VPA is considered the most appropriate method to study the cognitive abilities and processes of designers (Cross, 2001; Dorst & Cross, 1995; Ericsson & Smith, 1991), it is not an assessment tool appropriate for large subject populations due to the copious amount of time required for analysis. For this paper, the verbal reports of eight participants were analyzed.

2.1 Subjects

Eight students attending a private university in the northeastern United States were asked to participate in a design task at the end of the school year. It was a sample of convenience as the students were all known by at least one of the co-authors. There were five males and three females, from diverse engineering disciplines and academic years (See Table 1).

In addition to being at different stages in their educational career, participants had varying levels of design experience. Design courses for students in any of the engineering programs at this institution are not required until the senior year. However, some students may have had elective courses that included varying levels of design experience. Some students may have had summer internships or been involved with extracurricular activities (e.g., EWB, U.S. Department of Energy’s Solar Decathlon) where they may have been exposed to the design process. So the range of previous design experience varied considerably within this student sample.

2.2 Design task

A literature review was undertaken to search for an appropriate hands-on design task. The criteria included a project that could be assembled and modified relatively easily, cheaply, and quickly; that would involve students in the design process; that could be easily transferred to other sites (for future widespread testing); that had a relatively simple application; and that could ultimately be modified for a stand-alone, computer delivered assessment instrument. The search was narrowed down to National Science Foundation-funded projects within their Research to Aid Persons with Disabilities (RAPD) program. The projects within this program were assistive devices

<table>
<thead>
<tr>
<th>Participant code</th>
<th>Gender</th>
<th>Engineering discipline</th>
<th>Class level (undergrad)</th>
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<td>3</td>
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<tr>
<td>M-ME-4</td>
<td>M</td>
<td>Mechanical Engineering</td>
<td>4</td>
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<tr>
<td>F-EnE-4</td>
<td>F</td>
<td>Environmental Engineering</td>
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<td>F</td>
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<tr>
<td>F-ME-4</td>
<td>F</td>
<td>Mechanical Engineering</td>
<td>4</td>
</tr>
</tbody>
</table>
tailored for individuals with physical challenges and developed by undergraduate engineering students. There was a diverse selection of projects to choose from and most were relatively small and simple, which fit our task criteria. All the prototypes had ample descriptions along with photos, making the projects easy to visualize and understand. The task finally chosen was to build a prototype one-handed jar opener.

2.3 Procedure

This design task and procedure, described next, were beta-tested several times with an engineer as well as with engineering students, and modifications were made prompted by their comments. The study participants were asked directly via e-mail if they would be willing to participate in a research experiment on engineering design. After giving consent, students were tested individually in a small conference room on campus. A small audio-video camera was mounted on the ceiling to record speech as well as students’ hands. (Faces could not be seen.) Before recording began, the participants were told the purpose of the study, which was to investigate the engineering design process, and given a practice think-aloud project of putting together a 24-piece puzzle.

When the subjects finished the puzzle, they were given an information sheet that explained the design task: Develop a jar opener for individuals that had the use of only one hand. Laid out on a large table were 15 sets of cards listing activities that the students could choose to do. Each activity set was made up of five to eight cards that offered various pieces of information. The information sheet explained that participants could choose whichever cards they thought might help them in formulating a solution. The card activities were titled: (1) Talk to Jim (an amputee), (2) Speak with Mary (a stroke victim), (3) Learn about amputees, (4) Learn about stroke, (5) Look at other models, (6) Plan/draw/sketch, (7) View available materials, (8) Read technical descriptions of prototype jar openers, (9) Build a prototype, (10) Review first principles of physics, (11) Talk to jar manufacturers, (12) Examine elementary mechanics, (13) Look at jar variables, (14) Investigate aesthetic options, and (15) View unnecessary nonsense.

Except for activity 9, each of the activities contained some bits of superfluous information. In general, information in the first 8 choices listed was considered by the researchers to be helpful in solving the problem. The last 6 choices listed contained irrelevant information not required to complete the task. The purpose of the diverse card choices was to see if students could cull the important information necessary to solve the design task. We included ‘unnecessary nonsense’ to cue students to the idea that not every set of cards was pertinent to the design task.

The design task read:

Clients at the local rehabilitation center have diverse disabilities and physical challenges. For example clients may have an amputated limb, cerebral
palsy, multiple sclerosis, or they may have had a stroke. However, one difficulty they all face is opening a jar with one hand. As an engineering student, what can you do to help?

The information sheet did not specifically instruct participants to build a model so that we could observe whether students would naturally be inclined to build, or if they would need prompting. We were prepared to instruct participants to build if they needed prompting but this was not necessary. It should be noted that, although not all students read all of the cards, all did read the View Available Materials cards and at that point realized, if they hadn’t already, that they would be building a physical prototype.

LEGO pieces were used for building the prototype. When subjects chose the Build a Prototype card, they were handed a kit of LEGO pieces and instructed to use the pieces simply to get their idea across, and not to be overly concerned with any usability challenges arising from the materials. While the functionality of the pieces did not allow for heavy force to be used in opening a jar, the fact that the pieces could be assembled, taken apart, and reassembled quickly and easily outweighed this disadvantage. In addition, due to their long standing popularity, most students were at least somewhat familiar with LEGO pieces.

While participants designed and built their prototype, two researchers (the first two authors) were taking observational notes. When finished with the design task, each student was asked a few short questions regarding the design activity project. They were also asked to write a short reflection paper of their design process during this task. After the tapes were transcribed and coded, each participant was sent their coded transcript and asked to comment on the accuracy of our translation and codes. This member checking (Patton, 2002) was included as an element of triangulation to strengthen confirmation of our interpretations. While some of the students made a few clarifying comments, most concurred with how their thoughts and words were interpreted.

Finally, two focus groups were conducted, recorded, and the tapes transcribed. Although not all participants attended, additional reflective comments were gathered and added to our data base.

3 Data analysis

The transcribed texts (with time stamping) formed the main data for analysis. Content analysis (Creswell, 1997; Patton, 2002) was employed, using HyperResearch (by ResearchWare), a qualitative data software package. This form of analysis involved searching through text for recurring words, phrases, or themes. Frequencies and patterns emerged that helped define and construct categories or codes. Some phrases were coded for multiple categories. Once categories were created, constant comparison (Patton, 2002) was employed
to ensure internal homogeneity and external heterogeneity of the categories. Internal homogeneity concerns cohesiveness, or the extent to which each entry within a category is similar to every other entry in that category in a meaningful way. External heterogeneity concerns independence, or the extent to which differences between categories are distinct and clear.

To ensure objectivity, numerous sessions and lengthy discussions with two outside coders were conducted. All entries in each category were analyzed to see if each entry related to every other entry within that category in a meaningful way. If one coder thought a phrase did not fit in that particular category, the phrase was either moved to another category or a new one was created. If the decision was made to create a new category, all other cases were recoded to include the new category so that the tenability of that category was tested against all other data sets. Then we determined if the new category was strong enough to contribute to the interpretation and understanding of the data.

4 Results
Eleven categories emerged from the data analysis. They were:

- Idea Generation (Idea Gen): Formulates, explains, or discusses their plan, idea, or concept.
- Evaluates (Eval): Makes some sort of judgment or assessment of a prototype or their drawing, model, or idea.
- Metacognitive Strategies (Meta Cog): Is aware of their own knowledge building, knowledge searching, or organizational strategies.
- Describes Information (Des Info): Describes the prototypes, jars, or materials, or is reading pieces of information from the cards.
- Refers to the Client (Refer Clien): Makes a reference to the client or the client’s needs.
- Discriminates Information (Disc Info): Is able to discern important information from insignificant information.
- Clarifies Information (Clar Info): Reiterates some fact or brings a piece of information to attention.
- LEGO Limitations (LEGO Limit): Expresses the challenges of building with LEGO pieces.
- Miscellaneous (Misc): Phrases relating to design or building that do not fit into any other category.
- Kinesthetics (Kin): Uses, refers to, or requests hands-on manipulation of the pieces to clarify a concept or idea.
- Other Category (Oth Cat): Categories that were strong enough to create for some individuals but did not fit every participant. For example, one participant had numerous phrases (3%) regarding testing his model. But the category of ‘Test Model’ was not strong enough across participants to warrant keeping it as an independent category. In addition to the ‘Test Model’
category, the other categories were: Confusion, Global Perspective, Opportunistic Behavior, and Personal Experience.

All the categorized phrases were totaled (Total # Phrase) in order to calculate the percentage of phrases uttered in each particular category. (Table 2; Percentages were rounded to the nearest whole number.)

A number of patterns emerged within this sample of eight students. From the chart we can discern that, regardless of engineering branch or school level, these students were able to generate ideas and were aware of their metacognitive strategies. Most of these students traversed a similar path in that they described and evaluated characteristics of the prototypes as well as their own ideas and models. Most were able to discriminate useful from superfluous information, and most made comments that clarified or prioritized information for them. All were able to build a model from LEGO pieces. This paper will now address the Kinesthetics category. Although Kinesthetics may appear to be a weaker category due to its low percentage of phrases, it strongly influenced the most prominent categories for all of the students: Idea Generation and Evaluation.

4.1 Kinesthetics assists in generating ideas

Idea generation was a strong category for all of these students. Some students in our sample voiced their preference for the kinesthetic activity of hands-on building to help them generate ideas. After reviewing a number of cards, the F-ME-4 began drawing out her prototype idea. (Student comments are preceded by a time stamp in minutes and seconds.)

19:31: Okay, so next I’m gonna go to the activity of drawing a plan/sketch ‘cause I, I wanna get my hands into, now start building…drawing stuff out.

27:04: I’m almost kind of tempted to just start building a prototype. Maybe once I get my fingers on the pieces they might think of something. [Author note: interesting what is doing the thinking here!]

<table>
<thead>
<tr>
<th>Table 2 Percentage of phrases for each category</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Student</strong></td>
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<tr>
<td>-------------</td>
</tr>
<tr>
<td>M-ChE-2</td>
</tr>
<tr>
<td>M-EE-3</td>
</tr>
<tr>
<td>M-GE-4</td>
</tr>
<tr>
<td>M-ME-3</td>
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<tr>
<td>M-ME-4</td>
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<tr>
<td>F-CE-4</td>
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<tr>
<td>F-EnE-4</td>
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<tr>
<td>F-ME-4</td>
</tr>
</tbody>
</table>

Model building as an aid to engineering design
In the post-task interview, this student commented:

"Drawings are good because, you know, you can say, 'Okay. This is how I want to do it' and you know you are not limited...But then building it is good because, like, you know, I, I was doing the drawing and you know, I kinda got stuck. I wanted to get my hands on the pieces and start, you know, building...So I kind of like that aspect of it, of being able to build 'cause then, that kind of triggered my mind into...thinking about different ways of doing it."

Similarly, when asked what might help a student who was stuck in his design progress, the M-ChE-2 said:

"40:54: I’m not sure. I’m just trying to get the best way that I could (to) use these pegs and tires and stuff. Not quite sure, maybe actually building it and testing it out.

The F-EnE-4 said:

"35:29: I’m sketching some ideas here, thinking how I could translate that into the LEGO pieces.

She commented that it would be helpful to have some pieces to play around with:

"43:34: Just ‘cause it’s, you know, it’s easier to touch things and hold things."

The F-ME-4 sketched out her plans and laid them out to refer to as she was building, but the kinesthetic activity of manipulating the pieces also helped her generate ideas:

"29:26: Now I’m looking at this wheel, thinking about ways that I can design, turn it, if it’s locked down. So I’m gonna try and see if I can do that."

Obviously, this student knew what wheels are and what wheels do, but it took physically manipulating the actual artifact for this student to further develop her idea for a finished prototype. As can be seen in Figure 1, she did indeed use a wheel (under the jar) as a crucial piece in her solution.

4.2 Kinesthetics assists in evaluating ideas

Evaluation was a strong category for all the students in this sample. Analyzing and critiquing one’s own work and ideas are important components of the engineering design process and model building may enhance this process for some students.

The M-ChE-2 felt strongly about having a device that could be put away and out of sight when not in use. But when building his prototype, came to the understanding that this might not be possible.

"48:55: Need to find a way to make that secured, so it doesn’t rotate.

49:04: I know that I like this working like that, but I just need to find a way to have this be secure."
49:40: Actually I didn’t want to have to build a base. But a base may be necessary.

The M-GE-4 said in the post-task interview,

Not needing a top piece...probably would not have figured (that) out, um, as quickly if I hadn’t started building a rough prototype.

He brought this up again in his reflection paper when he wrote:

I originally wanted to have two (oil filter-type wrenches) wrenches and I had finished what I submitted as the prototype, (his sketch) and had begun work on the second ‘oil filter’ wrench when I realized that with the jar locked to the ground, it was likely that any amputee or stroke survivor would be able to open the jar (with just one wrench) once it was fixed to the ground (See Figure 2).

During the focus group discussion, the M-ChE-2 noted how model building helped generate and alter design ideas. He said that building:

Was able to bring about a few other ideas that I may not have thought of, or trumped a few ideas I did have once I started building and realizing how that’s not gonna work. Seeing it in a three dimensional design definitely helped.

The M-EE-3 similar noted that building a model

Was absolutely essential because I, I mean I know the drawing I drew down originally isn’t what I ended up with at the end. It never is in engineering. There is always something you didn’t think of when you’re starting to build it

These students came to understand how building a model can alter initial ideas.
4.3 Kinesthetics assists in exposing flaws

Through evaluation, model building can expose flaws in preliminary sketches and ideas. For example, the F-ME-4 commented:

41:18: I realized when I built this thing, I did it slightly off.
45:28: I didn’t really give myself much room to work with for the turning.
49:04: The problem is this rod is really long. So I’m gonna look for a smaller rod.
57:40: But alas, since I just put one on, it will turn freely. Whereas if I put two on…this whole thing would move when I move this.

The F-EnE-4 succinctly framed the problem, had a solid conceptualization of her prototype, and communicated her idea via beautiful sketches. However, as she started to build, she commented:

48:40: Definitely coming across um, things that I want to change.
53:48: It's kind of a mess right now. But how do I want this, because they would need to have this here and then put their H on top. We're gonna start with what I want it to be like and then go backwards and make sure they can do it.
1:07:37: What a nice long axle. But then it’s harder to do with one hand...It’s not as user friendly.

This student did develop a very nice working prototype (Figure 3) but needed the model building experience to work out the bugs.

4.4 Kinesthetics as a visualization aid for ideas

These engineering students were aware of their meta-cognitive strategies and preferences of learning styles (Felder & Silverman, 1988). For example, the M-ChE-2 noted that reading the technical descriptions was not much help...
because, ‘I like to be able to visualize.’ The M-ME-4 similarly noted, ‘I have to be able to put them (the LEGO pieces) in the right spots to be able to, to visualize it.’ While model building might help some students better visualize their ideas, it might also help those who have trouble visualizing their ideas. The M-ME-4 admitted that he was, ‘Not very spatial. I like numbers.’ When presented with the box of LEGO pieces, he responded with, ‘Oh. So I'm actually gonna try and build this now. Ahhh. Damn it.’

17:16: You'd need, let's see, a lever off of here. Some sort of lever that you can, you can crank, like crank down on. And then there'd be some sort of, to tighten in so this will be able to tighten. I'm not exactly sure how that would work yet

42:50: This is kinda the neck that will hopefully move up and down, um, an then, yeah, it'd be adjustable.

43:23: I'm not exactly sure what I'm envisioning.

But his ideas coalesced as he was building.

47:34: The way I have it now is like horizontal and then it'll go down…but I want it to go up this way. So it would have to be like this.

53:04: And so if I were (to) put it straight on top and then it wouldn't, it would start at the point that I wanted it to end and then it would go too far down.

53:21: What we want to have, is to go from vertical up this way to horizontal instead of horizontal to vertical downwards. And so we have to switch going from the blocks up this way to going across this way.
Building helped this student clarify his ideas and he incorporated a very elegant gear mechanism in his final prototype (Figure 4) that was not included in his initial sketches. In his reflection paper, he wrote:

Once I started building, different things just sort of fell into place. I came up with more ideas as I started building. For example, I wanted to have a complex tightening system to lock the jar into the bottom of the mechanism but when I started building, I had limited materials so it made more sense to have a simple screw tightening system.

The F-CE-4 similarly wrote in her reflection paper, ‘I tried drawing models, but my ideas didn’t really make sense to me until I actually started building.’

The physical activity of manipulating pieces helped these students generate and evaluate ideas and concepts. It is interesting to note that five of the eight students had comments concerning kinesthetics and of these five, four students had the highest number of meta-cognitive phrases. It may be that the students who were most aware of the benefits of hands-on were also those more skilled at expressing their meta-cognitive strategies. Or it may be that three of the five students that commented on kinesthetics were in engineering disciplines not traditionally viewed as hands-on (Electrical, Chemical, and Environmental) and therefore benefited more from the building activity.
4.5 Skill application
Generally, the students enjoyed the project. Some students commented about liking the project because it allowed them to apply their engineering skills. Initially anxious about building, the M-ME-4 said in the post-task interview:

After I got going, I was like, hey this is kinda fun. The gears, I like the gears because I had to apply a little bit of engineering knowledge... A lot of design doesn’t seem like you use... a lot of the engineering things or engineering like concepts and stuff... (This) is more design than what has been presented to us as engineering.

The M-GE-4 said in the post-task interview, ‘For an engineer like, I love this stuff... This is what engineers at heart like to do.’

The qualitative analysis from these eight students offers some insight into the benefits of model building when tackling engineering design problems. We also looked at quantitative relationships regarding time spent in different activities. We wanted to see if there were any relationships between the time participants spent researching information, the time they began sketching, the time they began building, and total task time.

5 Time spent building
To further analyze the design process of each participant, we looked at the time they began sketching, the time they began building, the percent of time spent building, the percent of time spent seeking information, and the total task time (Table 3). We used the time they began sketching as the cut off point to calculate information seeking because, although a few students perused the material cards while sketching, in general, information seeking ceased once they began sketching out their design.

We wanted to investigate whether or not there was any relationship between the amount of time seeking information and the amount of time building. Would our students be more solution focused, information focused, or

<table>
<thead>
<tr>
<th>Branch year</th>
<th>Begin sketching (min.)</th>
<th>% Time researching</th>
<th>Begin building (min.)</th>
<th>% Time building</th>
<th>Total task time</th>
</tr>
</thead>
<tbody>
<tr>
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<td>49</td>
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</table>
problem focused (Kruger & Cross, 2006)? The students spent anywhere from 10% to 51% of their total task time researching information. This differed from the results of Atman et al. (2005) who found that the average percent of time seeking information (by both freshmen and seniors) was less than 8%. This may be a function of different, shorter design tasks (less than 20 min) or perhaps a difference in how ‘time seeking information’ was defined. Creating a scatter plot comparing the percentage of time seeking information (% Time Researching) against the percentage of time building (% Time Building), it can be seen from Figure 5 that, even with only 8 data points (resulting in a fairly low $R^2$ of .41) a trend emerged. The negative correlation between the percentage of time researching information and the percentage of time building seems logical: More time spent planning and researching means less time building.

5.1 Sketch time vs. total time

Our next question was, ‘Would the point at which students begin drawing influence the total amount of time they spent on the task?’ As can be seen in Table 3, when students began sketching varied considerably (anywhere from 7 min to 37 min into the task). Although two of the students completed the task in less than 40 min, the remaining 6 completed the task within 60–72 min. As can be seen from Figure 6 (Total Time vs. Sketch Time), a scatter plot graphing when students began sketching (Begin Drawing) against their total task time (Total Task Time) shows that, in general, the process was fairly similar in length for most of the students, regardless of when they began sketching out their ideas.

![Figure 5 Time Researching (a) vs. Time Building (b)](image-url)
5.2 Begin building time
Looking at students’ Begin Building time allowed us to see if they were hesitant or eager to build. Just as Begin Drawing time varied considerably, so did the Begin Building time. Even if we only looked at the students who completed the task within 60–72 min, the time they began building varied from 28 min to 49 min into the task. The percentage of time spent building varied from 32% to 55%. So regardless of when they began sketching and regardless of when they started building, in general, the process was fairly similar in length for most of these students.

6 Discussion
This research project was designed to investigate whether a hands-on, model-building activity can benefit students during an engineering design task. We also had a number of other underlying questions and concerns: Would students just tinker with the materials? Would students more experienced with the LEGO pieces have an advantage? Would students in traditional hands-on engineering disciplines (e.g., mechanical, civil) likewise have an advantage over students in disciplines traditionally viewed as hands-off (e.g. chemical)? These issues are addressed below.

6.1 Tinkering vs. designing
When designing this research project to include a hands-on task, an initial fear was that the model-building component would lead to tinkering instead of design. Although one student did resort to opportunistic behavior and tinkering, the remaining seven students had framed the problem, conceptualized, planned, and sketched out their solution before starting to build. For most of these
students, the hands-on building component of this task was not tinkering, but critical in demonstrating the viability of their design. From their comments, it appears that model building helped these students generate and visualize ideas, as well as expose flaws in preliminary sketches and ideas. Building and evaluating their physical model helped these students understand the differences between real behavior/action and the conceptual model used to predict that behavior/action. Aligning with Kolb’s (1984) ELT, there was a constant process of experience, observation, conceptualizing, testing ideas, receiving feedback, and re-evaluating. This analysis suggests that model building might be a beneficial component that can assist some engineering students’ during a design task.

6.2 Unfair advantage
Another concern was that some students might have an unfair advantage from having participated in extra-curricular or service-based activities involving LEGO pieces. We were also concerned that some students from engineering disciplines traditionally viewed as hands-on (e.g., mechanical or civil engineering) might have a potential advantage. This did not appear to be the case. Although some students were more familiar than others with a few of the more sophisticated LEGO pieces, they had not used these materials to build a one-handed jar opener. In one sense, this project ‘levelled the playing field.’ Some subjects (e.g., the M-GE-4) told us how much they loved building with LEGO pieces. Others (e.g., the M-ME-4) voiced their disdain. But all 8 subjects were able to design and build a prototype jar opener, regardless of their level of familiarity or enjoyment.

6.3 Challenge and creativity
Model building as part of an open-ended problem has the potential to enhance creative thinking, and boost self-esteem, regardless of the engineering discipline. Although all the students in this group came up with a viable solution, this was not an easy problem for them. There were many variables to consider: different types of jars (e.g. screw tops, pop tops), different sizes of jars, different client disabilities, and building with un-cooperative materials. All the students came to design impasses and all had moments of frustration (e.g., ‘I’m stuck,’ ‘This is such a mess,’ ‘Right now, I’d like to just open the jar for them.’) But all persevered to reach a solution. Tackling ambiguity enhances creative thinking (Lemons, 2005). Successfully overcoming challenges strengthens self-efficacy (Bandura, 1997). One student, who said she would hire a mechanical engineer to design this because it was not her area, admitted that she enjoyed the intellectual challenge to be creative because, ‘You get limited when you’re an engineer.’ That the participants needed to push their creative limits, regardless of their discipline, is another potential benefit of hands-on building for some engineering students. In the end, every student said they were proud of their finished product. One student summed it up well when he wrote:

Initially, I was a bit nervous to have to design a solution to this problem. I like having clear cut answers to solutions and this problem did not have
a clear cut solution...Once I was informed that I would be using legos to build a prototype, I grew anxious. Overall it turned out to be a good experience. I feel this is because I was a little nervous of having to design something but am happy with the way things went.

6.4 Meta-cognition
Model building might also help students become more aware of their own design strategies. The M-EE-3 said in the focus group discussion that he enjoyed the project because:

It showed me how I, how I actually problem solve instead of how I think I problem solve...which was neat...That was interesting to see...It was good to see how I do it...now I take note of it more...I'll think through those steps.

The M-ChE-2 agreed, adding that model building offered some direction, ‘Of where your thinking was going’ and that now he’s ‘stepping back and kind of seeing how I do problem solve.’ He added, ‘I’m a little more conscious of the product and the clients.’

6.5 Functional prototype
An additional observation of many of the participants was their intent and focus on producing a functional prototype. Although it was explicitly explained that we were more interested in their design process and that their model was simply to be a representation of their idea, many wanted to make a prototype from LEGO pieces that could successfully open a jar. Some students did indeed achieve this goal.

6.6 Unnecessary nonsense
We added the View Unnecessary Nonsense card to cue students to the fact that not all the information presented was pertinent. (The cards contained science-themed cartoons.) It was intriguing that, while not every student looked at every set of cards, every student did choose to look at the nonsense cards. All commented that their decision was based on curiosity. Although six students realized the uselessness of the cards, two students believed the cards had some deeper philosophical application to the task. One student commented that perhaps the cartoons were ‘Trying to get me to think a certain way.’ But sometimes, ‘A cigar is just a cigar.’

6.7 Beneficial experience
An important note to consider is that we have hundreds of pages of transcripts from more than 16 h of recorded model-building sessions, as well as transcripts from 2 h of recorded focus groups. We also have reflection papers from the students and observational notes from the first two authors who were present during the taped sessions. No student made any comments saying the hands-on activity was detrimental to their design process or that it was leading to...
a worse prototype design. Although model building, like most learning, was challenging for the students, there were no negative comments regarding the building component of the task and all agreed it was a beneficial experience.

6.8 Hands-on model building

During the design task, some of the students in this group expressed surprise when they learned they would be building a prototype. Focus group discussions revealed a few different reasons for them being 'caught off-guard.' Some students mentioned that they did not see any building materials so did not expect to build. (The kit of LEGO pieces was out of sight until they read the Build a Prototype card.) Some brought up the fact that building a prototype for their senior project generally took months, so it did not occur to them that they would build a prototype for this short design task. Some students also mentioned that most of their course work required only that plans be submitted and that hands-on model building was not integrated into most of their courses. This is not surprising considering the somewhat limited experience with hands-on design for most of these students. Because model-building may prove beneficial for many students, this trend is hopefully starting to change.

The benefits of model building have been recognized and there is an emerging movement to integrate hands-on model-building in engineering programs. For example, a consortium of 23 universities has adapted the Conceive-Design-Implement-Operate (CDIO) framework pioneered by MIT. Based on the idea that product and system development are the innate context for engineering education, there is an emphasis to integrate hands-on, product-building skills during the freshman year and sustain this practice throughout the curriculum (Ho & Ryan, 2009). The design-and-build active experience enhances students’ design abilities, provides deeper learning of concepts, and lays the foundation for developing more theoretical knowledge structures (Malicky, Kohl, & Huang, 2007). It might be argued that the physical nature of build activities develops an individual’s knowledge of the physical world, and that there is a correlation between the physical manipulation of objects by hand, and an understanding of those objects and materials.

That kinesthetics can be an important pedagogical tool is demonstrated at Smith College, where dance is one of the approaches used to teach dynamics in context (Ellis, Rudnitsky & Scordilis, 2005). In learning and feeling the mechanics of the grand jeté and arabesque, students can better understand the constraints and laws of mechanics. Similarly, in learning and feeling the forces and constraints of the building materials, students can better understand the application of engineering and design concepts.

7 Conclusion

From our analysis of students’ verbal protocol during the design-and-build task, it appears that model building has the potential to help students generate,
visualize, and evaluate design ideas, as well as expose flaws in preliminary sketches and ideas. Model building can also help students investigate the differences between real behavior and the conceptual model used to predict that behavior. Model building as part of an open-ended problem offers opportunities for creative thinking, and helps develop meta-cognitive design skills.

By tracking the time students spent in various design activities, we found that, regardless of when participants began sketching out their idea and regardless of when they began building, the design task process was similar in length for most of the students. Not surprisingly, in general, the more time spent planning and researching, the less time spent building. This research project was designed to investigate whether a hands-on, model-building activity can benefit students during an engineering design task. In conclusion, we believe that model building is an often overlooked pedagogical tool that can enhance the engineering design process for students. Therefore, faculty of all engineering disciplines should strongly consider including a hands-on model building component in their courses.

This analysis was based on data collected from 8 students attending a private, cosmopolitan school in the northeastern United States. The size and homogeneity of the student sample negate generalizability of results. Future research directions are to modify the assessment to fit a digital workbook format in order to collect data on larger samples.

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