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Engineering Design Practices in a Freshman Mechanical Engineering Technology Course

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Abstract

An important outcome of a mechanical engineering technology (MET) program is a fundamental understanding of the mechanical design process, the development of solutions to design problems with consideration of specific requirements and constraints. This study is concerned with the idea generation phase of the engineering design process, specifically the ideational practices of freshman mechanical engineering technology students. The idea generation phase is a complex endeavor that involves defining the problem, generating potential solutions to the problem, the consideration of constraints of the problem, and converging on the most appropriate solution for the problem. The development of these skills is an essential component of future innovation. This research seeks to contribute to a baseline understanding of how freshman-level MET students navigate the solution space of a design problem while focusing on the requirements and constraints of the final design.

Eight mechanical engineering technology students were recruited and asked to generate potential solutions for an open-ended design problem. Semi-structured interviews were conducted to assess design strategies that were used during the concept generation phase, whether constraints of the problem influenced their solutions or otherwise limited the solutions developed, and whether alternative designs were considered and if so, how students determined the most appropriate design. While most design related activities tend to take place in the latter years of a 4-year MET program, this research can provide a baseline understanding of how MET students approach design problems so better strategies can be developed to provide appropriate scaffolding as design skills are taught throughout the program.

Introduction

Mourtos emphasizes the importance of engineering design by considering design as the heart of engineering [1]. Design capstone experiences have been a staple of engineering and engineering technology programs and are excellent tools for bringing practical engineering into the curriculum [2], however, typically such projects have been in the final year of typical undergraduate program. Recently however, a resurgence in first-year, or cornerstone engineering design experiences are becoming more prevalent [3, 4]. Moreover, ABET requires that graduates of an engineering technology program be able to design solutions to technical problems [5]. This study aims to provide some insight concerning how a sample of freshman-level mechanical engineering technology students approach an open-ended design problem in terms of framing the problem, strategies used to generate ideas, how constraints are considered and incorporated, as well as the evaluation of alternative designs. Through the characterization of freshman MET students initial design abilities, better strategies can be developed to provide scaffolding as appropriate design skills are taught throughout the program.

Background

Engineering design is an important aspect of any engineering or engineering technology program. Design is what engineers do, and hence the training should reflect this. Traditionally, design experiences have been relegated to senior year capstone experiences. Recently however, an increase in the number of design experiences in the freshman year, sometimes referred to as cornerstone design experiences, are being introduced into curricula. These design-focused courses have taken the form of project-based courses where the structure of the course focuses around the design of a single or multiple projects, and others have incorporated design-focused modules that provide scaffolding to students as they develop design skills. Additionally, many courses are interdisciplinary to illustrate the complexities of real-world design and range from individual to team-based design projects [3, 6, 7]. Such an introduction to design in the early years of an engineering and engineering technology program have been shown to increase students' intellectual development on the Perry scale as well as overall student retention [8-10]. Moreover, the inclusion of design experiences early in the curriculum can help cultivate design thinking skills such as an inquisitive mindset, the ability to approach problems from multiple perspectives, as well as question existing norms [6, 11].

Dym et al. defines engineering design as: a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints [3]. Previous studies that have focused on the design skills of freshman engineering students or novice designers found that often they often spend little time properly defining the problem, and often fail to generate alternative design ideas, and overall spend much less time information gathering than that of more experienced designers [12, 13]. Moreover, while novice designers display less skills than more experienced designers, research has shown that even experienced designers struggle to properly define a given problem, engage in divergent thinking during concept generation, and even properly assess alternative designs [14-16]. Moreover, how freshman students handle design constraints has not been extensively studied at all. A goal of implementing design experiences into freshman-level courses are to not only enhance student retention, motivation, and intellectual skills as discussed previously, but to use these experiences to inform curricula throughout the remaining years based on skill deficits or misconceptions discovered. Hence a baseline of skills and proper understanding of engineering design protocol must be developed.

Methods

This study was guided by the following research questions:

- How do students assess their level of understanding of the problem, i.e., problem definition?
- What strategies were utilized to generate design ideas?
- Were alternatives ideas considered?

- Were constraints considered throughout the design process?

Participants

Eight mechanical engineering technology students agreed to participate in the study. All students were enrolled in a freshman introduction to engineering technology course at a large Midwestern university. Students volunteered to participate in the study without any incentives offered.

Design of the study

An open-ended design problem was assigned to the class. A description of the design task as it was given to the students is provided below. Students were instructed to focus on developing a solution(s) to the given problem that satisfied the requirements and constraints of the problem. Students were also told that CAD drawings were not necessary, only simple sketches were required, and no prototype development or testing of solutions was necessary. Following completion of the design project, participants were interviewed using a semi-structured interview protocol using the research questions stated above to guide the interview. The semi-structured interview format allowed the participants to think and respond to the questions and then elaborate with specifics or issues they felt were important. The research questions were intended to allow participants the opportunity to describe their design process in detail, but were sufficiently open-ended enough to minimize the possibility of the interviewee responding in a narrow way.

Description of the Design Problem

Find a way to counteract Vacuum effect as product volume decreases. Liquid dispenser systems, such as liquid soap and sanitizer dispensers, utilize collapsible containers filled with the liquid soap or sanitizer. The collapsible containers collapse due to vacuum pressure created in the container as the fluid is pumped out of the collapsible container. Often the collapsible containers twist when collapsing and interfere with operation of the dispensers. In addition, as the fluid draws down in the collapsible containers, the vacuum pressure needed to remove the fluid tends to increase. As a result of the increased vacuum pressure required to pump the fluid out of the container, the volume of the fluid output by the pump is inconsistent. In addition, the increased vacuum pressure requires additional force to operate the dispensers, which is of particular concern in electronically activated dispensers.

Requirements of the Design Problem

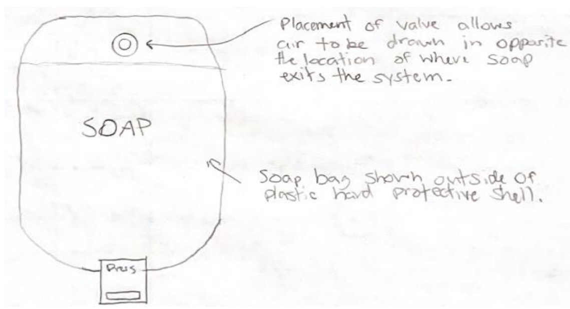
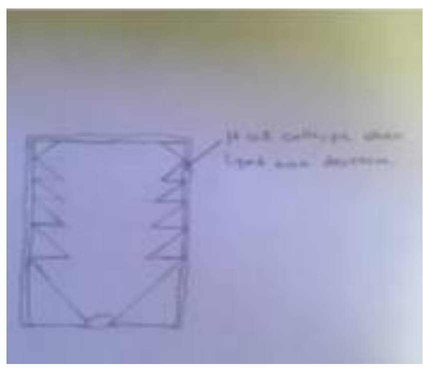
Re-design the system to avoid the issues described above. This could include bottle shape/material changes, additional components added or removed from/to the system, a completely new way of evacuating fluid from the dispenser, etc.

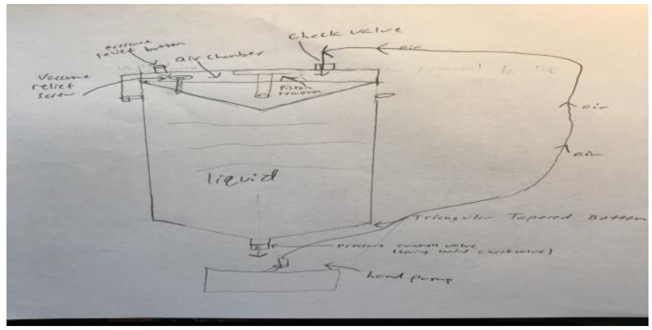
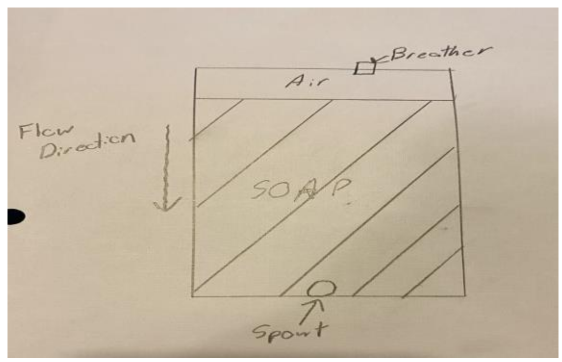
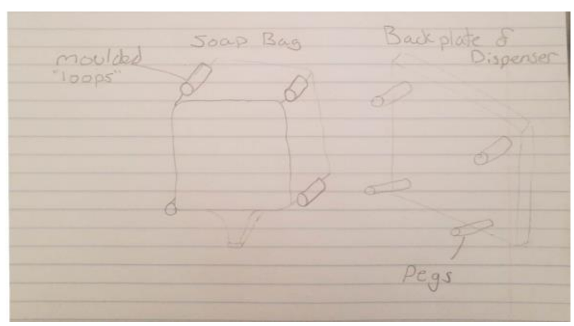
Constraints of the Problem

- Avoid making the system too complex (complicated for end user, expensive from manufacturing standpoint)

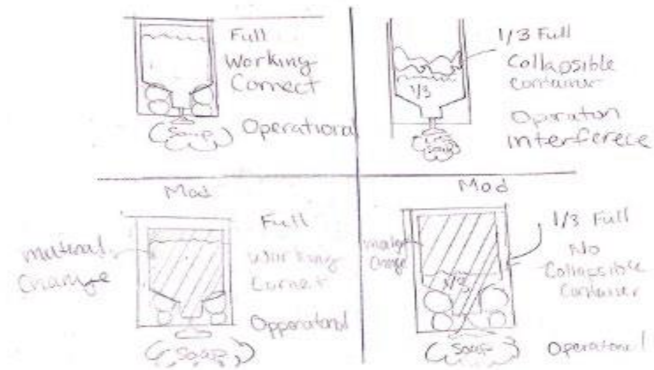
- Avoid making the system too bulky/cumbersome (additional weight added to the system not ideal; added transportation costs, added manufacturing costs, added installation time/difficulty.
- Avoid making the system too expensive (more expensive for manufacturer, more expensive for consumer)

Figure 1. Overview of Design Concepts

Pseudonym / Description of Concept	Design Sketch
Ben Use a small, one-way air valve, to allow a small amount of air into the system, relieving the negative pressure to allow the bag to not collapse as quickly as before.	
Rachel Redesign the bag so that it collapses in a controlled manner.	

Christian Eliminate the plastic bag, instead a rectangular plastic dispenser is filled directly with the fluid and a plastic air piston is placed on top of the fluid. As the user pumps the hand pump, the air pressure between the lid and air piston increases and causes the piston to push fluid out of the dispenser.	
Dan Install a plastic threaded breather cap at the top of each bag.	
Richard Add loops on each of the four exterior corners of the soap bag. Then add pegs either molded or threaded into the existing housing, this would hold the soap bag in an upright position and prevent it from collapsing and cutting off flow.	

<table>
<tr>
<td>John

Use a different material when creating the container. Change the material of
the container to something that is harder and stiffer with less ductility.</td>
<td>
</td>
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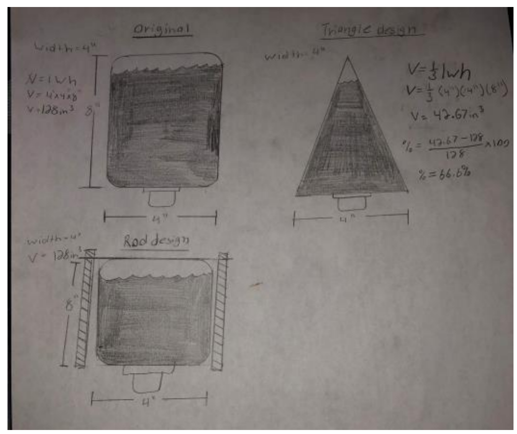
<tr>
<td>Ronald

Two potential designs: create triangle design that would prevent collapse or use two rods on either side of bag that would prevent twisting of bag.</td>
<td>
</td>
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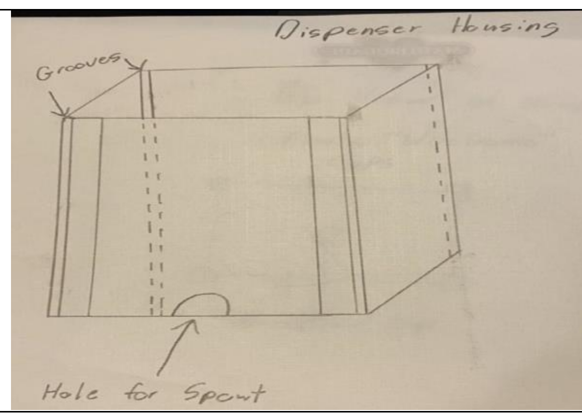
<tr>
<td>Eric

Install rigid plastic frame to prevent bag from twisting or deforming.</td>
<td>
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Findings

Defining the Problem

Defining the problem includes all activities necessary to ensure a designer understands the nature of the problem. This step is often considered trivial by inexperienced designers, and studies have shown first year engineering students often spend little time in the problem definition phase of design and this often results in lower quality solutions [12, 17]. Open-ended design problems are often poorly defined hence a certain amount of research is often required. The problem definition step often includes verifying what the problem is, understanding the end-user requirements that must be incorporated into any potential design, as well as the constraints inherent to the problem. These steps often require the designer to reread or question problem statements or information sheets, seek out similar designs to study there function, talk to end-users, search for and collect relevant data, among others [12].

Each student who participated in the study recognized the importance of adequately defining the problem. Rachel described how she attempted to put herself in the position of both the company manufacturing the product as well as the customer using the product to come up with a design that not only solved the problem, but was easy to use and manufacture:

> *"I did as much research as I could to understand why a vacuum gets created with each soap dispense, then I asked myself what type of design would make the company happiest, but not a make it harder for the end-user, or even the person installing this thing. Anyone can solve a problem, but that's what makes engineering so interesting, you have to consider other people as well, as well as manufacturing".*

Each student that was interviewed stated they began by reading the problem statement several times, a few students indicated they rewrote the problem statement in their own words, to make sure they had a grasp on what was being asked of them. Christian stated he wrote down the whole process of pumping fluid from the bottle to the user's hands and tried to understand everything from the initial force being generated on the dispenser to how this leads to a vacuum being created:

> *"This took a lot of time researching how the whole process worked, and granted I'm not sure I still understand, but I figured I couldn't design something properly if I didn't understand the process from start to finish, so I at least tried to do the research".*

While each participant indicated they researched the pumping operation online, only two students discussed observing the devices in-person. This was surprising considering each student had ready access to them as they are located across campus.

Strategies Used During Idea Generation Phase

The generation of ideas is a key activity in the design process [18]. However, research indicates students new to engineering design often do not devote enough time to concept generation, this leads to decreased innovative designs, as well as a lack of alternative designs with which to consider [19]. Several strategies were employed to develop ideas for initial concepts. Ben indicated that by focusing on the main problem, he was able to avoid becoming overwhelmed by the complexity of the entire system:

> *"I tried to focus on the main problem, air leaves the bottle every time you use it, and try to figure out how we can prevent that. I realized when I looked at the whole bottle and how it works, it was kind of overwhelming, but if you just look at the main problem, like I didn't even think about the bottle, just how can I prevent air from leaving, it made it easier to come up with a solution I think".*

Dan took advantage of the abundance of dispensers across campus and spent a significant amount of time experimenting with them, understanding how they operated, and visualized how a new design might be incorporated into it.

> *"We have tons of these across campus, so I went and used one over and over to get a feel for how it works, then I tried to see what device I could actually fit in there to prevent air from escaping. I really wanted to keep the overall size the same. I looked at each part of the dispenser separately and imagined modifying each of them separately, and then asked if this would solve the problem. If I could make a small change to an existing part, that would definitely be best".*

Rachel knew that she did not want to add anything extra to the dispenser, noting that anything she added would increase cost, and these were probably not designed to be expensive. Rather than prevent the problem, she attempted to control the consequence of the problem:

> *"I'm big on looking at problems from different angles you know, I couldn't find a way to add anything because I knew it would just make the whole thing bigger or more expensive, so I looked at the bottle, like is there way to make the bottle collapse how I want it to. You know, don't prevent it from collapsing, just try to control how it does if possible.*

<u>Dealing with Constraints</u>

Dealing with constraints is at the core of engineering design, it is what tailors a particular design to a particular context, and specifically it is what allows a design to satisfy a given set of user requirements. Often, constraints can be seen as limiting the potential design space, however, others have argued it allows for increased creativity because it forces a designer to go beyond obvious solutions and develop more creative concepts to solve a given problem [20].

Nearly every student described how the constraints of the problem helped them focus in on more practical ideas. Several reported that while it was still difficult to come up with the initial ideas, once you have it, the constraints allow you to focus the concept toward a more suitable design that would solve the problem and be feasible to manufacture.

Rachel described how the constraints helped her come up with a suitable design, while the absence of constraints would likely be overwhelming:

> *"I actually found the constraints helpful, it helped me narrow in on a useful design, rather than the infinite possibilities if we were allowed to design it any way we wanted"*

The first ideas that came to mind would have been to add extra parts or to make the bottle super rigid, but then I was like, wait, you are going to add all sorts of weight to thing not to mention increase the cost".

Christian described constraints as being central to engineering design, and how he always kept them in mind as he developed his initial concept. He admitted that he likely increased the cost of the product but felt his concept would have been more expensive without constraints:

"I know I added an extra cost to this product with my new design, but I feel like it would have been even more expensive if I were not thinking about keeping cost low the whole time. That's the hard part about engineering design, you can't just design what you want, that would be too easy. It has to fit within a certain budget. But I felt it also helped me come up with a design that's even better than I would have come up with otherwise"

Ronald described dealing with constraints as challenging because it seemingly adds additional complexity to the problem, but realized ultimately the constraints forced him to go beyond typical solutions and seek out more creative designs:

It can be tricky at first, because you're like there is no way I can design a new way for this to work without adding a bunch of weight or making the thing larger, but I feel like I was able to come up with a more creative design because the constraints kind of forced me too".

Consideration of Alternative Designs

An important stage in the engineering design process is the consideration of alternative designs, the evaluation of each of them, and the final selection of the alternative that is most appropriate to satisfy the requirements of the end user under the given constraints [12]. Only one student indicated they pursued alternative design for this project. Ronald described how he immediately came up with two designs that could work, however, after doing some initial calculations realized that while both would likely solve the problem, one design would considerably reduce the amount of soap in the bag, and therefore would not be appropriate:

"I wanted to solve the problem, but not have anything change too much, that was my goal. My triangle design would have worked but would have reduced the volume by nearly a third. Besides, I think it would have cost more to make, cost of new tooling probably".

Ronald indicated he considered other ideas, but decided one was probably more likely to work than the others, so he did not pursue any additional alternatives:

"I had another idea, but my first design seemed like the best, so I kind of let the other ideas go. I think I was focusing on the best one, I guess to answer your question, no, I didn't consider anything else".

No other student reported considering alternative designs. Rachel mentioned the difficulty in coming up with her initial design as her rationale for not pursuing alternative designs:

> *"I feel like I spent so much time thinking about my design and refining it, I feel like it was the best I could come up with, I don't think I could have come up with anything better. I feel like that's the hard part for me, I can understand the problem, and do testing and stuff, but coming up with the actual ideas is hard for me".*

John described being fixated with his initial design and commented on the difficulty with coming up with his initial design:

> *"I honestly didn't consider anything else once I had it in my head that my first idea would probably work. Honestly, it was so hard to come up with one idea that I don't think I could have come up with others. Besides, it would probably work fine, so there was no point in thinking about another design".*

Table 1. Observations of major themes

Themes	Observations
Defining the Problem	Three participants actively considered the end-user and manufacturing capabilities while they researched a solution to the problem. All participants noted reading the problem statement several times, and in some cases rewriting problem statement in on words to understand what is being asked. Two students reported breaking down the process into parts to understand how each component works and how this leads to the central problem. All participants researched soap dispensers/pumps online to understand their function. Two students reported studying the function of soap dispensers' in-person, to visualize the operation.
Strategies Used During Idea Generation Phase	One student used the strategy of focusing on the central problem rather than within the context of the whole system to avoid becoming overwhelmed by the complexity and losing sight of the problem. Two students reported observing dispensers' in-person helped them visualize the operation and made it easier to come up with a solution. One participant reported examining each individual component separately, and then imagined how it could be changed to solve the problem. One participant looking at the problem from different angles, and determined that rather than preventing the problem, try to control the consequence of the problem.

Dealing with Constraints	All students felt the constraints helped them decide on designs that would not be too expensive to manufacture or be too large. All students indicated they kept the constraints of the problem in mind as they came up with ideas. All students felt the constraints forced them to come up with more creative ideas.
Consideration of Alternative Designs	Only one student pursued an alternative design, it was determined that it would reduce the amount of soap available, so it was abandoned. Nearly all students indicated difficulty in coming up with alternative designs. Nearly all students went with their initial concept thinking that it was likely the best.

Discussion

This study examined how eight participants approached an engineering design task. Specifically, questions were devised to characterize how they approached defining the problem, to identify strategies used to generate ideas, understand how students navigated constraints of the problem, as well as whether alternative design ideas were considered. Table 1 summarizes the primary observations made regarding the primary research questions. The participants in this study had no prior knowledge of formal engineering design processes, thus any strategies or methods employed can be considered to have been initiated organically or possibly from prior exposure to other designers and their methods. Without formal training, many participants invoked strategies that are often used by advanced designers such as the consideration of the end-user, consideration of potential difficulties in manufacturing the product, as well as utilization of a top-down engineering design methodology whereby the whole system is broken down into its constitutive parts and examined separately.

Moreover, several students reported the use of sophisticated idea generation strategies to come up with potential solutions, including viewing the product from different angles, breaking down an assembly into its individual components and analyzing them separately, and working "with" the problem rather than trying to "fix" the problem. However, all students reported difficulty in coming up with alternative designs, suggesting they either fixated on their first concept or simply could not generate additional designs. It is clear that the participants took the necessary time to adequately define the problem and investigate possible root causes but spent less time than necessary generating alternative design ideas. This suggests while some students may have knowledge of idea generation techniques, students could benefit from formal training in how to generate alternative designs such as the use of heuristics [16, 19, 21].

Additionally, while all students reported performing online research to investigate the nature of the problem and gather additional needed information, only two indicated they sought out the actual product to see it in use so as to visualize the nature of the problem. Much information can be gained from viewing the actual device, including its physical size, real-time operation, as well as how other's use the product. This information can be useful in determining the root cause of the problem, as well as help the designer generate more potential solutions to the problem via improved visualization. Regarding constraints, the findings suggest participants were able to navigate the constraints of the problem well, and even used them to their advantage. Often novice designers complain that constraints narrow the range of possible solutions, thus making idea generation more difficult, whereas more experienced designers acknowledge that constraints allow for more creativity because obvious solutions would not likely satisfy the constraints.

Conclusion

This study used a small sample of participants to investigate how freshman mechanical engineering technology students, with no prior knowledge of engineering design processes, approach an open-ended design problem. This study found that while some students approach design in ways that are indicative of more advanced designers, in terms of some of the idea generation techniques used, and their ability to use constraints to generate ideas, there is a need for additional instruction to improve participants engineering design abilities. For example, training in more efficient techniques for determining the root cause of a problem during the problem definition phase, additional instruction in common methods of idea generation, as well as methods for selecting among alternative designs following the generation of ideas. Ultimately, the findings in this study have value for educators looking to improve their instruction in the area of engineering design.

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