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Design Conceptualization over Multiple Design Courses

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ABSTRACT

This research project's focus is to better understand how students are conceptualizing engineering design over their multiple design projects. We focus on a mechanical engineering program at a single institution that has course-based design experiences during each of the four years of the degree program. Data was collected through a survey given to 73 engineering students. The questions in this survey targeted student's conceptualization and relationship with design, as well as their demographics and course history. Open-ended questions focused on student responses about how they defined engineering design and what aspects of design they considered to be challenging or straightforward. Closed-ended questions focused on how often they have had opportunities to practice aspects of design, including working directly with a client and considering sustainability in their solutions. The open-ended questions were organized using a thematic coding system, then compared to the demographics and course history information. Themes among the responses indicate students' thought processes behind engineering design and their relationships with different aspects of design. For example, we found that students in the third-year level design course, which is mostly focused on technical details of design, are more likely to describe specific technical aspects of design as the most challenging parts of design, whereas students in the sophomore and senior level design courses are more likely to describe teamwork and communication as challenging parts of design. Additionally, we identified several areas where students have limited exposure to areas of design, including working directly with a client and considering the ethical implications of their solutions. These correlations point to areas where students may need additional help in design thinking.

BACKGROUND

A purpose of engineering design education is to support students' movement along the path from beginning toward informed designers. However, the pathways that students progress along this path are not straightforward. Often, students are introduced to engineering design as first-year students and do not see a design-focused course again until much later in their education, sometimes not until a capstone design experience in their final year. Both first-year and final-year engineering design courses have been studied in a variety of contexts (e.g. [1] - [4]). However, students' development of design skills in the 2nd and 3rd years of their undergraduate curriculum are not as commonly included in engineering curricula and require further understanding.

The curricula in several majors in our college include design experiences during each of the four years of the students' undergraduate education [5]. This study was conducted within a mechanical engineering program which requires courses with design projects each of the four years of the students' education. This curriculum offers students several opportunities to develop their design skills and for us to better understand how students' design skills develop through these different courses. In this study, we hope to shed some light on the ways that students understand engineering design at several points in their pathway. The aim of this research study is to address the research question: What are the changes in students' conceptualizations of engineering design over the course of their undergraduate education? This information can support the optimization of courses to better support student learning of engineering design.

Beginning engineering designers engage in engineering design in different ways than informed designers [6] - [8]. For example, informed designers are better able to weigh options and tradeoffs than beginning designers. Additionally, informed designers are more reflective in their practice and are better able to identify challenges in the design process. Effective engineering design requires professional skills beyond the purely technical, such as communication, teamwork, and time management [11]. However, these less traditionally technical skills are often not emphasized in engineering sciences courses and some studies have suggested that students' feelings about their professional responsibilities actually decrease over the course of their engineering education [9]. Additionally, these may not be as valued as important for their engineering education by students [10]. Having multiple engineering design experiences throughout their undergraduate careers offers students more opportunities to develop these skills in a variety of settings and to practice professional skills specifically without the added stress of also adding in high levels of technical knowledge and analysis.

METHODS

Context

This study was conducted at a large, undergraduate focused university in the western United States. The university is 48% women and 52% men, 15% of students are from out-of-state, 1% international students, and the remainder are in-state students. The College of Engineering has the largest enrollment. The student body is 53 % white, 19 % Latino or Hispanic, 13 % Asian, 1% Black and 0.1% Native American. The university focuses on a hands-on, experience-based philosophy.

This study was conducted within the mechanical engineering department. The mechanical engineering department has a series of design courses that span across the four year curriculum. Students take an introductory mechanical engineering course during their first term at the university that includes a small scale (about three weeks) design project and an introduction to the engineering design process. Students take a 2nd year level design course that is focused on a more in-depth look at engineering design and includes a larger design project. The 2nd year course focused primarily on aspects of design including teamwork, ideation strategies, creative confidence, communication of design ideas, and problem definition, including working with stakeholders and users. During their third year, students take a series of two technical design-focused classes that both include labs in which students engage in a variety of design projects. These two courses are heavily analytical. Lastly, students engage in a yearlong senior design experience working with an external sponsor. All of these courses are required components of the mechanical engineering curriculum.

Data Collection

To gain an understanding of engineering students' conceptualization of engineering design, a survey was given in the Spring Quarter of 2023. Several different instructors in the mechanical engineering department distributed the survey in their design classes as an optional, online survey. In total, 73 participants completed the survey. Approval from the institution's IRB was obtained before any survey data was collected. The survey included four open-ended questions, seven closed-ended questions, and questions about demographic information. The open-ended questions target students' conceptualization and relationship with engineering design. To begin, students were asked the following four open-ended questions:

1. In your own words, what is engineering design?
2. Describe up to two components of engineering design that you consider to be especially challenging.
3. Describe up to two components of engineering design that you consider to be straightforward or simple.
4. How and to what extent do you think you will use the engineering design process in your future career?

The closed-end questions recorded their experiences with design thinking. Students were asked how often they had experiences with each of the following. These questions only allowed the following answers: "Never", "Once", "2-3 times", or "4 or more times".

- Worked with a team on a design project.
- Had an idea you developed that failed.
- Tested and refined a solution idea.
- Considered ethical implications of your solution idea.
- Considered sustainability implications of your solution idea
- Communicated your design ideas directly to a client or customer
- Communicated your design ideas in multiple ways (e.g. written report, oral pres., etc.)

Additionally, after these questions, the survey contained questions about demographic information and course history/design experiences. These questions were:

1. Which of the following courses have you completed? Select all that apply. (Answer choices were a list of all design courses in the mechanical engineering curriculum)
2. Which of the following courses are you currently enrolled in? Select all that apply. (Answer choices a list of all design courses in the mechanical engineering curriculum)
3. What is your current level? Please include the total years you have been enrolled in post high school education, even if they weren't all at [University name]. (Answer choices were 1st year student, 2nd year, 3rd year, 4th year, 5th year, 6th year or more).
4. What is your major? (Fill in the blank response)
5. What is your race/ethnicity? (Fill in the blank response)
6. What is your gender? (Fill in the blank response)

Data Analysis

To begin the data analysis, the data were first organized based on the question type and each type of question was analyzed separately. Descriptive statistics were taken for the demographic information, course history, and closed-ended experiences questions. A thematic-coding system was utilized to organize and analyze the open-ended student's responses. A thematic code is an identified common theme or idea among various qualitative response [12]. The codes were created after initially reading all the responses and then identifying any recurrent patterns. One author developed the initial codebook and made iterative revisions through discussion with the other author. The analysis process for each open-ended question was conducted separately. Eight codes for Question 1 were created. Eleven thematic codes were created for both Questions 2 and 3. The codes for these two questions were the same since both questions are similar. The identical codes allowed for comparisons between what students find challenging and simple in engineering design. Finally, six codes were identified for Question 4 that describe the attitude or likelihood students will use the engineering design process in their future. Some of the responses may contain elements of various thematic codes. This is especially the case for responses to Question 1. Many students stated that engineering design is problem-solving but mentioned aspects of the other themes as well. In these cases, one code for any response that mentions problem-solving was created as "Problem & Find a Solution". All the other thematic codes to Question 1 do not mention problem-solving in any manner (as seen in Table 1). The codes and descriptions are included in Tables 1, 2, and 3. Examples are included in the results section.

Table 1. Question 1 Thematic Codes

Code	Description
Problem & find solution	Engineering Design is having or defining a problem and then finding a solution. This code applies to a response that has any mention of problem and solutions
Ideation/creativity	Engineering design is creating and developing ideas. The focus of the response is on these ideas, but they can be related to criteria and other concepts.
Engineering Design Process	The response to these questions outlines the steps of the engineering design process. It does not have to specifically write "engineering design process."
Meeting need of client / criteria	Designing for a user or based on given criteria and constraints.
Engineering principles and failure	Designing using engineering and scientific principles to prevent failure: strength, fatigue, materials, etc.,
Projects/design for communities	Responses include that designs or projects can impact people and communities.
Design is Building and Developing	Engineering design is the process of building products or developing designs / ideas. This is like the Ideation/Creativity code, but the focus is on the process of making something not the ideation.
Other	Too vague and/or too different from established codes

Table 2. Question 2 and 3 Thematic Codes

Code	Description
Ideation and Brainstorming	The initial process of ideation and brainstorming possible solutions.
Technical Work	The technical work behind engineering: mathematics, stress analysis, drafting, and 3D modeling.
Research & Stakeholders	Conducting research on the problem, previous solutions, and stakeholders
Finalizing a Design	The process of finalizing a design, knowing when to stop iterating.

Choosing and developing a Design	Initially choosing a design after the ideation phase includes weighing all the constraints and criteria. Also includes choosing a design that is innovative.
Finding and Defining a Problem & Constraints	Finding and defining a problem and the corresponding constraints.
Communication and Collaboration	The communication and teamwork aspects of engineering design. Working with others and communicating ideas and designs.
Modeling, Prototyping, building	The process of modeling one's idea (drawing, CAD, etc,.), prototyping and testing this idea, and then manufacturing it.
Iteration, Redesign, Troubleshooting	The portion of engineering design the requires the designer to iterate, redesign, and troubleshot issues that arise.
Collecting & Working with Feedback	Acquiring feedback on designs and then working with the feedback.
Other	Too vague and/or too different from established codes, miscellaneous

Table 3. Question 4 Thematic Codes

Code	Description
Want to Become a Design Engineer	Specify that they wish to work in design or be a designer engineer and that they'll use EDP a lot
Will use it	Specify that they are or expect to use the EDP in their future
Maybe / Unsure	Unsure whether they will use the EDP or are unsure of what they'll be doing in the future
Engineering Design Process is Useful	Doesn't specify that they will use it in their future career, but mentions that it is useful either in the mechanical engineering field to life's problem
Not Very Much	Specify that they will not use the Engineering Design Process that often in the future
Other	Too vague and/or too different from established codes, miscellaneous

After the organization of the open-ended responses into thematic codes, questions were compared against each other. Open-ended thematic codes were compared against course history information, demographic information, and the closed-ended responses. Closed-ended experience responses were compared against course history and demographic information.

RESULTS

In this section, we describe the results of first the demographic and contextual data, then the quantitative results, the qualitative results, and finally patterns across the data types.

A summary of the demographic information reported in the survey is displayed in Figure 1.

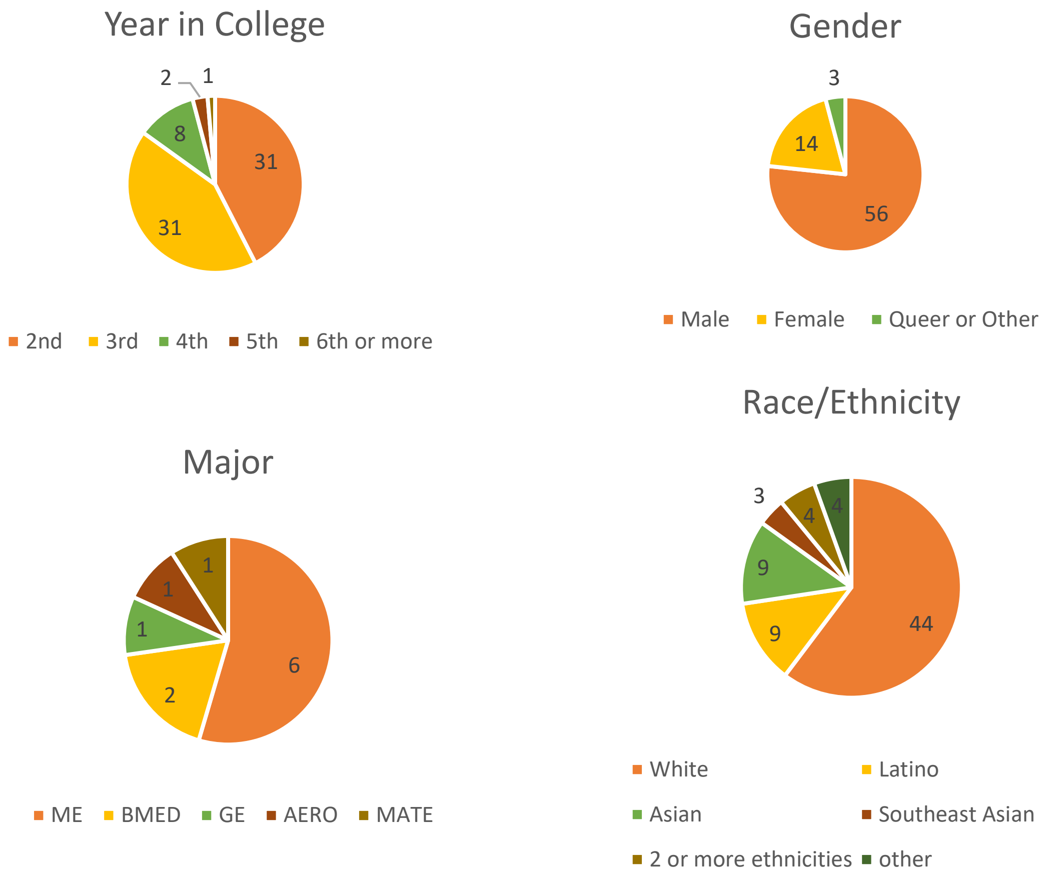

Figure 1. Students' self-reported demographic information. Ethnicity was self-described.

The demographic information of the students surveyed, particularly the gender and race/ethnicity demographics, are similar to the overall makeup of the college of engineering at the university. All the surveys were distributed in mechanical engineering courses, however, there are several majors represented outside of mechanical engineering because these students were enrolled in the mechanical engineering courses that the survey was distributed in and were taking these courses as electives.

Quantitative Results

Figure 2 shows the number of responses to each of the closed-ended survey questions.

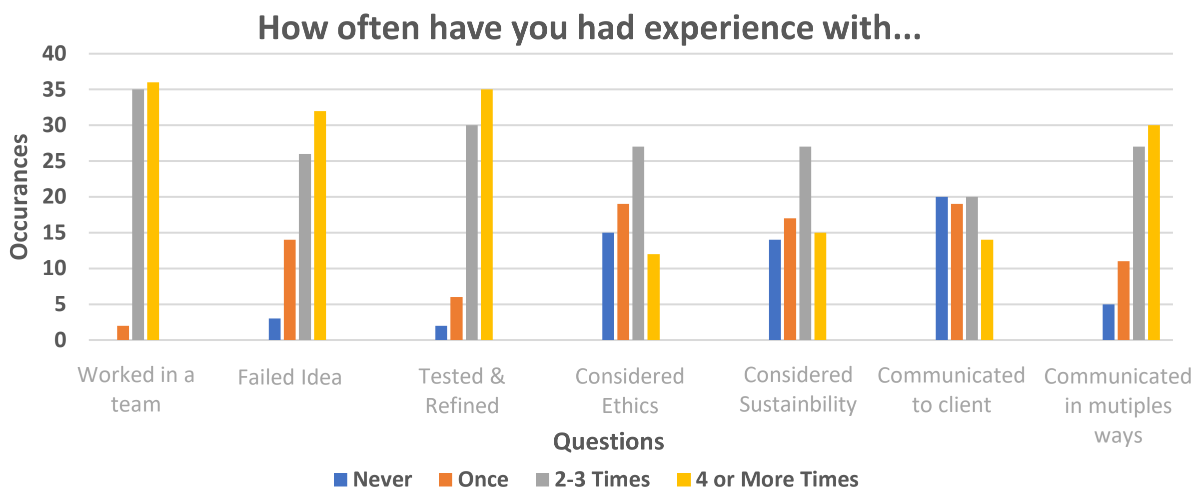

Figure 2. Summary of responses to the closed-ended questions.

As shown in Figure 2, all the student participants have worked in a team on an engineering design project at least once, with a majority having done so four or more times. Furthermore, a significant majority of the participants have tested and refined a solution idea at least twice. However, less students have considered the ethical or sustainable implications during design thinking. More participants answered "never" or "once" than those answering "4 or more times" to having considered ethical implications for their solution idea. A similar phenomenon is seen for considering sustainability. Additionally, fewer students have experienced communicating solution ideas directly to clients or customers. Most of the students either have never or only once communicated their ideas to clients. On the other hand, many more participants have communicated the solution ideas in various ways.

Qualitative Data

Summary of Thematic Code Analysis

In this section, we report the results of the open-ended survey questions. Specifically, we provide examples of the top responses for each of the coded themes, as well as comparisons across the themes and the demographic information. Table 4 summarizes the thematic code occurrence for each qualitative question.

Table 4. Total Thematic Code Occurrences

Code	Total Occurrence	Percentage of Responses
Question 1		
Problem and Find Solution	44	60.3
Ideation/creativity	3	4.1
Engineering Design Process	4	5.5
Meeting need of client / criteria	5	6.8
Engineering principles and failure	7	9.6
Projects/ design for communities	4	5.5
Design is Building and Developing	4	5.5
Yn		
Other	2	2.7
*Question **		
Ideation & Brainstorming	22	18.2
Technical Work	21	17.4
Research & Stakeholders	7	5.8
Finalizing a Design	5	4.1
Choosing & Developing a Design	18	14.9
Finding & Defining a Problem	15	12.4
Communication and Collaboration	6	5.0
Modeling, Prototyping, Building	14	11.6
Iteration, Redesign, Troubleshooting	5	4.1
Other	8	6.6
Collecting & Working with Feedback	0	0.0
*Question 3**		
Ideation & Brainstorming	23	18.5
Technical Work	16	12.9
Research & Stakeholders	9	7.3
Finalizing a Design	0	0.0
Choosing & Developing a Design	0	0.0
Finding and Defining a Problem	12	9.7
Communication and Collaboration	3	2.4
Modeling, Prototyping, building	47	37.9
Iteration, Redesign, Troubleshooting	2	1.6
Collecting & Working with Feedback	5	4.0
Other	7	5.6
Question 4		
Want to Become a Design Engineer	7	9.6
Will use it	51	69.9
Maybe / Unsure	4	5.5
Engineering Design Process is Useful	6	8.2
Not Very Much	3	4.1
Other	2	2.7

* Questions 2 and 3 percentages are based on their respective sum of responses for each question.

For Question 1, 60.3% of the responses were coded into the *Problem and Find a Solution* theme. Responses to this theme include "engineering design is finding a problem and coming up with a solution or looking at a similar design and improving upon it" and "process of creating for a solution for a specified problem while incorporating all human and machine aspects." The remaining codes have a similar percentage of responses each; all below 10%. The next highest percentage, 9.6%, was for the *Engineering Principles & Failure* code. Some examples include: "Being able to create anything and account for when things will fail" and "Engineering design is the art of creating and documenting parts that function as needed, in terms of rigidity, strength, effectiveness, and ease of manufacturing." Lastly, the code *Meeting need of customer / criteria* contains 6.8% of the responses and include examples such as: "producing a product or service within a client's parameters" and "identifying a thorough list of needs and requirements and designing with those in mind."

Questions 2 and 3 asked about challenging and straightforward aspects of engineering design. Because of the similarities in the responses, the same coding framework was used for both questions. Question 2 asked students to identify what they deemed up to two aspects of engineering design that they found challenging. The responses were much more distributed among the various thematic codes than question 1, with the top choices all being under 20%. The highest percentage of responses, 18.2%, said that *Ideation & Brainstorming* is the most difficult. Some responses simply stated "ideation", while others were more descriptive: "A good brainstorm is challenging. It is hard not to get too attached to ideas and to really get a good breadth of different ideas" and "It is challenging to brainstorm ideas without bias". The next most frequent code is *Technical Work* with 17.4%. Many of these examples, included specific technical aspects, such as "Castigliano's [method]" and "linear analysis." The third highest percentage of responses stated that *Choosing & Developing a Design* is challenging. Participants with responses in this code stated that it is challenging to know "what to use when multiple designs all seem to be a good fit" and that "it can be difficult to keep in mind all design considerations for a given problem." It is important to note that no one mentioned that *Collecting & Working with Feedback* was difficult, although four percent of participants mentioned this code in question 3.

The responses for Question 3, describe up to two things you consider to be simple or straightforward about engineering design, are more dispersed than the previous question. About 38% of the responses are separated into *Modeling, Prototyping, & Building* code. Examples include "manufacturing" and "one simple component of engineering is designing your project in SolidWorks or drafting it by hand". The next most frequent code is *Ideation & Brainstorming* with 18.5%. The responses within this code include "brainstorming ideas for the overall design," or simply, "ideation." About 13% of students also highlighted that *Technical Work* is a straightforward aspect of engineering design. For example, students stated that "pressure cylinders" and "mathematical representation" are simple.

Lastly, Question 4 asked students to consider the possibilities of using engineering design in their future. A high majority of about 70% of the respondents had responses that fell into the code *Will Use it.* Example responses include "I suspect frequently, whenever checking the parameters and durability of material or tool or product in service and production", "constantly", and "I will use it a lot". The next most frequent grouping of participants specifically state that they *Want to Become an Engineer* with 9.6% of responses in this code. Responses in this code include "a long-term goal of mine is to work in design for renewables, so I think it will be the most important aspect of my career" and "I want to become a design engineer so a lot." Next, about 8.2% of respondents simply mentioned that *Engineering Design is Useful* without stating any personal plans or if they would use it. Some examples of the responses in this code are "the engineering process can be used not only designing a new thing but also remodeling existing designs to improve their performance" and "even if not pursuing engineering directly, the engineering design process is a great fundamental tool to approach any decision in life and to some extent I apply aspects of it daily."

Comparisons between Questions: Differences across groups

Once the responses were all grouped into their respective codes, comparisons were made between the thematic codes of each question against the demographic and course history data. We report findings from these comparisons in this section.

After analyzing the qualitative responses, multiple observations were seen in the differences of responses across gender. One notable observation was that all 37 responses that specified *Technical Work* as either challenging or simple identified as male. Similarly, all the respondents whose definition of engineering design falls under *Engineering Principles & Failure* code identified as male. However, respondents who identify as female tend to consider ethical implications more frequently. Only 48% of male participants answered "2-3 times" or "4 or more times" to having considered ethical implications while 71% of the female participants answered the same. Likewise, female identified respondents more often specified *Ideation & Brainstorming* as a simple component of engineering design; 57% of identified females compared to 23% of identified males. However, the distribution among gender for the response saying *Ideation & Brainstorming* as challenging was more even; 30% male and 26% female.

Along with the differences across gender, disparities in the responses are seen between class levels and course history. Five out of the six participants who stated *Communication & Collaboration* as difficult in engineering design are both in their 2nd year of undergraduate study and were enrolled in the 2nd year design course, which is heavily focused on developing communication and collaboration skills. Many observations were seen among the students who were taking the 3rd year design course and responses. About 72% of the responses specifying *Choosing & Developing a Design* as challenging were enrolled in this course. In addition to identifying as male, all participants who either stated *Technical Work* as challenging or simple and whose definition or engineering design included *Engineering Principles & Failure* were enrolled in the 3rd year design course.

Limitations

A limitation of this study is the small scale of the survey. 73 student responses were collected (the department has about 1200 students). However, the demographic information shows that the sample of students in the survey was fairly representative of the major and college as a whole. We are interested in expanding our study to include more students to gain a better picture of more students' experiences. Additionally, we had very few responses from first year students. This was primarily because the survey was distributed during the spring term and we do not have a course all students in the major take during the spring term as first year students and it was harder to reach them.

Discussion and Implications

Our results show that students had a variety of ideas and experiences about engineering design. Almost all the students had multiple experiences with design that included working with a team, testing and refining an idea through failure, and communicating their ideas in a variety of ways. These are challenging skills and important skills for students to practice and it is encouraging that students are gaining experience and practice with these skills and recognizing that they have had these experiences. This is also in line with the "learn by doing" based learning philosophy of the university, so it is positive to see that students are gaining several design experiences. However, there were other design skills that students did not recognize having practiced, including considering ethical and sustainability implications and working directly with a client. This points to areas of design that instructors can work to include more of in their courses. These findings are in line with other work that have shown the difficulty of integrating ethics into design education and

Our results also show that through the course of their design experiences, many students in the survey have developed ideas about design that are in line with high quality design practices [5], as shown in their responses to the open-ended questions. For example, many students' definitions of engineering design focused on the problem that needed to be solved and students were able to identify the challenge of avoiding idea fixation and dealing with bias in their designs.

All the results of our study are based on students' self-reported experiences. Therefore, it is possible that students had experiences with these topics and did not recognize them as such. If this is the case, instructors can be more transparent about their course activities and help students recognize when they are practicing these skills. Additionally, these results yield insights into students' ways of thinking about complex design issues. For example, a large percentage of students described aspects of modeling, prototyping, and building as simple or straightforward aspects of design. This could potentially be due to how these topics are presented to students. For example, it could be that in their manufacturing classes, students are given relatively straightforward work and therefore see these topics as straightforward.

Our data indicates that students' conceptualization of engineering design is influenced by what course they are currently taking. For example, the students surveyed who were currently in the 3rd year design course, which is heavily focused on technical aspects of design, were more likely to mention the technical aspects of design as being either the most challenging or the most straightforward and less likely to describe communication as challenging in design than the students in the 2nd year level design course, which has a heavy focus on communication. This points to the importance of revisiting skills from previous courses in order to continue to strengthen those skills. For example, instructors should continue to emphasize communication in the third-year course, in addition to the technical aspects.

Interestingly, students were equally likely to report ideation and brainstorming as challenging (18.2%) and simple (18.5%). This could indicate that students are practicing these skills in other contexts, such as clubs, which are very popular at this university, and certain students are getting more experiences with them. It also supports the importance of having diverse teams of students that can support each other in developing these skills. Students who consider brainstorming to be simple can share strategies with their teammates who consider it to be challenging and students who consider brainstorming to be difficult can challenge their teammates to push their ideation to new limits.

CONCLUSION

This study aimed to examine how students' conceptualizations of engineering design changes over the course of the education in a curricular program that includes several courses with design experiences. Overall, we found that many students identify engineering design as focusing on a problem and finding the solution, in line with high quality design practices. We found that students had many experiences working on teams and testing their ideas, but less experiences with considering the ethical and sustainability implications of their designs. We found differences across gender and course history. However, our sample size was too small to make wider generalizations about these findings.

We hope to continue this work by conducting follow-up interviews and further interpreting the results. We are interested in how students' extracurricular activities may include the results as well, such as if they have completed any internship experience or been involved in any engineering design clubs. This question may reveal why students are getting little experience communicating solution ideas to clients. Along with the additional information collected from the interviews, the survey results can be further interpreted to identify ways to improve courses and support students learning of engineering design.

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