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Assessing the Impact of an Intro to ME Course on the Capstone Design Process

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Assessing the Impact of an Introduction to Mechanical Engineering Course on the Capstone Design Process

Abstract

Engineers use scientific principles to design and build machines, structures, and other items to support humanity. A fundamental understanding of the design process and applying it to novel, ill-defined problems and situations is integral to success as an engineer. Introduction to engineering courses have become ubiquitous in engineering programs across the nation. These courses provide first-year students with a broad overview of the engineering profession and often provide students an introduction to the process of design work. These experiences provide a foundation for further design implementation throughout the rest of their undergraduate curriculum. Creating these courses pulls design curriculum forward from where it has historically been taught as part of the capstone design experience. Correspondingly, implementation of these early introductory engineering courses may influence student aptitude in their capstone design experience.

The mechanical engineering program at The United States Military Academy (West Point) recently implemented a new Introduction to Mechanical Engineering course (Intro to ME) for first-year mechanical engineering majors (sophomore-level students). This course provides a range of introductory-level content to include the study and application of the design process. The course was developed with the intent to provide students a broad understanding of mechanical engineering profession and the design process so that further technical curriculum could be properly situated within the larger framework of engineering design and analysis.

The purpose of this paper is to assess the implementation of the Intro to ME course on the students' aptitude in their capstone design experience. This qualitative research examined the anonymous survey responses of mechanical engineering faculty that served as capstone design team advisors in the 2019 and 2020 academic years. These years provided longitudinal data corresponding to the last cohort of students that did not receive the new introductory course, and the first cohort that did. All data evaluated their skill levels during their senior year capstone design experience. Therefore, the survey was a direct opportunity to assess the result of an early introduction to the mechanical engineering profession and design process.

The paper assesses the effect of the Intro to ME course on student grasp of the design process and their ability to apply the process to their capstone design project. Overall results were mixed with faculty indicating that students who completed the Intro to ME course differentially applied the design process but also had fewer gaps in their knowledge of the tools associated with the design process. Furthermore, there were no indications that the Intro to ME course provided a negative impact on the capstone design program. Faculty indicated a need to further integrate elements of the design process across the curriculum. The results provide ME faculty insights into how implementation of an Intro to ME course may affect the capstone design process at their own institutions.

Introduction

Design is an essential element of engineering practice [1]. Early design experiences for undergraduate engineering students in the United States has been an increasing trend since the late 1980's, motivated by a recognition that undergraduate engineering students often began their exposure to this fundamental concept late in their engineering studies [2]. This exposure to design processes typically happened in a *capstone design course* where student engaged in a significant culminating design experience as encouraged by ABET accreditation requirements [3]. Unfortunately, engineering faculty began to recognize that undergraduate engineering students across the nation often did not see engineering faculty until their third year of study [3]. Leaving study of the design process to junior or senior year prevents students from employing multiple applications of design throughout the formative engineering study and may limit a student's ability to understand and apply the design process upon graduation.

Previous student design research has indicated that students may increase in their understanding and application of the design process as they progress in their undergraduate engineering studies. Koen [4] claims engineering design is a repertoire of behaviors that may take time and repetition to develop in undergraduate engineering students. Dym [5] advocates for project-based learning courses as the venue by which design is most effectively taught while acknowledging the in-efficiency of these types of courses in terms of time and faculty effort. Atman et al. [1] identified that senior-level engineering students produced higher quality designs when compared to first-year engineering students. Seniors gathered more information, considered more alternatives, transitioned more frequently between design steps, and progressed further down the design process than their first-year counterparts. Lulay et al. [4] explain the use of a "design spine" in the mechanical engineering curriculum—threading the concepts throughout the curriculum to better prepare undergraduate engineering students to apply the design process in their senior capstone course. Their experiences show similar trends of increasing comfort with the engineering design process for students in their third and fourth years. To the contrary, other research (i.e., [7]) indicates that design thinking skills may decrease throughout a four-year undergraduate engineering experience. Today, these early design experiences are often included in introductory engineering courses, typically taken in the first/freshman year, and referred to as *cornerstone design courses* [3]. In these courses, students often engage in problem-based education experiences that allow them to learn the design process by applying the process to one or more design problems.

Faculty in the mechanical engineering program recognized the need to create earlier design experiences for their students to allow for greater understanding and ability to apply the engineering design process in their senior capstone design courses. Therefore, they developed and implemented an Intro to ME course to expose the students as soon as they entered the major at the beginning of their sophomore year. This course will be further discussed in the section that follows. This study aimed to assess the efficacy of implementing the Intro to ME course toward increasing student understanding and application of the design process in their capstone design course. This study correspondingly addresses the following research question:

RQ: How does the implementation of a design-focused Intro to ME course change faculty perceptions of the students' ability to understand and apply the design process?

Background

This is an action research study; the researchers are using the assessment to make positive change within the mechanical engineering curriculum at West Point. The sophomore-level Intro to ME course was developed with the intention of exposing mechanical engineering majors to the concepts of innovation and design much earlier so that they could draw upon this knowledge throughout their engineering education. Specifically, the design process shown in Figure 1 is taught to the students to emphasize the steps of *Defining, Conceptualizing, Designing, Implementing,* and *Testing* within a cyclical, iterative framework. The Intro to ME course also uses the design process as a framework to introduce team dynamics, technical communication, and fundamental manufacturing processes. The program's traditional senior-level capstone design course taught in the fall of the 2019 academic year condensed the design-related instructional content into a ten-lesson sequence (over the course of four weeks) to maximize time for the two-semester capstone design project that was completed over approximately eight months. In many ways the sophomore-level course mimicked the senior-level course; however, the content was spread over an entire semester to provide more time for learning and repetition, culminating in a small-scale, six-week project that mimicked a capstone project. The sophomore-level course was taught for the first time in the fall of 2017 (2018 academic year) to the students that would complete their capstone course in the 2020 academic year. As seniors, those students subsequently participated in a four-lesson review of the design process content that they had learned two years prior. The timing of the course implementation provided the opportunity to survey two cohorts that received different instructional paradigms during two consecutive fall semesters: the last cohort to receive only senior-level instruction and the first cohort to receive sophomore-level introduction to the material through the Intro to ME course (2019 and 2020 academic years respectively).

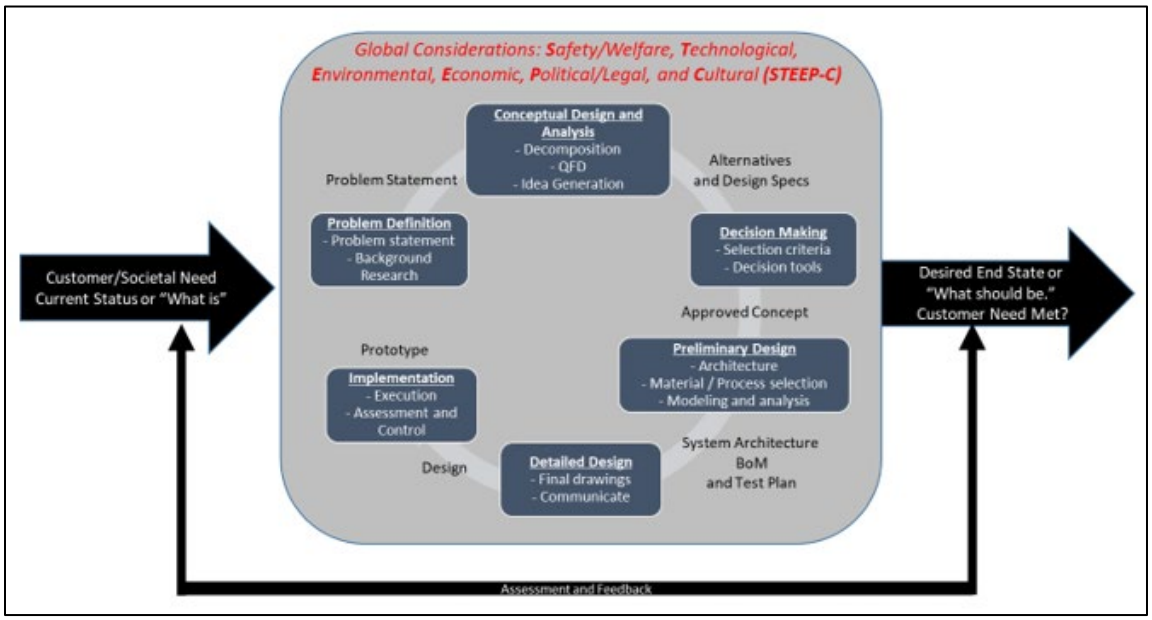

Figure 1: Civil and Mechanical Engineering (CME) Design Process

In addition to the faculty survey that is the subject of this paper, an analysis of when design is deliberately taught and assessed in the "middle years" (i.e., sophomore and junior years) was also conducted in 2019. While the middle-years design content was a control for both cohorts in the current analysis, it provided context to the authors for what the mechanical engineering majors in both cohorts experienced regardless of whether they completed the sophomore-level course. The results of this analysis showed that, of the eleven required courses in the mechanical engineering curriculum, four of them reinforced the aspects of the design process and seven provided assessment of the students' understanding. Further, most of the instruction and assessment occurred during the students' junior year. This suggested that the students in the traditional cohort had some prior exposure to the design process before it was formally taught to them in their senior year, and the students in the new instructional paradigm had that content reinforced after they first learned it in their sophomore year.

Methods

This informal, qualitative research study was implemented in the 2019 and 2020 academic years to assess the effects of implementing the Intro to ME course on faculty perceptions of senior-level students' ability to understand and apply the CME Design Process during their capstone design course. The last cohort of students to take the capstone design course without having taken the sophomore-level course was in the fall of the 2019 academic year. The first cohort of students to take the capstone design course, having also taken the sophomore-level course, was in the fall of the 2020 academic year. All faculty and lab technicians serving as advisors or co-advisors in the capstone design course sequence in the mechanical engineering program were the population of interest for this study. In the weeks prior to the completion of the spring semester, faculty and lab technicians were invited to voluntarily participate in an online survey administered by the capstone design course directors. The participants received the link to a Google Forms survey via email. The survey asked the participants to identify their role in the capstone design course (Advisor, Co-Advisor, or Technician), asked two closed-form questions regarding students' understanding and ability, and then asked faculty to identify problematic aspects of the CME Design Process from a pre-formed list. Verbatim question and response text is included in the figures for each question shown in the Results and Discussion section below. The final survey question asked the participants for any additional thoughts they may have. All results were exported to Excel. The closed-form responses were plotted in Excel and insights gained through discussion amongst the authors. The responses were converted from a count of responses to a percentage of total responses to normalize across two different response rates, further discussed below. The answers to the free response questions were analyzed by the authors to identify the themes that emerged. Results were socialized among the authors to confirm they adequately represented the voice of the participants and in-vivo coding (in the participant's own words) [8] used to summarize each of the themes that emerged.

An approximate permutation test [9] was used to assess the statistical significance of the closed-form results. To conduct the test, the responses to the *understanding* and *application* questions were quantized on an ordinal scale from zero to three with zero corresponding to "I don't know" and three corresponding with, "Yes they pick up the CME design process quickly" or "Yes they apply the CME design process seamlessly". A binary variable was established that defined "success" as whether the faculty response was a two or three on the ordinal scale. For the *skill*

question, a binary variable was developed for each skill. For these responses, "success" was defined by not lacking the skill. For all questions, the test statistic was defined as the difference between the "success" proportions of the without Intro to ME and with Intro to ME treatment. Additionally, for all questions, the null hypothesis was that the Intro to ME course has no effect on the results, allowing the treatment to be permuted (or shuffled) across the results, thereby providing a realization of the test statistic under the null hypothesis. This process was repeated 10,000 times for each question using the statistical program "R" [10], which yielded sampling distributions for the tests.

A total of 25 faculty and technicians participated in the Spring 2019 survey (without introductory course) and 18 faculty participated in the Spring 2020 survey (with introductory course). Figure 2 shows the breakdown of the participants across the two academic years. This figure shows that participants represent faculty that are both primary- and co-advisors (or both) for student capstone design teams. Capstone projects in the mechanical engineering program are assigned both primary advisors and co-advisors. The primary advisor's role is to provide the first level of oversight, supervision, and advisement to the team. They are typically with the team every class meeting, they serve as the primary grader of student work, and they naturally feel a significant degree of responsibility for team success or failure. Co-advisors are assigned to each project for several reasons. Co-advisors provide supplemental grading, especially for major events such as large design reviews with sponsoring organizations, major written submissions, etc. The co-advisors are also often assigned based on their technical subject matter expertise. Although they may not see the team each class period, they maintain close enough contact with the team that they can readily assess their application of mechanical engineering design. A significant number of faculty members serve as both a primary and a co-advisor, so they are involved with at least two projects. This population is depicted in the third group in Figure 2. This also helps faculty maintain broader situational awareness of team performance across the program. Finally, the lab technicians also work closely with students and have years of experience in seeing both high- and low-performing teams.

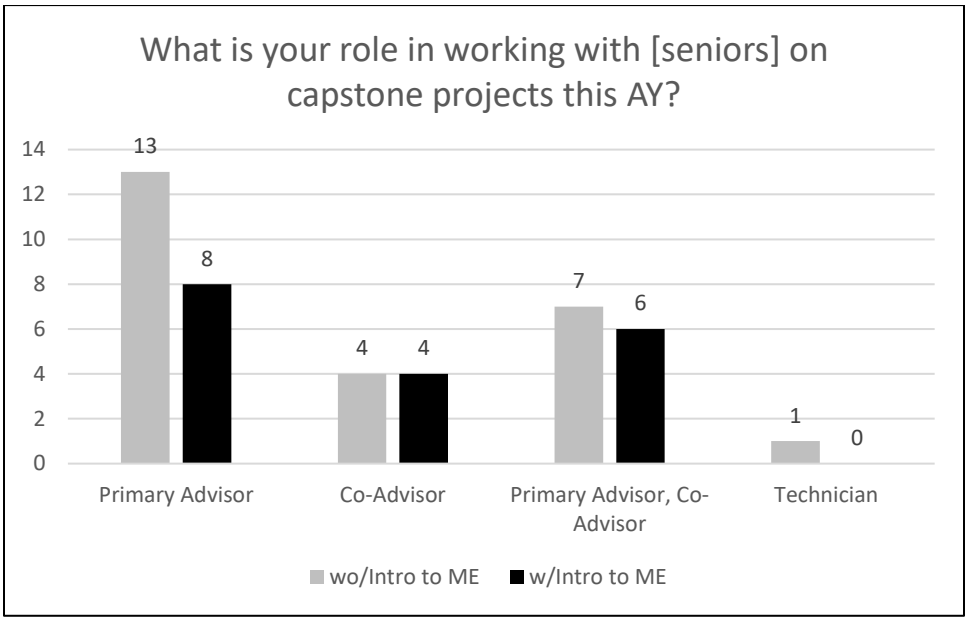

Figure 2: Breakdown of Survey Participants for each student cohort

Limitations

The authors acknowledge several limitations for this study that should be considered when interpreting results. First, this study was conducted as informal, action research aimed at continuous improvement of the mechanical engineering curriculum. Correspondingly, the results may be considered anecdotal at best. Because the authors are all capstone design faculty, there is an element of member-checking involved in the synthesis of results. A more robust process to ensure trustworthiness of the results was not undertaken. Second, the results may be biased toward a positive impact of the Intro to ME course on student performance. As discussed previously, the mechanical engineering program implemented the Intro to ME course to bring the CME Design Process forward in the curriculum and allow for greater practice and repetition prior to the capstone design course in the senior year. Correspondingly, faculty may tend toward a confirmation bias because faculty expected a positive result from the implementation of the Intro to ME course and were aware of the difference between the two cohorts of students. Third, this study may suffer from selection bias. The research process did not ensure a representative sample of the capstone design faculty. As a result, the faculty that participated may harbor either strong positive or strong negative perceptions of students' understanding and/or ability of mechanical engineering design that they wished to share with the authors.

Results & Discussion

The results of this study were separated into both the closed-form questions results and the themes that emerged from the free response question. Results are summarized and discussed below.

Analysis of closed-form responses

The first closed-form question asked faculty of their opinion regarding senior students' understanding of the design process within the capstone design course. Responses consisted of four closed form options shown verbatim in Figure 3 below.

Results from this question show a slightly positive perception of the cohort that took Intro to ME over the preceding cohort who did not. Several immediate observations can be made. First, faculty perceptions became more positive regarding an ability to apply the design process with specific instruction. The incidence of faculty rating teams at the lowest assessment level ("they don't seem to understand…") reduced by half in the cohort that had taken the introductory course. The more positive categories of assessment correspondingly increased with the highest category seeing a jump from 12 to over 16%. These results correspond with the faculty intention for the implementing of the Intro to ME course; however, the similarity in the responses between the two cohorts prevent the authors from drawing any strong conclusions. That said, whether the students had an introductory design course or not, students consistently seem to need guidance and advisement on fully understanding the design process—the significance of the tools, how the tools inter-relate, and how best to extract meaning from using the tools. These observations are validated by anecdotal feedback from advisors. Indeed, less experienced capstone advisors

have consistently reported that they do not fully grasp the design process and its associated tools that inform various steps in the process until they have experienced a few full rounds of the process. This fact is one reason that the mechanical engineering program typically assigns co-advisors to projects to supplement advisors who do not have as many repetitions with the process.

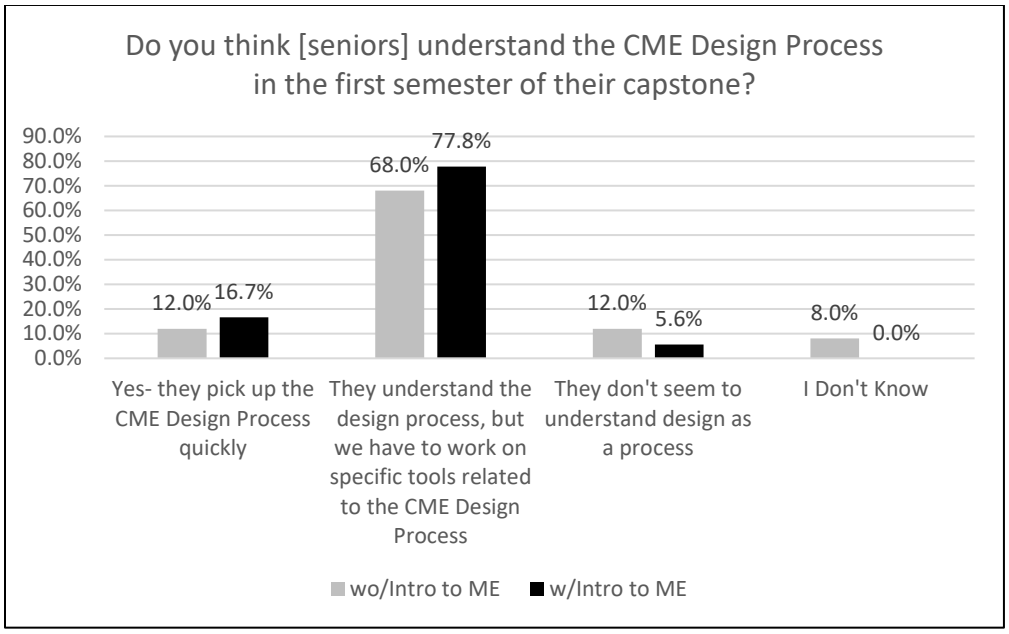

Figure 3: Perceptions of Design Process Understanding

Results for the question regarding the ability to apply the design process show mixed results (Figure 4). Faculty showed more positive impressions of the cohort that had not taken Intro to ME over the cohort that did take the course for seamlessly applying the CME Design Process. To the contrary, faculty also had a greater perception that the cohort who did not take the Intro to ME course failed to apply the design process in their capstones more than the cohort that did take the Intro to ME course. In a trend like the understanding of the design process, the application of the process to a real-world, open ended problem (i.e., their project) required significant advisement and oversight on the part of faculty. In both years, faculty had to not only clarify or reteach aspects of the design process to improve student understanding, but they also had to enforce the application of the design process when it really mattered—on their final capstone design.

Comparing similar questions between the two sections of the survey reveal further insights. The results seem to indicate that students' understanding of the design process was enhanced by their sophomore-level introductory course. However, it seems that their ability to apply the design process without faculty input was possibly degraded to a small degree. Two possible reasons are overconfidence and elevated expectations. First, students who understood the process better might have approached some parts of the process with less intensity, requiring more input from an advisor on one or more steps in the process. Furthermore, it is possible that faculty expectations were also higher, leading to more input as faculty attempted take a good product and make it even better in the second year.

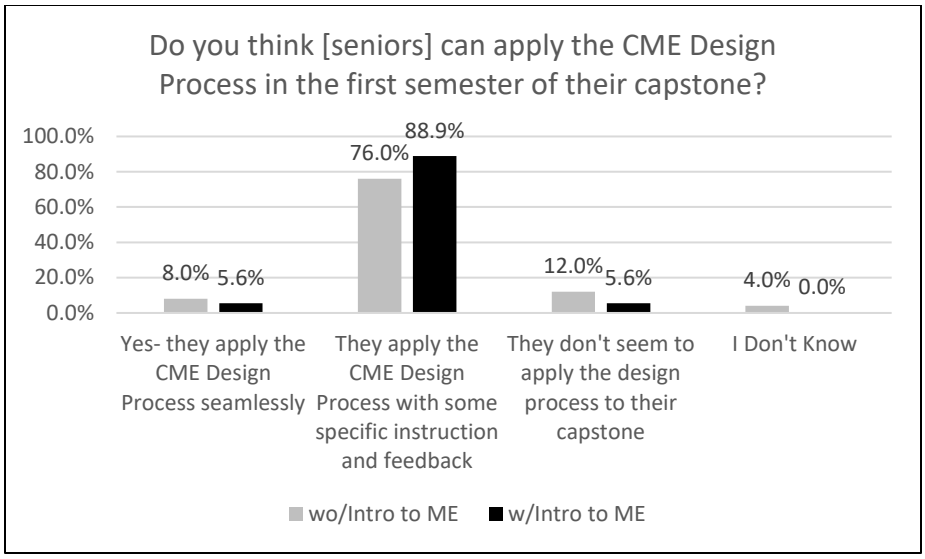

Figure 4: Perceptions of Design Process Application

The question regarding problematic aspects of the design process showed the most compelling results of the three questions (Figure 5). Except for the Problem Definition aspects of the design process, faculty reported that the Intro to ME students lacked fewer skills (or alternatively worded, exhibited stronger skills) than the cohort that had not taken Intro to ME. These general trends remain consistent across the breadth of skills addressed. The difference in each part of the design process appears non-trivial, except possibly for the Problem Definition phase, where the cohort without Intro to ME outperformed the other cohort. For this question, the difference is less than 4%, which might not be statistically significant. For all the other questions, the difference is quite dramatic and clearly favors the Intro to ME cohort.

Interestingly, results of the approximate permutation tests revealed a statistically significant difference for Conceptual Analysis skills only. No other significant difference between the without Intro to ME and with Intro to ME cohorts were observed at the $\alpha=0.05$ level (see Table 1). The results show that any perceived difference in performance between the two cohorts may be due to chance except for Conceptual Analysis skills. These results may largely be explained by the separation between the Intro to ME course and the capstone design experience. Although design problems are integrated into the curriculum between Intro to ME and capstone design, the design problems may not provide the level of design activity necessary to allow the design process to be fully implemented. The differences in Conceptual Analysis skills between the two cohorts may be explained by the level to which technical analysis is covered in the engineering curriculum between Intro to ME and the capstone experience. In addition, the ME faculty may be more capable of guiding the technical analyses undertaken by students given their technical background.

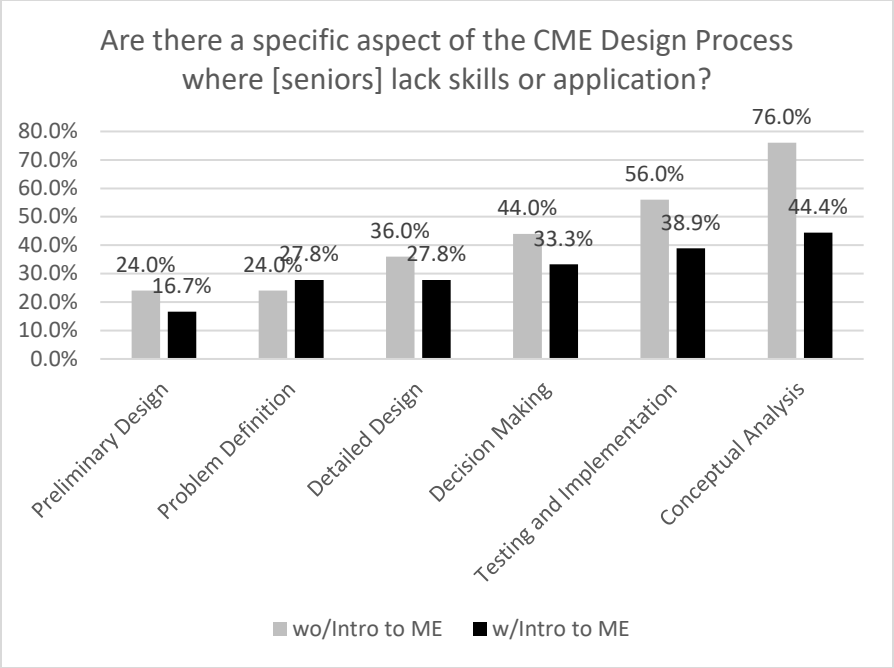

Figure 5: Identification of Skill Deficiency

Table 1: Approximate Permutation Test Results (α=0.05)

Question	P value
Understanding	0.4063
Application	0.4205
Skills: Preliminary Design	0.4237
Skills: Problem Definition	0.7325
Skills: Detailed Design	0.4077
Skills: Decision Making	0.3526
Skills: Testing and Implementation	0.2057
Skills: Conceptual Analysis	**0.0351**

Qualitative Analysis of Free Response

A thematic analysis of the free response question on the survey showed three themes that emerged. Participants clearly fell into one of the following patterns of thought:

Theme 1: "Intro to ME is the Answer!" Participants in the spring 2019 survey (without Intro to ME) indicated that senior students had little exposure to the design process within the curriculum prior to the capstone design course and that the one application of the process within their capstone design project was not enough repetition for the students to grasp and appreciate the benefits of using the process. One faculty member wrote, "Intro to ME is the Answer," while another indicated an impression that the "sophomores that he/she observed in Intro to ME that year actually had a better grasp of the design process than his/her capstone design team." The spring 2019 faculty participants were looking for Intro to ME to bolster understanding and application of the design process.

Theme 2: "Internalize the NEED for the design process." Faculty participants in the spring 2019 survey (without Intro to ME) indicated that seniors struggled to see the benefit of the design process and correspondingly fail to implement the process within their capstone design projects. Faculty comments focused on the early portions of the design process, to include problem definition and conceptual analysis and how early design work prevents wasted resources later in the process.

Theme 3: "Not Really." The participants in the spring 2020 survey (with Intro to ME) generally acknowledged only student-to-student and team-to-team variability on their comparison of design skills between the without and with Intro to ME cohorts. The general impression from the participants is that there was not major, discernable difference in design understanding or application between the cohorts that did and did not take the Intro to ME course. These sentiments are corroborated by the lack of statistical significance between the two cohorts mentioned previously.

Conclusion

Courses that provide early exposure to the design process will most likely remain ubiquitous in the mechanical engineering curriculum of the United States. Although they consume a portion of any program's resources, they tend to provide a relatively low-threat, high-impact first experience in engineering. These courses are often designed to be interactive, team-based, and applied, which are all reflective of how engineers typically operate in professional practice. These types of courses may also enhance recruitment and retention of students in engineering majors. There are many impacts, both obvious and subtle, that these courses can have on a program and its students. The purpose of this study was to determine the impact of the Intro to ME course on student proficiency with the design process and its associated tools by surveying faculty about their perceptions of student performance in these areas. In short, the exposure of the process may have elevated design tool proficiency in virtually every step of the design process. The Intro to ME course did not alleviate the need for significant mentorship by faculty in the application of design to their capstone projects. Even as seniors, students are still novices at implementing the design process. The Intro to ME course appears to make students more comfortable with the tools of design, but there is ultimately no substitute for experience and there may be insufficient time in the undergraduate experience for true mastery to be developed with the design process.

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