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Incorporating Human-Centered Design to Restructure a Materials Science and Engineering Capstone Course

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Abstract

Capstone design is the culmination of a learner's academic progress, where students utilize knowledge gained throughout the program's curriculum to complete a design project. This paper investigates the ongoing work of restructuring a traditional one-semester, 3-credit spring capstone experience in materials science and engineering into a two-semester fall (1-credit) and spring (2-credit) experience. During the restructuring of the capstone experience, the Human-Centered Design (HCD) framework, a method to formalize the design process in discrete stages, was integrated into the course content. Due to course catalog constraints, a 1-credit fall course was piloted in Fall 2022 as an elective for seniors (enrollment was approximately 30% of the senior population); the traditional 3-credit course was still required of all seniors in Spring 2023. Aspects of HCD were introduced and practiced in the fall pilot course and (re)introduced in the spring course.

To examine the uptake of these changes by students, the research team used a qualitative case study approach to closely investigate the work of two small groups in the second materials science and engineering capstone design course in Spring 2023. Both groups had four students; however, the members of one group had taken the one-credit pilot course in Fall 2022. The poster and progress reports from each group were collected. In addition, a group interview was conducted with each of the two groups during the final poster presentations event. The Human-Centered Engineering Design (HCED) framework was used to develop a coding scheme to categorize the content of the posters, progress reports, and interview transcripts under the HCED practices.

Findings from analyzing the data indicated that both groups have incorporated HCED processes into their design projects, especially when building knowledge and prototyping. Both groups did not incorporate HCED processes to connect with all stakeholders and generate ideas before narrowing down concepts. Moreover, the group that took the one-credit pilot course prior to the capstone course was more fluent in utilizing the HCED processes in their project than the other group. Modifications to the course's content, activities, and structure are discussed considering these findings.

Introduction

In engineering education, capstone courses are critical milestones that provide students with learning experiences that require them to apply their accumulated knowledge to tackle authentic real-world design challenges [1, 2]. Such courses mark the culmination of an engineering curriculum and play a critical role in accreditation processes such as ABET. However, to increase the impact of these courses on students' learning, they must incorporate design learning experiences that engage students in both divergent and convergent thinking [3]. They must also engage students in design thinking processes that can help them navigate the complexity of the design challenges that are presented in these courses and can lead to innovative, creative, and inclusive designs; it can also increase productivity, improve quality, and minimize errors and development costs [4]. One way to do this is to integrate Human-Centered Design (HCD) into engineering capstone courses. Nevertheless, integrating HCD into existing engineering courses is challenging; moreover, research studies indicate that the uptake of HCD processes by engineering students is complex and requires careful development and implementation of instructional strategies and course materials [5, 6].

Building upon research that highlights the complexities and nuances of implementing HCD in engineering contexts, this study aims to explore how students engage with HCD processes in the context of the material science capstone course that was redesigned to incorporate explicit HCD instruction and materials. By examining the specific HCD processes students employ and how they apply them in their design projects, this study seeks to shed light on the efficacy of integrating HCD in material sciences capstone courses, which in turn will inform future iterations of these courses.

Background/Theoretical Perspectives

Capstone courses in engineering

Capstone courses are crucial in engineering education as they allow students to utilize the assimilated knowledge of their collegiate career to practice and solve design challenges. Senior design courses are often billed as capstone courses that serve as completion markers. In theory, these courses aim to utilize the entirety of the knowledge gained in the curriculum through a multi-faceted "design" project [1]. Ideally, design projects incorporate real-world objectives and constraints [2]. Often, students are required to balance several, at times competing, objectives. A classic example in mechanical applications is a high-strength, low-density material. Aside from the technical feasibility of the design project, students are also forced to consider business feasibility, environmental impacts, social, political, and ethical implications, manufacturability, and unintended consequences.

Additionally, accreditation by ABET is only possible if ABET's Criterion 5d is satisfied where the engineering curriculum must include "a culminating major engineering design experience that 1) incorporates appropriate engineering standards and multiple constraints, and 2) is based on the knowledge and skills acquired in earlier course work" [7]. This design experience is most often a capstone course or series, allowing the students opportunities to engage with course material in a project environment. ABET Student Outcomes, now labeled as 1-7, are also required from the curriculum as a whole; capstone design can target several of these outcomes during the design iterations. This capstone project, as required in the ABET accreditation process, aims to bridge the theoretical and foundational knowledge of their chosen subject with the practicality and feasibility constraints present in post-graduation careers (e.g., industry or graduate school).

The design experience for the students must be tempered with design learning, that is, learning how to effectively design a solution that meets the multiple objectives and constraints. Learning how to design is imperative for a successful design project, yet the teaching of design remains challenging [3]. Project-based learning (PBL), where teams of students are set upon a design project, has been extensively utilized in capstone courses to motivate and engage students in this learning.

As Dym et al. state, the broad engineering curriculum focuses on convergent thinking, asking questions to arrive at a correct and verifiable solution or outcome, e.g., the resultant forces and deflection of a beam with an applied load. These answers are verified truth and are imperative to understand an engineering system. Design, however, is much more nebulous, where several alternative solutions and unknown solutions exist. Engineering design thus requires divergent thinking, not limited to verified solutions but more to solution possibilities. These two diametrically opposite thought processes operate in two separate domains: convergent thinking in the knowledge domain and divergent thinking in the concept domain [3].

For a successful design experience, both domains and, thus, both convergent and divergent thinking are necessary. For capstone design courses, the students' previous experience in the curriculum has prepared them well with regard to convergent questions, namely, "What is the correct solution?". However, the divergent questions requiring students to tolerate ambiguity pose significant challenges, especially if an underlying framework is absent. A fundamental problem is that teams of learners, although tasked to "solve" or "innovate" in response to a particular challenge, do not have prior experience in designing new solutions, nor do they have a framework to guide them systematically [1, 3, 4, 8].

Our department recognized this problem and committed to a major restructuring of the senior design experience. Pedagogically, we recognized the need for a formalized design perspective that provides the systematic framework for possible innovative solutions. Additionally, feedback from recent graduates highlights the great foundational knowledge the learners received during their four years, yet little design instruction and practice prior to the senior design course. A common critique in this feedback is the lack of business and entrepreneurial knowledge the learners have obtained in previous courses yet are expected to utilize in their capstone projects.

Integrating HCD in capstone courses

Human-Centered Design (HCD) is a problem solving approach that uses design thinking methods and tools to understand the unmet needs of a population to collaboratively and iteratively develop solutions [9]. HCD relies on the principles of empathy and iteration. Its processes include empathizing with stakeholders to understand their perspectives and better frame the problem before collaborating with them to generate solutions via multiple iterations [9]. Solutions that are generated following HCD are usually meaningful, relevant, and take into consideration factors such as economy, society, and environment [10].

Research studies have shown that HCD can promote situated learning in engineering design projects, and it facilitates students' learning of modern engineering skills such as communication and collaboration [11]. Moreover, HCD approaches to design in engineering can lead to innovative, creative, and inclusive designs; it can also increase productivity, improve quality, and minimize errors and development costs [4]. Therefore, the role of HCD is critical to the engineering design process and cannot be viewed as a separate process or outcome of the engineering design process [11]. Given the pivotal role of HCD in engineering design, higher education institutions are supporting the integration of HCD in existing engineering courses.

Several research studies included the integration of HCD in existing engineering courses such as mechanical engineering [12] and electrical engineering [13]. The integration was guided by an evidence-based human-centered engineering design (HCED) framework that merges the HCD processes with the engineering design processes and lists a set of practices that students can implement within the context of a design project [11]. These processes are understanding the challenge, building knowledge, weighing options and making decisions, generating ideas, prototyping, reflecting, and revising/iterating. Research studies indicate that learning about these processes and implementing them in the context of a design project that is situated within a semester-long course is complex [5]; moreover, certain course experiences, instructional strategies, and project requirements can inhibit or promote ways of experiencing HCD [6].

The purpose of the study

In this study, we build on findings from these studies to integrate HCD in a materials science and engineering capstone course. Key integration elements included providing students with explicit instruction on HCD and its role in engineering, an HCD framework that provides students with a flexible structure to navigate the design challenge [14], authentic, real-world design challenges with real clients, and reflection prompts to reflect and document progress on design challenges. The purpose of this study is to investigate how students applied the HCD processes in the context of their design projects. The study is set to answer the following research questions:

1) What HCD processes did students engage in during their design projects?
2) How did students apply the HCD processes in their design projects?

Methods

Design

This study is part of a design-based project [15] that aims to revise the capstone course experience for material sciences and engineering students at a large midwestern university. In this study, we use a case study approach [16] with two groups of students who took the capstone course in the Spring semester.

Participants

The participants were eight undergraduate students in their senior year. These students consented to participate in the study, and they worked on their capstone project during the Spring semester in small groups of four students each. These students composed two different project groups in the course. Other project groups in the course did not have all members consent, and thus, only these eight students were selected. Group 1 was composed of 2 females and 2 males; Group 2 was composed of 3 females and 1 male. Group 1 worked on designing a new biodegradable replacement for Styrofoam. Prior to this course, students of this group did not take any course that introduced them to human-centered design and its role in engineering. Group 2 worked on designing more concussion proof helmets. Prior to this course, students of this group took a 1-credit course that introduced them to human-centered design and its role in engineering in the Fall semester.

Description of the redesign process and the current courses

Prior to Fall 2022, the capstone design course was a 3-credit, spring-only course labeled MSE 395 “Materials Design”. Due to course catalog constraints, a shift to a two-semester design sequence was not possible for the 2022-2023 academic year. Instead, in Fall 2022, a 1-credit MSE 398 “Materials Design Thinking” course was piloted. This optional course targeted learners who would be taking the traditional senior design course in Spring 2023 and resulted in an enrollment of 27 learners (30% of the senior class). MSE 398 successfully introduced Human Centered Design. Spring of 2023 still had the 3-credit MSE 395 for legacy reasons. The class enrollment of 89 seniors included the 27 who took the optional MSE 398 the previous fall. Elements of HCD were also introduced in the spring MSE 395 course: new material for most of the class but a refresher for the ones who took MSE 398. Starting in the academic year 2023-2024, the new two-semester design sequence is now the standard, now labeled MSE 494 (1-credit, fall) and MSE 495 (2-credit, spring).

Data Collection Procedures

To answer the research questions, we collected three forms of data from each group. Throughout the semester, each group submitted seven progress reports where they were prompted to summarize their progress, achievements, and challenges to date. At the end of the semester, a researcher collected these reports from both groups. Also, at the end of the semester, both groups participated in a poster session where they were required to design a poster to share their projects' journey and outcomes with their peers and other engineering students and professors. A researcher visited the poster session, took a picture of each poster, and conducted a 20-minute semi-structured interview with each group on the role of HCD and HCD instruction in their project. A rubric was provided to guide the students in preparing their poster. Relevant to this study, achieving "Exemplary" in the "Final Design" category required a "Brief description of the design process and the determination of the final design; all 5 HCD stages are discussed." Other rubric categories included (i) Objectives, Constraints, and Boundaries, (ii) Alternative Designs, and (iii) Simulation and Fundamental Equations.

Data Analysis Procedures

To analyze the data, the two interviews were transcribed; then, two researchers used the coding scheme shown in Table 1 to mark indicators of the two groups applying HCD to their design projects in the progress reports, the content of their posters, and the transcripts of the interviews. The coding scheme was developed based on the Human-Centered Engineering Design framework presented by [11]. MAXQDA, a data analysis software, was used to code all the data.

Table 1. Coding scheme for data analysis

Code	Definition
(a) Understand the challenge	Any statement or phrase that indicates the group engagement in empathizing with users and stakeholders to understand the design challenge from their perspective.
(b) Build knowledge	Any statement or phrase that indicates the group engagement collecting any form of data or reviewing relevant literature to define and frame design opportunities.
(c) Weigh options and make decisions	Any statement or phrase that indicates the group engagement in considering different options, parameters, and trade-offs while prioritizing solutions that best align with stakeholders' needs
(d) Generate ideas	Any statement or phrase that indicates the group engagement in exploring a wide range of ideas or solutions.

(e) Prototyping	Any statement or phrase that indicates the group engagement in creating any tangible representation of design concepts to gather feedback or test functionality.
(f) Reflect	Any statement or phrase that indicates the group engagement in critically evaluating design decisions, stakeholder feedback and ideas to identify pros and cons and inform iterations.
(g) Revise/Iterate	Any statement or phrase that indicates the group engagement in refining and improving design solutions based on stakeholder feedback, testing results, and evolving requirements.

Results

Table 2 shows the frequency of the codes per all seven progress reports submitted by Group 1 and Group 2. Overall, the analysis of the progress reports indicated that both groups engaged in all HCD processes but had more engagements in the (c) weighing options and making decisions and (e) prototyping processes compared to engagements in (a) understanding the challenge and (f) reflecting challenges. Both groups had a similar number of engagements in (d) generating ideas, (e) prototyping, (f) reflecting, and (g) revising/iterating. However, the numbers indicate that Group 2 had more engagement in (b) building knowledge and (c) weighing options and making decisions compared to Group 1. For example, in one report, Group 2 stated:

"The group decided on the specific idea we will be moving forward with. Initially, we were between designing a replaceable, external attachment that dissipates force by breaking, and designing a porous layered helmet structure that mimics that of the human skull. This week, we assessed the two ideas, considering their potential, their novelty, their environmental impact, and our possible contributions. We finally decided to go with the second idea (porous material)"

Table 2. Frequency of codes in groups' progress reports.

Codes	Group 1	Group 2	Total
(a) Understand the Challenge	1	1	2
(b) Build knowledge	1	4	5
(c) Weigh options and make decisions	4	7	11
(d) Generate ideas	3	2	5
(e) Prototype	9	7	16

(f) Reflect	1	1	2
(g) Revise / iterate	3	1	4
Total	22	23	45

Table 3 shows the frequency of the codes per poster presented by Group 1 and Group 2. The analysis of the content of Group 1 poster indicated the presence of all HCD processes. Group 1 poster showed the stakeholders' research and the review of the literature that was performed to understand the challenge and build knowledge. It summarized the goals, objectives, boundaries, and constraints of the project. Group 1 poster showed the different options and alternatives that the group generated and discussed before arriving at a final solution. The poster had detailed explanations of their prototyping and iteration processes. It also had reflections of different possible designs and future work that could be done to improve these designs.

The analysis of the content of Group 2 poster indicated the presence of all HCD processes except (c) weighing options and making decisions and (f) reflecting. Group 2 poster had a brief overview of the problem the group was trying to solve, the need for an improved football helmet, and the objectives and requirements of the project. Group 2 poster had no information associated with weighing options and making decisions or reflecting; nevertheless, it had a detailed description of the design idea and the evidence supporting it in addition to the prototyping processes.

Table 3. Frequency of codes in the content of the groups' posters

Codes	Group 1	Group 2	Total
(a) Understand the Challenge	4	3	7
(b) Build knowledge	5	1	6
(c) Weigh options and make decisions	1	0	1
(d) Generate ideas	1	2	3
(e) Prototype	3	4	7
(f) Reflect	2	0	2
(g) Revise / iterate	2	2	4
Total	18	12	30

Table 4 shows the frequency of the codes per each of the Group 1 and Group 2 interview transcripts. Group 1 had an average of 1.77 codes per minute, and Group 2 had an average of

2.05 codes per minute. Overall, the analysis of the interview transcripts indicated that both groups engaged in all HCD processes, specifically in HCD's two key principles of empathy and iteration. For example, both groups took the initiative to understand the challenge and build knowledge. For example, a member of Group 2 said "we actually interviewed one of the defensive backs here, just to see, to see, their perspective on what they like". Moreover, both groups reported the implementation of prototyping processes in their projects and both groups emphasized the importance of using an HCD model that provided them with the ability to track their progress and reflect on their design journey. For example, a member of Group 1 mentioned "Also, like with ideate and prototype stage, you kind of have to like to go back and forth back. And so like, I think that yeah, just having a structure of like, the whole process, like something that was really helpful, I think."

Table 4. Frequency of codes in groups' interview transcripts

Codes	Group 1	Group 2	Total
(a) Understand the Challenge	3	2	5
(b) Build knowledge	3	6	9
(c) Weigh options and make decisions	4	2	6
(d) Generate ideas	1	4	5
(e) Prototype	3	4	7
(f) Reflect	7	2	9
(g) Revise / iterate	2	1	3
Total	23	21	44

Discussion

The purpose of this study was to examine the HCD processes students engaged in when completing a design project in the context of a redesigned material sciences course. In academic year 2022-2023, the redesigned course was split into a semester-long optional course that was taught in Fall 2022 and another semester-long capstone course that was taught in Spring 2023. Both courses were taught by the same instructor and integrated HCD into the curriculum and instruction by providing students with explicit instruction on HCD and its role in engineering and an HCD framework that equipped the students with a flexible structure to navigate the design challenge [14]. In addition, the Spring 2023 course required students to work on authentic, real-world design challenges with real clients, answer reflection prompts to reflect and document progress on design challenges, and present their final design in a poster session at the end of the semester.

Taken together, the analysis of the progress reports, content of the posters, and interview transcripts indicated that groups engaged in all HCED processes, mainly building knowledge, weighing options and making decisions, and prototyping followed by understanding the challenge, generating ideas, reflecting, and revising/iterating. Furthermore, the coded statements that were associated with these processes indicated a limited implementation of practices related to these processes. This suggests that the integration of HCD in the curriculum and instruction of the Spring 2023 course may have promoted the groups to engage in all the HCD processes. Nevertheless, future iterations of the course must emphasize and introduce groups to more stakeholders' engagement approaches, brainstorming methods, and iteration procedures so they can better engage in understanding the challenge, generating ideas, reflecting, and revising/iterating. Data must be collected from all groups in the course to verify if these changes will further transition groups from designing in a technology-centered fashion or with the user as a source of information to designing with a commitment to all stakeholders and a human-centered fashion [6].

Findings also indicated noticeable differences between Group 1, whose members did not take the optional course in Fall 2022, and Group 2, whose members took this course in Fall 2022. The analysis of the progress reports showed that Group 2 had more engagements in (b) building knowledge and (c) weighing options and making decisions compared to Group 1. The analysis of the content of the posters and interview transcripts suggested that Group 1 had followed a linear HCD structure while implementing the HCD processes; Group 2 presented more fluency in implementing different HCD processes during their design projects. This finding is supported by studies in other higher education contexts that show that novice designers need prolonged experiences in HCD processes to acquire fluency in applying these processes and integrating their outcomes [14]. This suggests that teaching students in the Fall about HCD, its role in engineering, and the HCED framework before they actually engage in the capstone project can be beneficial. Nevertheless, more data is needed to validate this claim.

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