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Merging Human-Centered Design with Engineering Design: Synthesizing a Human-Centered Engineering Design Framework

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Merging Human-Centered Design with Engineering Design: Synthesizing a Human-Centered Engineering Design Framework (RTP)

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Human-centered design (HCD) has been an important player in the future direction of engineering education. HCD offers a promising approach to promote situated learning in engineering design projects, and to facilitate students' learning of modern engineering skills. Many higher education institutions are seeking ways to integrate HCD into their engineering programs. This integration should be done in a way that supports and complements existing learning objectives of established programs. However, doing so is challenging given that each engineering course has its own unique opportunity areas and needs. Thus, there is a significant need to develop tools and methods which support this endeavor. We have developed an evidence-based human-centered engineering design (HCED) framework to facilitate program development at course and departmental levels. Our framework helps identify connections between human-centered design processes and mindsets and literature-based engineering design activities. It also supports collaboration by building on our previous work, which identified four necessary collaborative problem-solving processes to support group-level work. We intend for educators to use this framework to understand engineering students' journeys and build learning trajectories for engineering students to build human-centered engineering design knowledge, skills, and abilities. In this paper, we introduce the framework and its utility and explain how it can be used as a tool to help instructors identify opportunities to create HCED learning experiences, make classroom-level connections to ABET outcomes, develop assessment tools, and create organizational changes.

Introduction

Human-centered design (HCD) [1] has been an important player in the future direction of engineering education. HCD offers a promising approach to promote situated learning in engineering design projects, and to facilitate students' learning of modern engineering skills [2]. In our work with engineering faculty and students, we observed a disconnect between engineering sciences, especially those taught in the middle years of a program, and the open-ended design problems that learners must address in the workplace. For example, students may be well-prepared to compute the deflection of a beam and even redesign its cross section to optimize for some stated requirement. However, it is unrealistic to expect that a construction worker would ask for a ladder that "has a deflection of 1 cm under a load of 300 lb." They are much more likely to request a ladder that is "sturdy and easy to move." HCD has the potential to enable learners to traverse this gap. By seeking to first understand real-world needs and then develop engineered solutions to address them, students are given the opportunity to meaningfully apply the theoretical skills they learn in the classroom to address authentic unmet needs.

It follows that many higher education institutions are seeking ways to integrate HCD into their engineering programs [3], [4], [5]. This integration should be done intentionally and in a way that supports and complements existing learning objectives as well as the varied goals of established programs. However, doing so is challenging given that the needs of each engineering course may be hard to predict without immersing in the course material and environment. Thus, there is a significant need to develop tools and methods which support this endeavor. In this paper, we present a research-supported framework that can support engineering faculty and program heads to evaluate their existing courses and programs and find concrete ways to integrate human-centered engineering design (HCED) processes and practices into these courses and programs.

Background

Technical Engineering Design

The Accreditation Board for Engineering and Technology (ABET) defines engineering design as the "process of devising a system, component, or process to meet desired needs and specifications within constraints. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions" [6]. Traditionally, engineering design has been visualized as a linear process, such as the step-wise progression of phases illustrated in the waterfall model [7]. However, the idea of engineering design as a prescribed, linear process does not necessarily capture its true nature [8], [9]. More work is needed to embrace the uncertainty, unpredictability, and iterative non-linearity of the process. In addition to these aspects, more work is needed to highlight aspects of the process that involve collaboration and communication with stakeholders to better frame the problem and come up with a more innovative and relevant solution.

Human-Centered Design

Human-centered design (HCD) is a problem-solving approach that uses design thinking tools to identify unmet needs of a population in order to collaboratively and iteratively develop meaningful and innovative solutions [10]. HCD relies on empathy and iteration [10]. Our previous work summarizes characteristics of HCD that are relevant to engineering [3], such as its placement of humans at the center of the design journey through emphasizing and collaborating with stakeholders [11], [12] and the structure it provides for solving ill-structured problems [13]. Indeed, education researchers advocate for integrating HCD in higher education curricula [14], [7]. When using an HCD approach, designers focus on the human elements in the project and implement processes such as exploring, empathizing, reflecting, brainstorming, and iterating to identify and connect with stakeholders, generate ideas, and create and test prototypes of solutions [10], [11]. Within HCD, solutions may be products, services, experiences, or changes. Authors [15] visualized the HCD process as consisting of five spaces and 20 processes (Fig. 1).

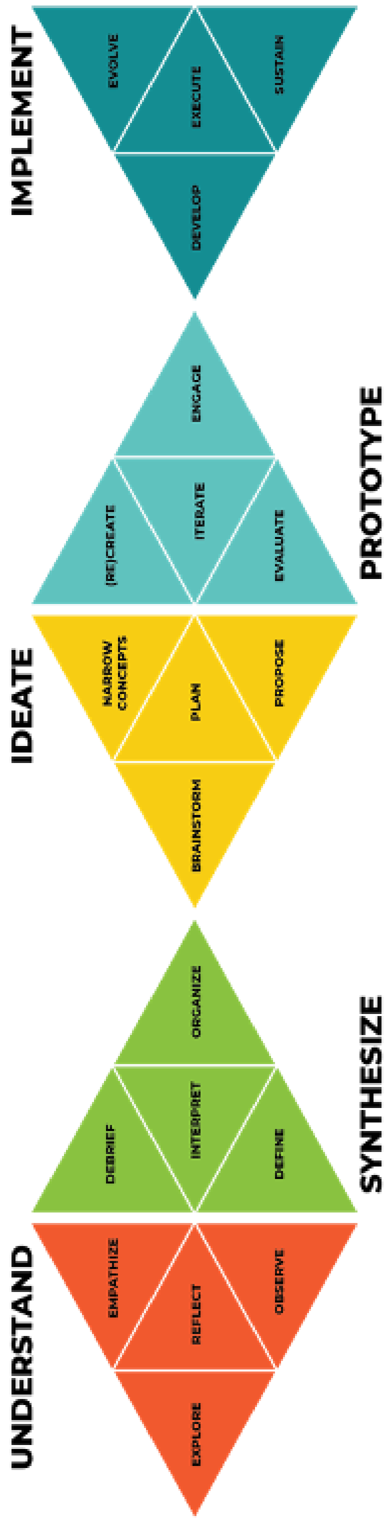

Figure 1: The human-centered design spaces and processes

Merging Engineering Design and HCD: The Conception of Human-Centered Engineering Design Framework

In this paper, we argue that it is important to support human-centered design as a core component of engineering curricula. We argue that using a human-centered design approach can empower engineers to focus on the human element in a design project. The human element refers to the engineer, their design team members, and any other direct or indirect stakeholders that may be involved in the design project. Consequently, integrating HCD in engineering curricula can better prepare students for a diverse, collaborative workplace in industry as well as help them to balance their technical and subjective design decisions. Because HCD collaborates with users and stakeholders, it can help engineers ensure that the resources spent in design and development are used productively. In using HCD, the design team can work toward a shared goal with their stakeholders or end-users. The focus on stakeholder needs also helps the team to clarify the root problem and ensure that they are working toward the correct solution, as opposed to merely an obvious or easy solution. In other words, the HCD process does not try to just solve any problem, but rather a specific, need-based problem faced by the users or stakeholders [16].

Since 2019, a newly established design center at a large, public Midwestern university has been using the HCD framework shown in Figure 1 to develop programs and design activities that can help students learn about HCD processes and practices and develop its mindsets [15]. This work started through collaborations with engineering faculty and staff to better understand where students were exposed to design topics as well as how design was taught. In our collaborations, we conducted formal interviews and casual conversations with faculty and students as well as observations of existing courses and extracurricular design opportunities. Through the iterative development of various learning experiences for use in both existing and new engineering courses, we began to identify opportunities to integrate HCD and engineering design [17], [4], [3], [18].

Early in our immersion process, we observed that engineering courses, even those with significant design elements, tended to be heavily focused on the mastery of specific engineering learning objectives and that all available seat time tended to be dedicated to that goal. Importantly, this meant that there was little room to focus on the design knowledge, skills, and abilities (KSA) that are integral to supporting engineering design work, but may sometimes be considered separate from “hard” engineering skills (e.g., technical and computational skills). KSA may include communication and collaboration skills as well as design-related skills such as ideation, sketching, or synthesis. To address this, we sought opportunities to integrate design lessons that promote student learning of critical support skills directly into the engineering learning process. Our intent was to use HCD as a means to build engineering competency, which led us to establish the commonalities and synergies between HCD and engineering design processes.

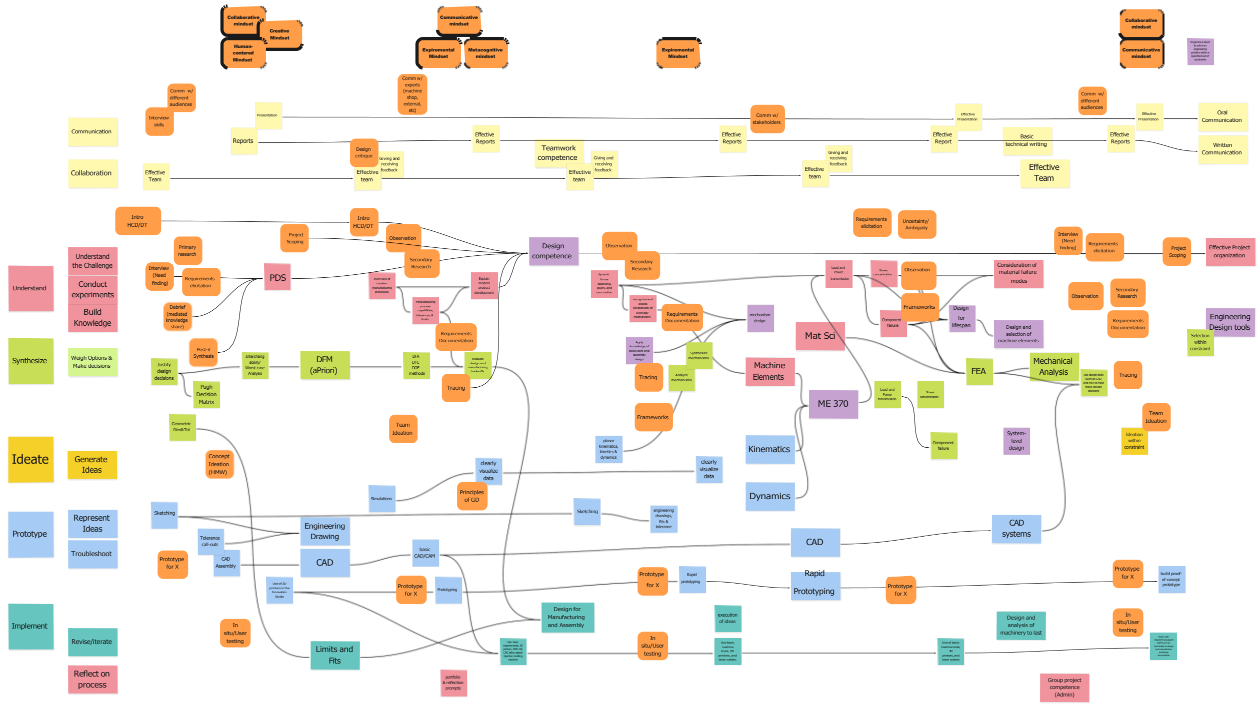

Figure 2: Early concept for students' learning trajectories in a mechanical engineering curriculum.

Working with a cohort of design faculty from a large engineering department, we created a map of the design courses offered in that department (Fig. 2). Using the learning objectives from each course, we laid out the learning trajectories that students were expected to traverse over a four-year program. Each of these was color-coded and categorized according to its location in the design process presented in [15], as well as its alignment to the design activities presented in The Informed Design Thinking and Teaching Matrix [19]. Using this learning trajectory map, we identified opportunities to support student learning of design topics by adding HCD elements to new and existing lessons. While the implementation of these lessons is ongoing and not without its own challenges, notably instructor familiarity and preparedness, this approach was key in understanding what a human-centered engineering design learning trajectory might look like within the context of a large and well-established engineering department.

In light of our ongoing collaborations with faculty and students, we present a research-supported framework that can support engineering faculty and program heads to evaluate existing courses and programs and find concrete ways to integrate human-centered engineering design (HCED) processes and practices into these courses and programs.

Framework Overview

We developed an evidence-based human-centered engineering design (HCED) framework (Fig. 3) to facilitate program and course development in engineering departments. Users check boxes corresponding to the design activities, from Crismond & Adams [19], in which students engage during each course, which allows them to visualize course characteristics and map learning trajectories across years of the program. These design activities are associated with human-centered design spaces, as presented in [15]. The blank column can be populated with an engineering course. Users can also identify potential outcomes that may be supported by participation in each course.

Potential ABET Outcomes	Collaborative Problem-Solving Process	Potential Designer Mindsets	Engineering Design Activities	Taxonomy Spaces
2, 3	P1: Explore the Problem	Communicative, human-centeredness	Understand the Challenge	Understand
7	P1	Metacognitive	Build Knowledge	
2, 3, 4, 5, 7	P2: Plan How to Solve	Collaborative, communicative, human-centeredness, metacognitive	Weigh Options & Make Decisions	Synthesize
1, 3, 5	P2	Collaborative, communicative, creative	Generate Ideas	Ideate
1, 3, 5	P1	Collaborative, communicative, creative	Represent Ideas	Prototype
1, 3, 5, 6	P3: Attempt to Solve	Creative, collaborative, communicative, experimental	Experiment	
1, 3, 6	P3	Creative, communicative, experimental	Troubleshoot	
1, 3, 5, 6	P4/P3	Collaborative, communicative, creative, experimental	Revise/Iterate	Implement
2, 4, 7	P4: Evaluate Solution and Consider Alternatives	Human-centeredness, metacognitive	Reflect	

Figure 3: Human-centered engineering design framework.

To the left of the taxonomy spaces and engineering design activities, there is a series of columns that are intended to map connections to other relevant design frameworks. The collaborative problem-solving process column lists the types of collaborative processes associated with each engineering design activity. We previously developed a framework that built on Ge & Land's work [20], [21], which outlined four problem-solving processes necessary for solving an ill-structured task. Ill-structured design tasks require justification during solving because they have more than one right answer and may be nebulous to solve [22]. Our framework [23], [24] characterized the four problem-solving processes in the context of collaborative ill-structured tasks implemented in undergraduate engineering courses.

The potential designer mindsets column conveys the potential designer mindsets a student could achieve by fully engaging in the engineering design activity. Instructors may orient the design of their activity toward developing a certain mindset. Research studies continue to show that engaging students in learning about and applying these processes and practices can help them develop mindsets such as human-centeredness, creativity, metacognition, communication, collaboration, and experimentation [15], [25], [26], [27]. These mindsets are key to successful performance in any future workspace [28].

The potential ABET outcomes column conveys the potential ABET outcomes a student could achieve by fully engaging in the engineering design activity. It was important to visualize connections among the engineering design activities and ABET student learning outcomes [6], as these learning outcomes are necessary achievements for students in accredited engineering programs. In the next section, we will present how we developed this framework and give examples on its uses in making changes to existing engineering courses and programs.

Framework Development and Validation

To pilot the course map development process, we created maps for aerospace engineering, computer engineering, engineering mechanics, electrical industrial engineering, materials science & engineering (biomaterials), materials science & engineering (general), mechanical engineering, and systems engineering & design. For the initial drafts, we relied heavily on syllabi and other course information as well as anecdotal knowledge to hypothesize which activities were applicable for each class in each department.

We consulted with engineering faculty and department heads with backgrounds in aerospace engineering, bioengineering, computer & electrical engineering, computer science, mechanical engineering, and systems engineering & design as well as members of our research team to iterate and validate the framework. We also worked with an ABET expert from our partner university to test the framework and its related materials. In each one-on-one interview, we asked the faculty member to provide feedback regarding both the usability and accuracy of the framework. We also welcomed questions, which often helped to highlight weaknesses. To set up the sessions, we provided the framework and a guide to its use in advance.

Based on feedback from each faculty member, we iterated the framework or course map. For example, some departmental faculty provided insight toward which design activities applied to a particular course. Our department heads and ABET expert were helpful in validating connections between design activities and desirable outcomes, as well as identifying information that should be included. After we implemented changes, we followed up with each faculty member to confirm that the changes were accurate and open the door for any additional suggestions.

ABET student learning outcomes. To explore connections, we held brainstorming sessions within our interdisciplinary team and with our ABET expert to devise connections among engineering design activities, human-centered design outcomes, and ABET student learning outcomes. We consulted relevant literature [e.g., 29] to support our suggested connections, which are reflected in the "Potential ABET outcomes" column. For purposes of developing the framework, we focused specifically on the learning outcomes specified within ABET's Criteria for Accrediting Engineering Programs (EAC) [6]. Future work will validate these connections experimentally.

Supporting collaboration. Research has established that collaboration is inherently beneficial for problem-solving outcomes [30], [31]. Furthermore, engineering education is seeing a shift toward group learning [32], [33]. Thus, it was important to align the engineering design activities, which were characterized by Crismond & Adams [19] for individual problem solving, with our collaborative problem-solving processes. In other words, we want to see students engaging in these activities collaboratively. The framework can be used to direct faculty toward specific problem-solving processes associated with the activities, which in turn can help them in finding relevant resources for supporting those processes as students engage in the given activity.

Visualizing student learning trajectories. We intend for educators to use this framework to understand engineering students' journeys in existing courses and in programs so they can build learning trajectories for students to learn the HCED processes and mindsets. To do this, we developed prototype course maps in which we applied our framework to a specific engineering department. The middle segment of our original framework had space reserved for required courses per each year of a four-year engineering curriculum. Because there is no way to reliably predict what supplemental courses students will choose to take on their own without extensive analytics, we only included courses that were required for all students in the program.

When specific courses are assigned to the framework columns, users can then check boxes for engineering design activities in which students typically engage during the course. With the engineering design activities mapped, users can begin to visualize learning trajectories. For example, the sample course map shown below (Fig. 4) demonstrates gaps in students' learning trajectories within the aerospace department at a large, public Midwestern university. Reading across the "Revise/Iterate" row, we see that students do not have many opportunities to engage in the activity. The visual gap represents learning opportunities, where faculty change or augment elements of their course to better engage students in the activity throughout the curriculum. In contrast, students are engaged in building knowledge throughout their curriculum.

	Year 1		Year 2					Year 3								Year 4					
Engineering Design Activities	Intro to Aerospace Engineering	CAD	Engineering Materials	Introduction to Statics	Aerospace Flight Mechanics	Thermodynamics	Introductory Dynamics	Incompressible Flow	Compressible Flow	Mechanics of Aerospace Structures	Applied Aerospace Structures	Aerospace Dynamical Systems	Aerospace Control Systems	Aerospace Numerical Methods	Electrical and Electronic Circuits	Aerospace Propulsion	Aerospace Systems Design I	Aerospace Systems Design II	Dynamics and Propulsion Lab	Autonomous Systems Lab	Taxonomy Spaces
Understand the Challenge	X	X		X	X					X	X			X		?	X	X	?	?	Understand
Build Knowledge	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Weigh Options and Make Decisions	X	?		X	X		X	X		X	X		X	X			X	X	X	X	Synthesize
Generate Ideas	X	X		X				X		?	?		X				X	X	X	X	Ideate
Represent Ideas	X	X		X						X	X		X				X	X	X	X	Prototype
Experiment	X			X									X		X				X	X	
Troubleshoot	X			X									X		X				?	?	
Revise/Iterate	X			X									X		X		X	X	?	?	Implement
Reflect on Process	?	X		X											?		?	?			

Figure 4: Sample course map showing gaps in learning trajectories.

Using the Framework at the Course Level

After developing the framework, we sought opportunities to collaborate with engineering courses and test the framework's ability to identify learning opportunities and visualize student learning trajectories. We collaborated with an aerospace engineering faculty member to co-design new materials, and make adjustments to existing projects, for a 300-level required aerospace engineering course taught by that faculty member. The course, which focused on control systems, included four pair-based design projects.

Design project format. Each project included the following sections: The (controller) system; Equations and parameters; Your tasks; Your deliverables; Evaluation; and Frequently asked questions. Deliverables included a sequence of rough drafts and final draft of the design report, a 70-second video that includes simulations of the working control system, and the code that runs the system. The design report required the following sections: Abstract, Nomenclature, Introduction, Theory, Experimental methods, Results and discussion, Conclusion, Acknowledgements, and References as well as an appendix with a work log that describes the work completed by each student.

Participants. We debuted our co-designed materials during the spring 2023 semester, for which 120 students were enrolled in the course. The vast majority of students in the course were in their third year of the aerospace program. As a result of applying our framework to the aerospace course, our team was able to make the structural changes described below.

Industry context. We consulted departmental faculty with decades of industry experience to help us situate the projects in real-world context, such as remote sensing spacecraft for the control system in project 1.

Stakeholder consideration. We added a prompt to the video component requiring students to make the case for their control design to their stakeholders. This introduced the need to understand their stakeholders' characteristics and values.

Individual reflection prompts. Following each design project, we provided students with a series of questions to prompt them in reflecting on their teamwork and experience during the project. Prompts were graded for completion. For each subsequent project, the individual reflection prompts included a question regarding their responses during the previous sequence. Responses will be analyzed in future work.

Team reflection prompts. In addition to the sequences of individual prompts, we added a team-based prompt to the design report for each project. For example, project 1 included the prompt, “Summarize your team’s experience during the project. How well did you work together to solve the problem? What did your communication look like?”

Human-centered design warm-up activity. In addition to changes to the design projects, we added a warm-up activity to the beginning of each lecture session throughout the semester. 50-minute lectures were held three times per week for each of sixteen weeks. For roughly five minutes at the beginning of each lecture, students were provided a “How might we…” question to explore with their neighbors. “How might we” questions are phrased to suggest that a solution is possible. They are open-ended enough to support a variety of solutions without suggesting a particular direction, but contain enough information to motivate innovation. For context, “How might we redesign seating on an airplane?” would be too broad to identify need, whereas “How might we create a seat with adjustable height?” already poses that users’ need is for an adjustable seat…which designers may not necessarily know right away. A sample question implemented in lecture was, “How might we make the International Space Station accessible to blind astronauts?”

Human-centered design orientation. During the second week of lecture, we implemented a brief orientation to human-centered design. The orientation prepared students for the changes to the design projects and prompted them to consider stakeholders during their design process.

We are in the process of collecting data to assess the impact of our changes on students’ understanding and application of HCED. Future work will evaluate these efforts and iterate on co-design materials to further evolve the design projects and course content.

Using the Framework at the Departmental Level

Our previous work has demonstrated the efficacy of collaborative engagement in the HCD process [4]. From our team’s immersion in engineering departments, we also recognized the need to support students’ development of design-related skills as well as communication and collaboration skills, all of which are valuable and necessary in the engineering workplace [e.g., 35]. To address this, we sought opportunities to integrate design lessons that promote student learning of critical support skills directly into the engineering learning process, which led to the development of the human-centered engineering design framework as a means of establishing connections between the HCD and engineering design processes. There is inherent value in the HCED process as a means of engaging students in collaboration within engineering tasks, which is impactful for their learning outcomes [24], [30]. Furthermore, engaging students in complex design early in their undergraduate education is beneficial to their interest in the field of engineering [5]. Tools like our HCED framework support the integration of design thinking in engineering curricula, which is critical for evolving engineering education toward comprehensive teamwork that helps students develop a well-rounded industrial skillset that includes both technical and empathic design skills. Indeed, literature has established that engineering design behaviors include weighing options and making decisions rather than focusing solely on design solution features [35 p. 9], which means that students should be able to incorporate and synthesize design considerations beyond the technical and content-related skills heavily emphasized in typical engineering curricula.

Thus, it is worthwhile and valuable to pursue the integration of frameworks such as our HCED framework in engineering departments. We envision applying HCED at the department level to identify learning trajectories across courses. We can demonstrate an example of this application by going back to our work in the mechanical engineering curriculum Figure 5 shows the course map for mechanical engineering, which includes the sequence of four design courses (namely, Computer-Aided Design, Design for Manufacturability, Mechanical Design I & II, and Senior Design Project).

	Year 1	Year 2			Year 3							Year 4	
Engineering Design Activities	Computer-Aided Design	Design for Manufacturability	Introductory Dynamics	Introductory Solid Mechanics	Fundamentals of Fluid Dynamics	Heat Transfer	Engineering Materials	Dynamics of Mechanical Systems	Signal Processing	Mechanical Design I	Mechanical Design II	Senior Design Project	**Taxonomy Spaces**
Understand the Challenge	X	X		X		X	X			X	X	X	Understand
Build Knowledge	X	X	X	X	X	X	X	X	X			X	
Weigh Options and Make Decisions	X	X	X	X		X	X			X	X	X	Synthesize
Generate Ideas		X		X		X	X			X	X	X	Ideate
Represent Ideas		X		X		X	X			X	X	X	
Experiment		X		X		X	X			X	X	X	Prototype
Troubleshoot		X		X		X	?			X	X	X	
Revise/Iterate		X		X		X	?			X	X	X	Implement
Reflect on Process		?		X		X				?	?	X	

Figure 5: Mechanical engineering course map with design sequence highlighted.

Based on our previous development work in these courses, we can identify concrete examples of the selected engineering design activities manifested in each course. Figure 6 shows the relevant boxes for each of the four courses populated with these items.

Engineering Design Activities	Computer-Aided Design	Design for Manufacturability	Mechanical Design I	Mechanical Design II	Senior Design Project	Taxonomy Spaces
Understand the Challenge	Intro to HCD in engineering lecture	HCD and storytelling lab	Recognize and assess functionality of everyday mechanisms	Consider material failure modes	Meet with stakeholders to define need	
Build Knowledge	Understand lab	Research sustainability issues in the field			Research stakeholder field and similar design challenges to learn about previous work in the field	Understand
Weigh Options and Make Decisions	Synthesis lab	Choose topic of focus for design mini-project	Synthesize mechanisms	Explore component failure through FEA	Devise plan for pursuing solution	Synthesize
Generate Ideas		Brainstorm solution	Brainstorm/sketch	Brainstorm/sketch	Brainstorm solution	Ideate
Represent Ideas		Present solution to classmates and instructors; detail work in technical report	Visualize data/create engineering drawings	CAD	Present solution proposal to stakeholders and judging panel; detail work in technical report	
Experiment		Develop solution	Prototyping lab	Rapid prototyping	Develop prototype	Prototype
Troubleshoot		Test solution	Prototyping lab	Rapid prototyping	Test prototype and receive feedback from stakeholders and judges	
Revise/Iterate		Improve solution based on testing results	Use machines to execute improved product	Design and analysis of machinery	Incorporate feedback to evolve prototype toward viable working product	Implement
Reflect on Process		ePortfolio with reflection prompt			Evaluate quality of solution and teamwork; suggest future work	

Figure 6: Examples of classroom elements that fit each design activity per course.

With this information, we can then visualize potential learning trajectories from year 1 to 4, as well as opportunity areas associated with these trajectories for which our team could present future intervention. A sample of trajectories and opportunity areas are presented below.

Evaluating the impact of the HCED foundation in Y1 and Y2. We see that HCED is introduced in year 1 and built upon in year 2. Students are then expected to apply their foundation in years 3 and 4, where HCED content is no longer explicit. This presents an opportunity to evaluate the impact of HCED on students' performance, or competence, in years 3 and 4, which in turn will provide guidelines for improving the foundation built in years 1 and 2.

Building knowledge in years 1 and 2 to apply in year 4. Students can engage in building knowledge relevant to design thinking and the design process in years 1 and 2. In year 3, this process may not be explicit. However, students are then expected to be able to engage autonomously in this process during their senior design project. This learning trajectory presents the opportunity for our team to support students' engagement in building knowledge in year 3, as well as to evaluate their ability to self-engage in this activity in year 4.

Design process introduction. We see that year 2 introduces students to the engineering design process by engaging them in a series of projects that encompass all relevant activities. Students are then able to build on these activities in years 3 and 4. This learning trajectory presents the opportunity for our team to build introductory HCED-related modules to implement in year 1.

Supporting opportunities to reflect. Students have the opportunity to engage in reflecting on their design process in year 2, but are not explicitly prompted to do so again until year 4. This presents the opportunity for us to bridge the gap between years by supporting them in engaging in reflection in year 3.

By understanding students' learning trajectories, we can then develop interventions to address gaps or strengthen foundational knowledge. We have argued that the engineering design process contains uncertainty, unpredictability, and iteration, and that supporting the human-centered design elements that are an inherent characteristic of common engineering activities will better prepare students to communicate and collaborate effectively in a diverse engineering workplace. We present our HCED framework as a tool with which educators can make more accessible the elements of HCD that are already woven into engineering design.

Conclusion

We developed a research-based human-centered engineering design framework that can be used to visualize student learning trajectories across engineering curricula. We deployed the framework in a third-year required aerospace engineering course. As a result of our investigation of the course, we implemented several structural changes to the design projects as well as introduced new material to course lectures. Future work will analyze the effectiveness of these changes. We will also host workshops intended to engage faculty in using the framework and guide them in applying it to their own course. The framework is significant for engineering educators because it allows them to visualize students' learning trajectories and design strategically to support or improve the learning trajectory so that students achieve desired learning outcomes.

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