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WIP: Using a Human-Centered Engineering Design Framework to Develop Learning Progressions in an Aerospace Engineering Program

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Introduction

Human-centered design (HCD) [1], which offers a promising approach to promote situated learning in engineering design projects, and to facilitate students' learning of modern engineering skills [2], can enhance engineering design. Human-centered design is a problem-solving approach that uses design thinking tools to identify unmet needs of a population and collaboratively and iteratively develop meaningful and innovative solutions for that population's benefit [3]. The HCD process encompasses five taxonomic spaces; namely, understand, synthesize, ideate, prototype, and implement, each of which are defined by a set of characteristics and processes [4]. It is becoming more common for post-secondary institutions to seek ways to integrate human-centered design methods into their engineering programs [5], [6]. Indeed, research studies show that integrating HCD in engineering programs can better prepare students for a diverse, collaborative workplace in industry and help them to balance their technical and subjective design decisions [7]. The integration of HCD into an engineering curriculum should be done 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 all engineering courses have unique opportunity areas and needs. Thus, there is a significant need for tested tools and methods that support this integration.

For this integration, it is important to consider engineering education at both the course and program level. In our ongoing collaboration with an accredited, four-year aerospace engineering program, we are working both to implement tools for integrating human-centered design at the course level as well develop longitudinal tools to evaluate students' learning at the program level. In this paper, we discuss the co-development of program-level learning progressions that connect directly to program educational objectives as well as ABET (formerly Accreditation Board for Engineering and Technology) student learning outcomes [8]. These progressions also connect to the Kern Family Foundation (KEEN)'s entrepreneurial mindset [9], which proposes a set of attitudes, dispositions, habits, and behaviors that shape a unique, desirable engineering problem-solving approach.

Background

We are an interdisciplinary design team at the University of Illinois Urbana-Champaign that is composed of Grainger College of Engineering faculty and researchers from the Siebel Center for Design (SCD) [10] . Since 2019, SCD researchers have been using HCD to develop programs and design activities that can help students learn about HCD processes and practices and develop its mindsets [4]. 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 previous work, we developed an evidence-based human-centered engineering design (HCED) framework [11] that identifies connections between human-centered design processes [4] and mindsets [12], [13] and literature-based engineering design activities [14]. With this framework, we argue that there are inherent connections between human-centered design and technical engineering design and that these are characterized by practices that we describe as human-centered engineering design. It can also be used to align these connections with broader frameworks such as ABET's student learning outcomes [8] and the KEEN entrepreneurial mindset [9]. Table 1 shows a version of the framework with space to brainstorm connections to an engineering course.

Table 1: Human-centered engineering design framework [11].

ABET EAC Outcomes	KEEN Framework (design skills, opportunity skills)	Your Course	Taxonomy Spaces	Engineering Design Activities	Example HCED Practices
2, 3	Determine design requirements Identify an opportunity		Understand	Understand the Challenge	●Frame the problem ●Implement empathic techniques with users and stakeholders ●Organize and validate information
7	Investigate the market			Build Knowledge	
2, 3, 4, 5, 7	Determine design requirements Analyze solutions Create a preliminary business model Assess policy and regulatory issues Evaluate		Synthesize	Weigh Options and Make Decisions	●Debrief with team members ●Seek feedback from stakeholders ●Define parameters and constraints
1, 3, 5	Perform technical design		Ideate	Generate Ideas	●Brainstorm range of ideas with team members and stakeholders
1, 3, 5	Perform technical design		Prototype	Represent Ideas	●Explore and investigate different ideas using lo-fi prototypes ●Communicate with stakeholders and seek feedback ●Justify decisions
1, 3, 5, 6	Create a model or prototype Perform technical design Test concepts			Experiment	
1, 3, 6	Validate functions			Troubleshoot	
1, 3, 5, 6	Analyze solutions Evaluate		Implement	Revise/Iterate	●Iterate toward most viable hi-fi prototype ●Evaluate quality of design solution with team members ●Evaluate user experience
2, 4, 7	Analyze solutions Assess policy and regulatory issues Evaluate			Reflect on Process	

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 progressions. We collaborated with an aerospace engineering faculty member to co-design new materials, and make adjustments to existing projects, for a third-year required aerospace engineering course taught by that faculty member [11].

These included framing each design project in terms of stakeholders and end-users, adding individual and team reflection prompts to each project report, introducing HCED activities to lecture, and orienting students to HCED prior to the first of their four design projects. Since the beginning of Spring 2023, we have been implementing these changes and collecting data to understand their potential impact on students' teamwork skills and project-related learning outcomes. To keep students' data confidential, the faculty member has been excluded from data collection and can only discuss anonymized results.

Human-Centered Design in Aerospace

In an aerospace context, human-centered design (HCD) is an approach that focuses on the needs, preferences, and capabilities of the passengers, operators, or other end-user of an aerospace system or service. It can be applied to the broad range of aerospace systems, such as aircraft, crewed spacecraft, satellites, rockets, drones, or air traffic control systems. HCD can help improve the safety, efficiency, and mission success of these systems by centering the ways in which human performance and human-automation interactions affect the system concept of operations, the formulation of functional and performance requirements, and the architectural assignment of the requirements to physical entities.

The aerospace industry is characterized by high levels of complexity, uncertainty, and risk, as well as rapid technological changes and evolving customer demands. These factors pose significant challenges for the design and development of aerospace systems that often involve multiple stakeholders and a variety of technical disciplines. Education in HCD can help address these challenges by ensuring that the design process is driven by a deep understanding of the problem, the context, and the users, rather than focusing solely on technical specifications or assumptions.

Educators can prepare aerospace engineering students for their future careers by equipping them with the appropriate HCD skills and mindsets to design high-performance aerospace systems that are user-friendly, safe, and reliable. Students develop critical thinking, problem-solving, communication, collaboration, and empathy skills, which are essential to graduate to working on multidisciplinary and multicultural teams. HCD education and experience with design thinking can also help students understand the latest trends and technologies in the aerospace industry and inspire them to pursue their passions and interests in this field.

Learning Progressions in Engineering Education

Learning progressions are important for assessing students' achievements in an educational program. These are strategic tracks that outline students' journeys through an entire program in the context of developing a specified competency or knowledge base [15]. A learning progression framework presents a broad description of essential content and general sequencing for student learning and skill development [16]. Given the characteristics of the HCED framework, we argue that it can assist educators in planning and building curriculum maps that can be used to identify learning progressions [17] for engineering students to develop human-centered engineering design knowledge, skills, and mindsets.

Literature has defined the value of learning progressions in K–12 science and math education and how to design them in these contexts. The National Research Council stipulates that learning progressions are designed to help children continually build on and revise their knowledge and abilities [18]. Furthermore, learning progressions can depict "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time" [19 p. 219]. These learning progressions, designed based on a reasonable sequence of increasingly sophisticated content, can therefore also be used as the foundation for design practices relating to assessment and curriculum development [20].

Despite the efficacy of learning progressions as a valuable tool for curriculum development and assessment, these progressions are not well explored or implemented in post-secondary education. The Accreditation Council for Graduate Medical Education suggests a progression structure to track graduate students that includes questions such as "What are the expectations for a beginning resident?" and "What are the key developmental milestones mid-residency?" [21] However, learning progressions that explicitly focus on HCED in four-year engineering programs have yet to be explored. Given that engineering programs typically employ program educational objectives (PEOs), we argue that engineering education needs methodology for designing strategic learning progressions at the program level that aim to scaffold, track, and assess students' progress toward PEOs.

ABET defines PEOs as "broad statements that describe what graduates are expected to attain within a few years of graduation" [8]. PEOs may be thought of as the visualization of what an ideal graduate looks like. In other words, a student who graduates from the program and obtains all its PEOs has achieved the ideal set of characteristics and skills as set by that program. For example, one PEO from our aerospace engineering department states that graduates will "advance their careers by demonstrating leadership, teamwork, and communication skills in addition to technical knowledge." [22] It follows that strategic planning and ongoing assessment, which are features of robust learning progressions, are necessary to track students' progress in terms of developing these skills.

Learning Progression Framework

Literature has shown that learning progressions that are empirically validated can serve as instruments for the development of assessments and curricular materials [23]. Indeed, Cutrer et al. [24] describe the ideal graduating state of students as that of "master adaptive learners" who have moved from a novice skill level to that of adaptive expertise. In our ongoing collaboration with an accredited, four-year aerospace engineering program, we are piloting the development of program-level learning progressions that connect directly to program educational objectives and ABET student learning outcomes. Our process thus far has included the theoretical development of six learning progression tracks: understanding of HCED, application of empathy-related processes, application of iteration-related processes, consideration of implementation dimensions, application of written and oral communication skills, and application of cognitive and social collaboration skills. These are categorized within three major competencies supported by literature [25]: technical, global, and professional.

Our categories were brainstormed collaboratively among the interdisciplinary team, taking into account firsthand experience from faculty members, PEOs, and engineering education characteristics for which literature advocates [26] [27] [28] [29]. In particular, several sources argue that design thinking practices such as human-centered design are important for the breadth of engineering education [30] [31] [32] [33]. It is also important to verify that the progressions effectively move students toward desirable learning outcomes established in broader frameworks. In particular, we are investigating connections to ABET's EAC student learning outcomes [8] and KEEN's entrepreneurial mindset [9].

Development of Learning Progressions in Aerospace Engineering

As we developed the learning progression categories, we used a sequence of three required aerospace courses, one in each of years two, three, and four of the program, to pilot potential progressions. Using the assumptions that 1) the average student entering a freshman- or sophomore-level course would likely display novice disciplinary skills whereas 2) the average student entering a senior-level or capstone course would likely display intermediate or informed disciplinary skills, we then generalized the framework to reflect novice, intermediate, and informed skill levels for each progression category. Table 2 displays the framework, with columns for our six categories within three major competencies and rows for descriptions of each skill or knowledge level. We have populated the boxes with potential performance indicators, or behaviors that students would likely display when engaged in activities related to each competency. Ongoing work seeks to develop an assessment layer to evaluate these performance indicators.

Table 2: Learning Progressions Framework

Competency Category	***Human-Centered Engineering Design (technical) competency***			***Global Competency***	***Professional Competency***	
Progression	**Understanding of HCED**	**Application of Empathy-Related Processes**	**Application of Iteration-Related Processes**	**Consideration of Implementation Dimensions**	**Application of Oral & Written Communication Skills**	**Application of Cognitive & Social Collaboration Skills**
Overview of Progression	Use knowledge of HCED to synthesize working definition	Identify and apply empathic processes to advance a design problem (e.g., empathic design; commitment to involving stakeholders; keeping user needs in mind) [31] *Identify an opportunity [8]*	Identify and apply iterative processes to advance a design problem (physically, digitally) (e.g., technology-centered) [31] *Assess and manage risk (connections) [8]* *Persist through and learn from failure (value) [8]*	Consider design problem and solution through ethical, cultural, social, environmental, health, safety, and economic dimensions [7], [25], [28]. Consider the implementation phase of HCED *Communicate an engineering solution in terms of economics/social benefits [8]* *Demonstrate constant curiosity [8]*	Lead, support, and participate in effective communication with diverse audiences. Behaviors may include group discussions, composition of technical reports, and composition and delivery of visually-supported presentations [33] *Communicate an engineering solution in terms of economics/social benefits [8]*	Lead, support, and participate in effective collaboration with diverse groups. Behaviors may include interaction, perseverance, negotiation, audience awareness, and self-evaluation [27] *Develop partnerships and build a team [8]*
Description *Expected average naive understanding or low skill level*	Students develop naive understanding of HCED	Students develop awareness of stakeholders Students understand examples of requirements *Create value by identifying stakeholders' need [8]*	Students encounter engineering tools through guided exploration	Students develop naive understanding of needs-based considerations *Make connections among various perspectives of need [8]* *Create value by identifying ways to meet various considerations [8]*	Students apply novice communication skills in engineering projects	Students apply novice teamwork skills [27] (e.g., share and connect information) [34] *Facilitate connections among team members and between team members and stakeholders [8]*
Description *Expected average intermediate (i.e., under development) understanding or medium skill level*	Students develop intermediate understanding of HCED	Students receive and apply requirements and verifications in context of stakeholder need	Students participate in prototyping and iteration through the use of relevant tools	Students develop intermediate understanding of needs-based considerations	Students apply informed communication skills in engineering projects	Students apply intermediate teamwork skills (e.g., strategize planning and executing) [34]

Description *Expected average informed understanding or high skill level*	Students develop an informed understanding of HCED	Students establish requirements and verifications for design problems *Determine design requirements [8]*	Students apply prototyping skills to advance and iterate design problems *Create a model or prototype [8]*	Students develop informed understanding of needs-based considerations	Students identify and communicate effectively with various audiences	Students autonomously apply teamwork skills (e.g., work together efficiently) [34]
Potential Performance Indicators *Faculty may select fitting indicators or draft their own*	Students compose definition of HCD and describe its relation to engineering	Students brainstorm stakeholders in industry context Students identify correct requirements for given context Students apply requirements to controller design and verify them Students justify requirements using stakeholder need Students identify specific customer requirements that lead to value proposition Students brainstorm stakeholders in industry context Students identify correct requirements for given context	Students use CAD to brainstorm Students write and test controller code in Python/Matlab Students use relevant software to draft and verify solution model	Students collaboratively engage in big-picture thinking Students collaboratively identify and diagnose failures	Students complete project report and presentation Students compose rigorous technical reports Students create videos that communicate design to stakeholders (demonstrate audience awareness) Students seek feedback from stakeholders to develop design requirements	Students actively participate in small teams Students self-direct collaboration on project tasks Students reflect on their teamwork skills to track improvement Students participate on their team and advance project work with minimal input from instructor (demonstrate negotiation)

Ultimately, we expect that the implementation of learning progression-related activities and assessment in earlier courses will result in a richer senior design experience, with students arriving to senior design demonstrating more developed competencies as a result of participating in strategically designed tracks.

Preliminary Data Collection

Pre-/Post-Test Survey

We are currently implementing preliminary activities in each course and collecting data in the forms of classroom observations and pre-/post-test surveys to begin empirically validating each progression track. The first iteration of our pre-/post-test survey (see Appendix) was collected at the beginning and end of the 16-week Fall 2023 semester. The same survey items were provided in both surveys and the pre-test survey was given during the first week of classes to avoid influencing students' responses. For the sophomore-level course, 58 out of 60 students responded to the pre-test survey and 56 responded to the post-test survey. For the senior-level (capstone) course, 97 students across two class sections (section 1 had 50 students, section 2 had 47) with the same instructor responded to the pre-test survey and 52 responded to the post-test survey.

The survey contained a short-answer prompt for Understanding of HCED and sections with Likert-scale items pertaining to each of the other learning progressions (i.e., Application of Empathy-Related Processes, Application of Iteration-Related Processes, Understanding of Aerospace Safety, Application of Oral and Written Communication Skills, Application of Cognitive and Social Collaboration Skills). We validated each Likert-scale section using Cronbach's alpha, which resulted in values of 0.876, 0.834, 0.940, 0.704, and 0.867 respectively. The survey was iterated for the Spring 2024 semester to include a section of items pertaining directly to KEEN's entrepreneurial mindset [35]. This version was given to the same sophomore-level course as well as the junior-level course. Results will be discussed in future work.

Ethnographic Classroom Observations

Near the beginning of the semester, the team identified existing activities in the sophomore- and senior-level courses that connected to the drafted learning progressions. Ethnographic observations [36] were then recorded during these activities by members of the research team using an observation protocol that focused on student behavior and engagement, students' interactions with one another and with the instructor, and characteristics of the activity/lecture. For each activity, the researcher remained in a corner of the classroom and typed observations on a laptop. For all sessions, the researcher did not interact with the instructor or students. Observations were later reviewed and discussed with the team to inform current classroom behaviors and annotate potential connections to the learning progressions and opportunity areas to make stronger future connections. For example, without intervention, do the lectures or activities make explicit connections to human-centered design? Is this isolated to a single course, or does it happen in multiple courses in the sequence? This format was piloted during the fall 2023 semester; observations are ongoing.

Piloting Requirements Mini-Project

In both courses, we also implemented and observed a new requirements mini-project that was developed by the team. The students were tasked with building a small-scale catapult given office supplies such as binder clips, hot glue, duct tape, and popsicle sticks. The project's goal was for students to iteratively create a reliable catapult that would perform as expected on a day designated for data collection. This required the students to prototype catapults, create their own experiments, collect data, photograph their experimental setup, predict performance, and demonstrate reliability of the final product. With these many project requirements and only four working days, reasonable division of required work within the groups was emphasized during class. The project furthered the design experience by requiring the students to write a methodology report that outlined the steps to build the catapults, assess their structures and experimental results, and detail stakeholder concerns for a hypothetical application of the catapult if scaled-up. Students worked in self-selected groups of three students per catapult.

Iteration of this project is ongoing, but preliminary observations by the instructor indicated that students adapted well to the engineering challenge, experimentally validating their own catapults and creating designs with reliable performance. However, a stronger connection to aerospace technical content is intended by replacing the initial projectile (ping pong balls) with student-built miniature gliders. This will allow the methodology documents that the students create to be tied directly into course content related to aerodynamic forces and aircraft performance. Additional efforts in the current iteration of the project are focused on engineering around empathy-related processes, identifying stakeholder needs, and evaluating engineering prototypes with stakeholder concerns at the forefront, which allows for applied discussions on aviation safety, glider stability and control, and human-centered engineering design within the context of the project.

Ongoing Investigation of Learning Progressions at Department Level

All of our preliminary data collection and implementation efforts have been focused on multiple courses (e.g., piloting the mini-project in the second- and fourth-year courses), which ties to the idea of using the sequence of courses as a pilot for designing progressions at the program level. These efforts are grounded in our human-centered engineering design framework, which supports us in integrating human-centered design within our engineering courses to facilitate students' competency development.

While preliminary findings show promise, validation of the learning progressions will not be completed until the first cohort in the sophomore-level course has graduated from the program. Thus, ongoing work will continue to track students as they move through the sequence of required courses, primarily through the use of the pre-/post-test survey. We are also planning future implementations, such as adapting a version of the requirements mini-project to a first-year and third-year required course to create and evaluate an embedded project sequence that students encounter over multiple years in the program. It is also important to note that a finalized progressions framework would ideally be applied to all required courses throughout the four-year program. Ongoing work seeks to validate and refine the progressions framework using evidence-based findings from the variety of sources we are exploring (i.e., classroom observations, survey results, insights from faculty, project performance) and to continue developing assessment tools, such as a competency assessment rubric, for evaluation of activities, content, and pedagogies related to the progressions.

Limitations

One perturbation whose impact on learning progressions is still not fully understood is the effect of the COVID-19 pandemic on university students who had to switch to remote learning for the first two years of the curriculum. Several negative impacts on their learning abilities and socialization skills have been observed anecdotally. Indeed, remote learning resulted in reduced opportunities for social interaction and peer engagement, which are important for learning and development. Students faced more distractions, challenges, and stressors at home, such as family responsibilities, internet issues, or health concerns. They also sometimes struggled to manage their time, organize their work, or stay focused on their tasks. The lack of social support and resources that they would have normally received from their peers, teachers, or counselors may now be adversely affecting their ability to relate to HCD concepts as they finish up their academic careers. To effectively implement HCD in engineering programs in ways that meet students' needs, future work should investigate this area.

Conclusion

The integration of human-centered design throughout engineering curricula can better prepare students for a diverse, collaborative workplace in industry and help them to balance their technical and subjective design decisions [7]. However, doing so at the program level can be challenging to track and evaluate. To effectively meet engineering program educational objectives, as well as track students' competency development, it is necessary to employ learning progressions across required courses. Our in-progress study seeks to develop and empirically validate a learning progression framework using a sequence of three required aerospace engineering courses as the basis for collecting data and implementing relevant activities. These six progressions fit within technical, global, and professional engineering competencies [25]. By designing tools to strategically structure and assess students' development of desirable competencies, this work supports the successful implementation of program-level goals such as PEOs and ABET roadmaps.

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Appendix

Fall 2023 Pre/Post Survey Items

Understanding of HCED

What is your definition of human-centered engineering design?

Application of Empathy-Related Processes
Rate your degree of confidence to perform the following tasks by recording a number from 0 to 100 (0 = low, 50 = moderate, 100 = high)

- Conduct background research (e.g., internet search, market investigation)
- Empathize with stakeholders to identify underlying needs
- Resolve conflicting information from stakeholders
- Define the goals of the design problem
- Frame design needs so that solutions can be developed
- Communicate design solution to stakeholders

Application of Iteration-Related Processes
Rate your degrees of confidence to perform the following tasks by recording a number from 0 to 100 (0 = low, 50 = moderate, 100 = high)

- Assess feasibility of design ideas

- Create rough prototypes to get intermittent feedback
- Select viable prototyping methods (e.g., physical prototyping, wireframing, simulations)
- Iterate based on findings from prototyping
- Clearly identify the purpose of creating the prototypes
- Evaluate the effectiveness of an implemented design solution

Understanding of Aerospace Safety

On a four-point scale, rate the satisfaction you have with your skill in the following engineering topics. Satisfaction in your knowledge skill would be that you think you have already been successfully taught the skill or have a good understanding of it on your own. Dissatisfaction would be that you have not been taught the skill, have patchy understanding of the skill, or would not know what to do if you encountered a problem in this knowledge area. (1 = dissatisfied, 4 = satisfied)

- Knowledge about the aerospace engineering industry
- Knowledge about aircraft
- Knowledge about spacecraft
- Knowledge about aerospace vehicles
- Knowledge about the aerospace engineering vehicle design process
- Knowledge of applied mechanics: statics and dynamics
- Knowledge of incompressible flows
- Knowledge of compressible flows
- Knowledge of viscous flows
- Knowledge of aerospace materials
- Knowledge of aerospace structures
- Knowledge of aerospace dynamical systems
- Knowledge of aerospace control systems
- Knowledge of aerospace propulsion systems

Application of oral communication skills

Rate the extent to which you do the following (never/rarely/sometimes/often/always)

- Present with ease in front of an audience
- Take the lead in a group discussion
- Give constructive feedback to peers
- Consider the knowledge of your audience when giving a presentation (Hesse)

Application of written communication skills

Rate the extent to which you do the following (never/rarely/sometimes/often/always)

- Gather information from different sources for a report
- Use published standards (e.g., IEEE, AIAA) to structure a technical report
- Compose professional correspondence (e.g., emails to colleagues)
- Produce error-free technical reports

Application of cognitive collaboration skills

When working in groups, I tend to (never/rarely/sometimes/often/always)

- Remind the group how important it is to stick to schedules
- Construct strategies from ideas that have been raised
- Clearly define the roles of each group member
- Move the group’s ideas toward a strategy
- Evaluate how well the group is progressing toward a goal
- Use feedback from group members to suggest a possible solution (Hesse)

- Take initiative to interact with group members (Hesse)

Application of social collaboration skills

When working in groups, I tend to (never/rarely/sometimes/often/always)

- Provide emotional support to my group members
- Be sensitive to the feelings of other people
- Show that I care about my group members
- Be there for others when they need me
- Be open and supportive when communicating with others
- Negotiate different ideas with group members to achieve a resolution (Hesse)

Demographics

Race/Ethnicity: Which of the following best describes you?

- Asian or Pacific Islander
- Black or African American
- Hispanic or Latino
- Native American or Alaskan Native
- White or Caucasian
- Multiracial or Biracial
- A race/ethnicity not listed here
- Prefer not to answer

Gender: Which of the following best describes you?

- Female
- Male
- Transgender
- None of these
- Prefer not to answer

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