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Developing a Human-Centered Engineering Design Self-Assessment Survey

Mr. Alexander Pagano, University of Illinois at Urbana - Champaign

Alex Pagano is a PhD student studying engineering design. His work is focused on the early phases of design and the use of human-centered design or design thinking as a teaching tool. Alex holds a BS in Materials Science and Engineering from University of

Ms. Taylor Tucker Parks, University of Illinois at Urbana - Champaign

Taylor Parks is a research fellow in engineering education at the Siebel Center for Design. She earned her bachelor's in engineering mechanics and master's in curriculum & instruction from the University of Illinois Urbana-Champaign. Her research focuses on promoting teamwork in complex engineering problem solving through collaborative task design. She currently co-leads the integration of human-centered design principles within select courses across the Grainger College of Engineering.

Mr. Saadeddine Shehab, University of Illinois at Urbana - Champaign

I am currently the Associate Director of Assessment and Research team at the Siebel Center for Design (SCD) at the University of Illinois at Urbana-Champaign. I work with a group of wonderful and talented people at SCD's Assessment and Research Laboratory to conduct research that informs and evaluates our practice of teaching and learning human-centered design in formal and informal learning environments.

My Research focuses on studying students' collaborative problem solving processes and the role of the teacher in facilitating these processes in STEM classrooms.

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Introduction

In this paper, we will present the development of an assessment tool intended to measure Human-Centered Engineering Design (HCED) self-efficacy over a multi-year sequence of courses in undergraduate engineering. We will discuss our motivations and intentions for this work and how these informed the design of the survey, including the reasoning behind using self-efficacy measures. We will also present our early analysis of the validity of this tool and its utility in measuring HCED learning. Findings from this paper cover data collected at the beginning of the Fall 2023 semester. Future work will include pre/post comparison and longitudinal analysis.

Design is a central part of engineering and continues to play an important role in engineering undergraduate education [1]–[3]. Design projects have been positioned in the freshman and senior years as cornerstone and capstone projects [1], [4]–[7]. Beyond these design-focused courses, many engineering courses employ a project-based learning approach, often utilizing design projects as a way to engage students in experiential learning [8]. We have noted growing interest in design projects, especially from faculty teaching technical electives. These courses and design experiences cover topics from all manner of engineering disciplines and are wide ranging and diverse in their topics and approaches. This means that one student's exposure to design learning experiences may differ greatly from another's. Because design is a central part of engineering, we should expect that students receive appropriate training in design throughout their undergraduate career. By developing assessment tools that can be used to measure design self-efficacy over time, we can facilitate a better understanding of how students are developing the design knowledge, skills, and abilities necessary for their success.

Learning progressions outline students' journeys through an academic program in the context of developing a specified competency or knowledge base and are important for assessing students' achievements [9]. A learning progression framework presents a broad description of essential content and general sequencing for student learning and skill development, providing scaffolding for curriculum design [10]. By developing HCED frameworks and assessment tools, we seek to assist educators in planning and building curricula for engineering students to develop human-centered engineering design knowledge, skills, and mindsets [11].

We represent the Siebel Center for Design at the University of Illinois Urbana-Champaign. Part of our mandate is to support the integration of Human-Centered Design [12]–[17] concepts within the College of Engineering. This study is motivated by the design question, "How might we develop assessment tools to measure student learning of human-centered engineering design over a four-year undergraduate degree?" To this end, self-efficacy has been selected as an indicator of learning progress. While not a perfect analog for learning [18], self-efficacy has been shown to track with achievement in a variety of contexts including engineering education [19]–[23]. For our purposes, self-assessment provides an accessible way to collect data without significant effort or cognitive load from our participants, allowing for data collection at various touchpoints throughout their undergraduate education. This led us to the research questions for this study:

RQ1) How do self-efficacy assessments differ between students at various academic levels?

RQ2) Can we assess self-efficacy in various content areas and differentiate between them?

Methods

In this section, we will first provide an overview of the study design and how it relates to these research questions. Then we will present our methodology for participant recruitment and selection, as well as the demographics of our sample. We will then describe our analysis methodology, the results of which can be seen in the Results section.

Study Design

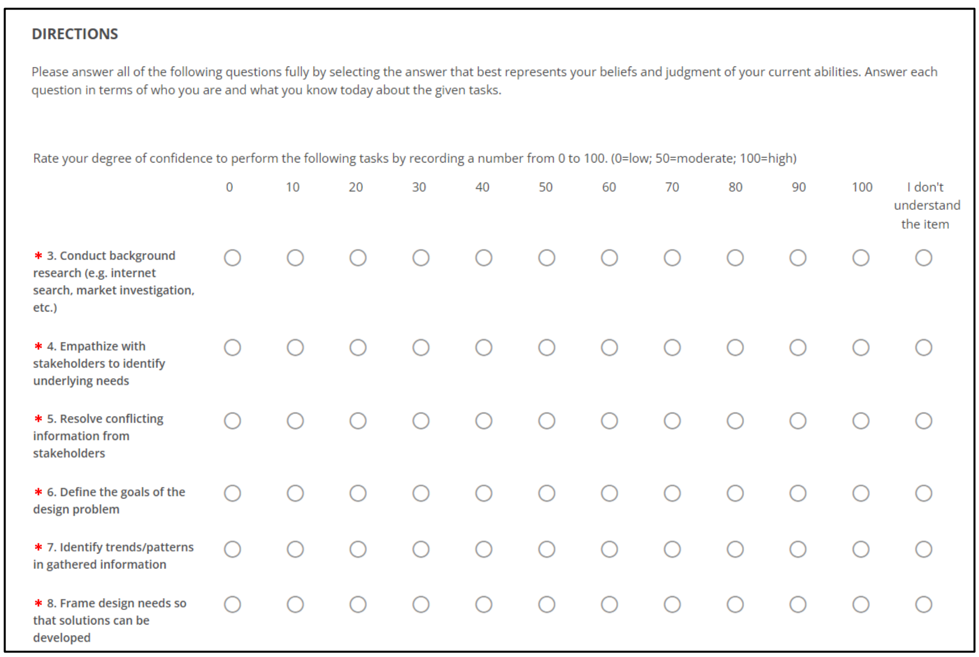

Figure 1 – Screenshot showing sample questions from the survey.

This paper represents our findings from the development and initial pilot deployment of our HCED self-efficacy assessment. The intention is that this tool may be used to measure students' learning at various touchpoints throughout their four-year engineering undergraduate education. Our initial goal was to collect pre/post data in all courses affiliated with the design center, in each semester, over the next several years. However, differences in response rates from pre-test to post-test, and the proximity of the Fall post-test to the Spring pre-test may result in changes to this schedule.

At each instance of data collection, students respond to a short survey (see **Figure 1)** which includes items intended to measure students' self-efficacy in various aspects of human-centered engineering design. These questions ask students to "Rate your degree of confidence to perform the following tasks by recording a number from 0 to 100." In addition to these questions, students are asked a series of demographic questions to facilitate demographic sorting. Responses are submitted through a university provided web portal and linked to the student's university ID. These identifiers are removed, and data is anonymized using an automated python script before the data is accessible to researchers. This process maintains a record of which response belongs to which anonymized ID. This will allow us to explore longitudinal data in future work. By seeing growth in a specific semester, we can learn more about what is being learned in those classes. This will help us understand what is working at a college-wide level. It is important to note that in this study, only data from the beginning of the Fall 2023 semester is used. Therefore, in this work, students are not tracked as they progress from freshman to sophomore to junior, however data from students at each of these levels will be explored. The same survey is sent to all students, regardless of academic year or department. Therefore, the items must be generic enough to apply to a verity of types of engineering design (e.g. both mechanical and software design). As the scope of data collection is expected to grow over time to theoretically cover all students in the college of engineering, we have chosen multiple choice answers to simplify data analysis.

Student responses to the HCED items are combined into five factors relating to HCD taxonomy spaces. To answer RQ1, we've collected data from 100-, 200- and 300-level students, and will compare the factor scores of each group using an independent sample t-test to determine whether there is a significant difference among self-efficacy at various academic levels. Each of these factors is associated with a different HCED content area. We seek to answer RQ2 by verifying that these factors can be measured independently.

Participant Recruitment and Selection

A link to a web survey was distributed to faculty members teaching design courses within the College of Engineering. The link was then passed on to students. The first page of the survey, which contained all of the required information for informed consent, asked potential participants 1) to confirm that they were at least 18 years old and had read the sheet in its entirety, and 2) whether they agreed to participate in the study. All those who were at least 18 years old and provided informed consent were included in the dataset. Informed consent is collected each time the survey is deployed, and no compensation has been provided for participation. Upon investigation of responses, we rejected those with missing responses to the core HCED items as well as those with obvious faults (e.g., selecting the first option for every question). This paper will focus on responses to the pre-survey from Fall 2023. A pre/post comparison and additional longitudinal investigations are planned for future work.

Survey Design

We started with an existing Engineering Design Self-Efficacy instrument, developed by Carberry, Lee, and Ohland [24]. Students are asked to "rate your degree of confidence to perform the following tasks" on a scale of 0 to 100. This simple survey seemed like an ideal basis for expansion to measure HCED learning progressions. Firstly, it had already been used in the context of engineering design learning and was shown to track with design experience, that is those with more experience also had higher self-reported confidence scores. We aimed to add items to the survey which further covered the activities of Human-Centered Engineering Design. Early, pilot survey deployments included the nine original Engineering Design items from Carberry *et al.* in order to verify that the responses to these questions were in line with existing work. However, these were dropped from subsequent versions to reduce the overall length and focus on HCED concepts. Importantly, there is significant overlap between "traditional" engineering design and HCED. However, as you may imagine, HCED has an emphasis on stakeholder engagement in the design process, which is not typically emphasized to the same extent in the generalized views of engineering design.

We used the Human Centered Design Taxonomy [25] to inform the development of new survey items covering HCED. For each space in the HCD taxonomy (Understand, Synthesize, Ideate, Prototype, Implement), we asked, "What is the goal of this space in the context of engineering design?" From there, we asked, "What are the activities necessary to accomplish this goal, in the context of engineering design?" From this process, we came up with a set of 24 potential items. After discussing as a team, we reached a consensus on the set of 17 in the table below. These items were then reviewed by a third-party researcher with PhD qualifications and relevant experience in the field. These became the items for our HCED Self-Efficacy Instrument and are listed in **Table 1**. As there is no agreed set of HCED activities available in the literature yet, these items may not be sufficient to capture the desired level of detail in all cases. Further work is necessary to confirm the completeness of the set in its coverage of HCED concepts and tasks, as well as the robustness of interpretation of these items. We have taken some early steps toward the validation and verification of this instrument, which are outlined in the subsequent sections.

Table 1 - HCED Self-Efficacy Instrument items

Q#	**Survey items**	**HCD Taxonomy Space**
12	Conduct background research (e.g. internet search, market investigation, etc.)	**Understand** Goal: To attain a good understanding of the unmet need
13	Empathize with stakeholders to identify underlying needs	
14	Resolve conflicting information from stakeholders	**Synthesize** Goal: To synthesize information to identify insights
15	Define the goals of the design problem	
16	Identify trends/patterns in gathered information	
17	Frame design needs so that solutions can be developed	
18	Collaboratively generate design ideas	**Ideate** Goal: To generate multiple potential solutions
19	Generate a range of design ideas	
20	Assess feasibility of design ideas	
21	Create rough prototypes to get intermittent feedback	**Prototype** Goal: To create representations of design concepts
22	Select viable prototyping methods (e.g., physical prototyping, wireframing, simulations, etc.)	
23	Iterate based on findings from prototyping	
24	Clearly identify the purpose of creating prototypes	
25	Create a plan for the implementation of a design solution	**Implement** Goal: To implement a design concept in the real world
26	Evaluate the effectiveness of an implemented design solution	
27	Communicate design solution to stakeholders	
28	Ensure the design solution continues to work in the future	

Cronbach's alpha

To explore the internal consistency between related items within our sample, we computed the Cronbach's Alphas for the groups of items belonging to each HCD taxonomy space [26]. The Cronbach's Alphas for all categories were above 0.8 and are shown in **Table 2**.

Table 2 – Cronbach's Alphas for the groups of questions belonging to each HCD taxonomy space	
HCD Taxonomy Space	**Cronbach's Alpha**
Understand	0.829
Synthesize	0.923
Ideate	0.925
Prototype	0.959
Implement	0.937

Factor Analysis

We can further explore the relationships between items through factor analysis [27]. This gives us a sense of the underlying factors which are being measured by our items. Theoretically, our items represent five underlying factors corresponding to the five HCD taxonomy spaces. To verify that we have five factors represented in our data, we can look at the eigenvalues to determine how many are greater than one (kaiser criterion), or above the 'elbow' (skree plot), or greater than the corresponding eigenvalue of randomly generated data. In our case, these methods all suggest two factors, but using just two factors results in multiple questions with roughly equal weight in both factors. This suggests that these items do not measure five independent constructs. However, this is not entirely unexpected. Our theoretical model allows for the overlap of HCD taxonomy spaces, i.e. one can simultaneously engage in Ideate and Prototype spaces. Yet our items were intended to cover all five spaces. Thus, we proceed with factor analysis with five factors, and will compare how the factor loadings align with our expected model.

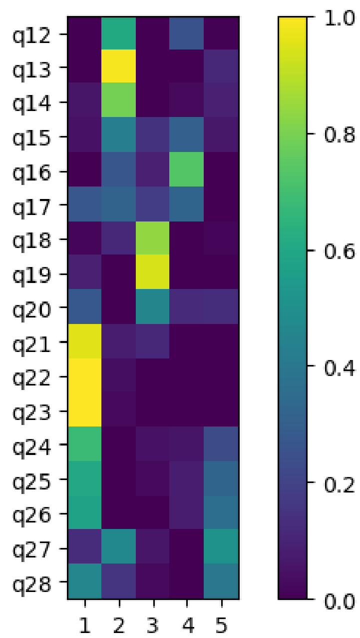

Figure 2 – Heatmap of factor loadings

A heatmap of factor loadings for five factors is shown in **Figure 2.** Loadings vary from 0 (dark purple) to 1 (bright yellow). Each row represents one question, each column represents one factor. Recall that we expect to find a factor related to the Understand space and associated with questions 12 and 13. A "Synthesize" factor associated with questions 14-17. An "Ideate" factor associated with questions 18-20. A "Prototype" factor associated with questions 21-24, and a "Implement" factor associated with questions 25-28. The factor loadings computed through Exploratory Factor analysis do not perfectly match our expected model, though there are notable similarities. Factor 1 has high loadings for questions 21, 22, and 23 and no other factors include these questions in a meaningful way. This suggests that Factor 1 roughly corresponds to our "Prototype" space. Interestingly, we also see contributions from questions 17, 25, 26, and 28, which are related to problem framing, planning and decision making. Factor 2 is most strongly associated with questions 12, 13, and 14, with lesser weights for questions 15, 16, 17, and 27. This seemingly aligns with the "Understand" space. The inclusion of question 27 is also notable in light of the shared term "stakeholder" which appears in 13, 14 and 27. Factor 3 is most strongly associated with questions 18, 19 and 20. This is a good match with the "Ideation" space, though there is some overlap with items expected to fall under "Synthesis." Interestingly, these expected synthesis questions 14-17 are spread among these first four factors. Questions 15 (Define the goals of the design problem), 16 (Identify trends/patterns in gathered information), and 17 (Frame design needs so that solutions can be developed) contribute to the "Understand" and "Ideate" factors as well as Factor 4, which is most strongly associated with question 16. Thus Factor 4 is roughly mapped to "Synthesize." The nebulous nature of this factor is appropriate for the synthesis space, which is notoriously difficult to pin down. Finally, Factor 5 is most strongly associated with question 27, as well as 24, 25, 26, and 28. These reasonably represent the "Implement" space. To summarize, Factor 1: Prototype, Factor 2: Understand, Factor 3: Ideate, Factor 4: Synthesize, Factor 5: Implement. Additionally, items expected to be related to synthesis were found to be associated with understanding, ideation, and synthesis. Finally, participants seemed to associate questions which included the word "stakeholder." This suggests some latent factor related to stakeholder interactions. While these factor loadings don't perfectly match the expected theoretical model, they are a reasonable match for many items. The distributed nature of question 17 (Frame design needs so that solutions can be developed) and question 20 (Assess feasibility of design ideas) which appear to contribute to many factors each, suggests that these questions may need to be clarified. Otherwise, this might be an indication that respondents in our sample do not strongly associate these items to a particular construct. This could be because the item itself is not associated with a particular construct, or that the respondents are not aware of the underlying association. More could be learned by changing these items and comparing the results.

We will use these factor loadings to compute a factor score for each of the five spaces, Understand, Synthesize, Ideate, Prototype, and Implement. Only items with positive factor loadings will be included. This is because including items with negative weight means that the maximum factor score corresponds to a low response on some items. Since all of our questions ask for a degree of confidence from 0 to 100, having a maximum factor score associated with a degree of confidence less than 100 makes little conceptual sense. Therefore, factor scores for each factor are computed as the linear combination of items weighted by their factor loading, ignoring any items with negative weight.

Results

In the beginning of Fall 2023, there were 307 respondents. These students were affiliated with 10 different courses in the College of Engineering, at the 100, 200, and 300 levels. The

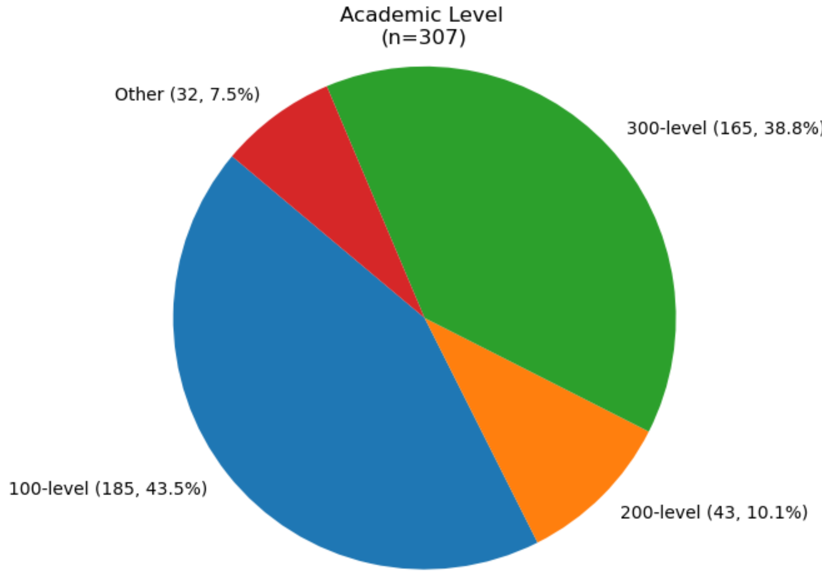

Figure 3 – Pie chart of academic level of students in sample.

demographics of the sample can be seen in **Table 3** and a pie chart showing the number and percentage of students at each academic level is shown in **Figure 3**. The 'other' category includes students who did not respond to this survey question, or whose response could not be interpreted as an academic level.

Table 3 – Demographic Distributions			
Race/Ethnicity	**Number (%)**	**Gender Identity**	**Number (%)**
Asian or Pacific Islander	127 (41.4%)	Female	67 (21.8 %)
Black or African American	2 (0.7%)	Male	233 (25.9 %)
Hispanic or Latino	22 (7.2%)	Transgender	1 (0.3 %)
Native American or Alaskan Native	1 (0.3%)	None of these	2 (0.7 %)
White or Caucasian	125 (40.7%)	Other or prefer not to say	0 (0 %)
Multiracial or Biracial	21 (6.8%)	N/A	4 (1.3 %)
A race/ethnicity not listed here	7 (2.3%)		
N/A	2 (0.7%)		

Each student rated their own degree of confidence related to the 17 HCED items described previously. The distributions of confidence levels for each item are shown in **Figure 4**. Students at the 100, 200, and 300-levels are shown in blue, orange, and green respectively. Note that these histograms are plotted with counts on the y-axis, so differences in the sizes of each group result in different heights. Note that for several questions (e.g., 17, 21, 22), there is a clear increase in confidence from the 100-level to the 300-level. Individual items were combined into larger factors as described in the Methods section.

The average factor scores for each academic level are shown in **Figure 5** as well as **Table 4**. Note that the Prototype factor score is the lowest for all three groups but increases substantially from 100 to 300-level. An independent samples t-test was used to compare the average factor scores at different academic levels. There was a significant difference in every factor from the

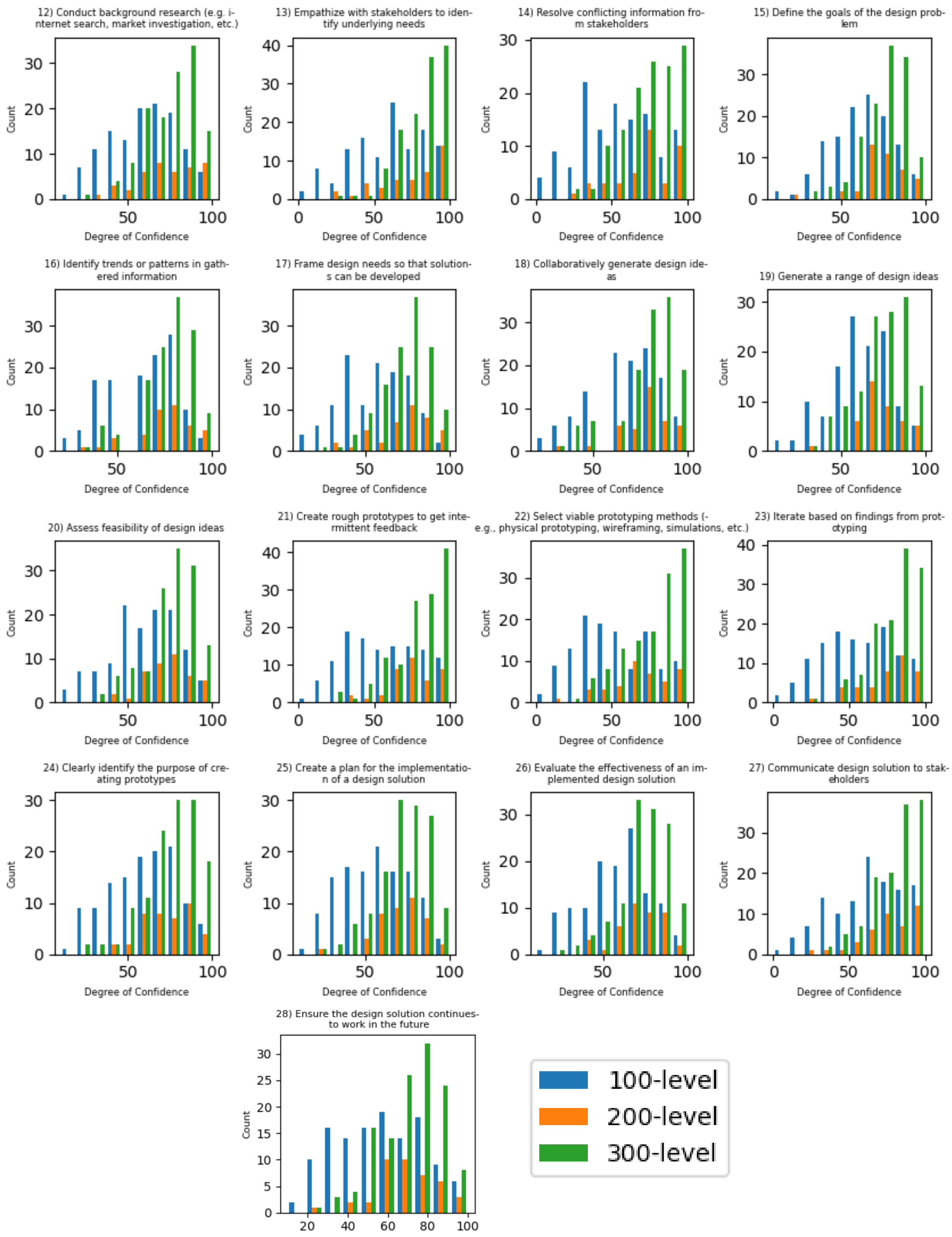

Figure 4 – Histograms for each HCED item in the survey showing the distribution of degree of confidence for 100, 200 and 300-level students.

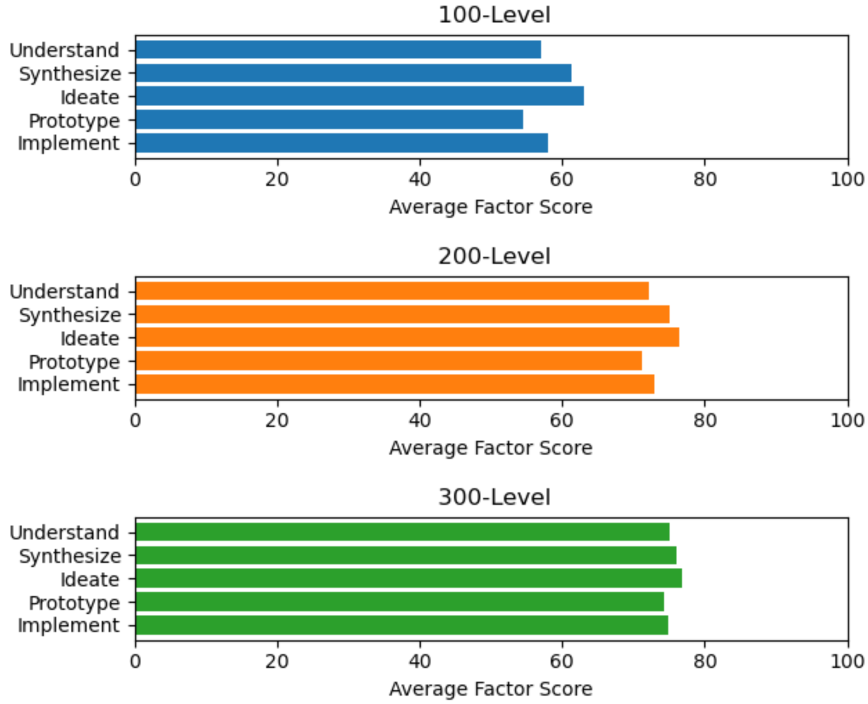

Figure 5 – Average factor scores for 100, 200 and 300-level students

100 to 200 level, but no significant difference from 200 to 300 level. The results of these t-tests can be seen in **Table 5**. Because this data was collected at the beginning of the Fall semester, students at the 100-level represent incoming freshman, and the change from 100 to 200 may be due to the learning experiences during the freshman year. Similarly, changes from 200 to 300 may be due to learning experiences during the sophomore year.

Table 4 – Mean factor scores			
Factor	**100 level**	**200 level**	**300 level**
Understand	57.07	72.18	75.05
Synthesize	61.25	75.14	75.98
Ideate	62.97	76.36	76.88
Prototype	54.57	71.28	74.28
Implement	58.05	72.87	74.84

Table 5 – T-test results indicating change from year to year		
Factor	**100 → 200 level**	**200 → 300 level**
Understand	t = -4.552, p = 1.035e-05	t = -1.144, p = 0.254
Synthesize	t = -4.664, p = 6.420e-06	t = -0.355, p = 0.723
Ideate	t = -4.470, p = 1.460e-05	t = -0.207, p = 0.836
Prototype	t = -4.896, p = 2.332e-06	t = -1.128, p = 0.261
Implement	t = -4.515, p = 1.209e-05	t = -0.797, p = 0.427

Conclusions

In this paper, we've presented our early findings around the development and deployment of a Human-Centered Engineering Design self-efficacy assessment tool. Data was collected during the Fall 2023 semester, with 307 responses from students at the 100, 200, and 300 levels. Cronbach's alpha was computed for each group of items belonging to each of the HCD taxonomy spaces and was found to be >0.8 for all constructs. Additionally, factor analysis was carried out to explore how factor loadings compare to the theoretical model. While agreement was not perfect, five emergent factors from exploratory factor analysis were mapped to the five HCD taxonomy spaces. Notably, questions intended to be associated with the "Synthesis" space were found to contribute to factors for "Understand", "Ideate", and "Synthesis." Additionally, questions around stakeholder interactions were found to be related even when describing different parts of the design process. This suggests that students consider stakeholder interactions as a separate aspect of the engineering design process. Items 17 and 20 were found to be weakly associated with multiple factors, suggesting that these items may need to be clarified or otherwise revised.

These factor loadings were used to compute factor scores associated with "Understand", "Synthesize", "Ideate", "Prototype", and "Implement" spaces. The average factor scores for 100, 200 and 300 level students were compared to answer RQ1) How do self-efficacy assessments differ between students at various academic levels? A significant difference was found for all factors between the 100 and 200 level students. Notably, Prototyping confidence increased from an average of 54.57 for the freshman to 71.28 for sophomores. While there is significant growth indicated from the 100 to 200 levels, we cannot yet attribute this to learning experiences in freshman design courses. A major limitation of this work as it currently exists is a lack of control groups or other control measures. This means that we cannot differentiate between a change caused by a design learning experience and a change due to other unknown circumstances. One might expect that students naturally mature and gain confidence as they move through their undergraduate careers. Ideally, this effect will be measured in future work in two ways. First, by collected data from students who are not receiving significant training in human-centered engineering design, and second, by including questions to measure background maturation and increases in confidence unrelated to engineering design education. Future work will also focus on the generalizability of these items, and their validity beyond our context of use.

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