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Development of Survey Instruments to Measure Undergraduate Engineering Students' Entrepreneurial Mindset: Connections and Creating Value*

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The inclusion of entrepreneurial concepts into undergraduate engineering curriculum has proliferated over recent years. Entrepreneurially Minded Learning (EML) is a common approach for teaching the Entrepreneurial Mindset (EM) and is grounded in opportunity and impact recognition as well as attributes including Curiosity, Connections, and Creating Value (3C's). Faculty across many institutions have made efforts to include EML into curriculum and developed instruments to assess the efficacy of these efforts on student outcomes. However, existing assessment instruments fail to adequately characterize individual attributes that make up an EM. In this study, we describe the development of two indirect surveys to assess the EM attributes of Connections and Creating Value. The two Likert-type scale surveys were constructed using the Kern Entrepreneurial Engineering Network (KEEN) EML framework and institutionally developed EM Learning Objectives and were implemented into a First-Year Engineering Program at the beginning and end of the 2021–2022 academic year. An Exploratory Factor Analysis (EFA) on the Autumn 2021 data (n = 215 student responses) suggests four factors that describe the variance in Connections survey data; these factors contain content we describe as (1) Integrate Outside Information, (2) Consider Social, Economic, and Environmental Factors, (3) Define Connections, and (4) Make Connections within Engineering Design. An EFA on Creating Value survey data (n = 206 student responses) suggests three underlying factors: (1) Create Value within Engineering Design, (2) Attitude and Approach Toward Value Creation, and (3) Create Value for Others. A paired analysis of 101 student responses between the beginning and end of the academic year was conducted for survey validation. This analysis reveals that students' views on their believed ability to "Integrate Outside Information" and "Make Connections within Engineering Design" increased significantly over the academic year. Student views on their abilities to Create Value across all factors also increased significantly. Collectively, these findings suggest where students experience growth in these attributes of EM over their first year in engineering and provide evidence that EFA solutions can reasonably detect such growth over time. Future work includes more rigorous validation efforts and expansion to broader populations. This study presents a first step toward establishing validated instruments for the characterization of Connections and Creating Value EM constructs across institutions.

Keywords: entrepreneurial mindset; exploratory factor analysis; assessment; first-year engineering

1. Introduction

The field of engineering has been evolving over the past decade to emphasize entrepreneurial concepts in addition to the technical mathematical and scientific skills that are fundamental to the profession [1, 2]. These entrepreneurial concepts include entrepreneurship as a learned activity on its own and a focus on components of thinking entrepreneurially, such as mindset and behavioral attributes. This notion is evidenced by the rise in entrepreneurship engineering programs and increasing reports of entrepreneurship being integrated into other "more traditional" engineering domains [3]. The benefits of the integration of these concepts are reflected in student and employer reports that some level of entrepreneurial training increases employability of graduates and better prepares them for the workforce [4, 5]. Due to these positive reports, efforts to integrate an entrepreneurial mindset are supported by educational administrators and potential employers alike [6, 7]. Moreover, an entrepreneurial mindset better prepares young engineers to approach the complex problems of our world with a global awareness and an intention to create value for society, the environment, and the economy [7, 8].

1.1 Entrepreneurially Minded Learning Framework

A leader in efforts to establish and disseminate a framework focused on entrepreneurial ideas into undergraduate engineering is the Kern Entrepreneurial Engineering Network (KEEN), a partnership of colleges and universities across the U.S. [9, 10]. KEEN's grounding framework for the Entrepreneurial Mindset (EM) emphasizes *opportunity recognition* and *impact skills* together with the "3C's": Curiosity, Connections, and Creating Value [9, 10]. Each "C" is considered an attribute

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of the mindset. Curiosity refers to the ability to understand the broader world, look forward to the future, and explore multiple perspectives [10]. Connections refers to thinking outside the box, gaining new insights, and connecting disparate information together to position old information into new contexts [10]. Creating Value is the attribute defined by the ability to seek opportunities with the lens of the stakeholders in mind and to design while striving to have positive societal, economic, and environmental impact [10]. Together, the 3C's are fundamental components of KEEN's Entrepreneurially Minded Learning (EML) framework. As of 2020, components of EML have been adopted and/or adapted by nearly 3,000 engineering faculty across over 70 institutions with the unifying goal of transforming engineering with the EM [11].

Despite the extent to which academic institutions have integrated aspects of KEEN's EML framework into their curriculum, the assessment of the impact of those efforts remains a challenge. Several "calls-to-action" have been articulated regarding the need for EM and/or entrepreneurship assessment tools [1, 12] due in part to assessment being necessary to inform the validation and iteration of EML curricular efforts that are proliferating [11]. In response to such calls, several researchers have developed self-report instruments to evaluate students' EM wholistically. In the context of KEEN's EML framework, wholistically refers to the evaluation of all three "C's" in addition to a broader range of mindset (idea or attitude) and behavioral (action) attributes [5, 13–15]. Wholistic EM assessment instruments include the Engineering Student Entrepreneurial Mindset Assessment (ESEMA) [14], the Entrepreneurial Mindset Profile (EMP) [15] and an unnamed survey based heavily on KEEN's EML framework [13].

Factor analyses on wholistic EM assessment instruments like the ESEMA and EAP suggest that there are underlying latent variables that make up the definition of an "Entrepreneurial Mindset" for an undergraduate engineer [14, 15]. However, the salient factors described by wholistic surveys cover a wide range of themes and make up scales that are highly multidimensional. For example, the ESEMA, EAP, and the unnamed survey by Li et al. contain 7, 14, and 10 factors, respectively, with several factors containing only two items [13–15]. Researchers have argued that such surveys, while comprehensive, dilute the complex constructs that make up something as nuanced as a "mindset" and contribute to an overall lack of consensus for the definition of EM [12, 16]. Consequently, there is a need for *attribute-specific* instruments to refine our understanding of EM constructs and to develop those instruments such that they can be used across institutions.

1.2 Background

The Ohio State University (OSU) began its partnership with the Kern Entrepreneurial Engineering Network (KEEN) in 2017 and was led by a team of educators housed primarily in the Department of Engineering Education. Efforts to infuse EML into undergraduate engineering at OSU began in the design-build courses in the First-Year Engineering Program (FYEP) [17]. This work was guided by a set of best-practices that were established following a multi-institution investigation of EM formal learning approaches in first-year engineering courses [18–20]. Since then, EML efforts have been expanded and refined in the FYEP and in the College of Engineering senior Capstone courses. Training efforts [21] and learning communities [22] have also been implemented to support the instruction of EM. Collectively, the goal of these efforts was, and remains, to institutionalize EM as a cultural norm in pedagogy, course design, and student learning outcomes across the college.

In parallel with this work to infuse EM across the College of Engineering, we have developed and implemented assessment instruments to measure students' EM and to inform our understanding of the effectiveness of our training and formal learning efforts. Through a backwards-design process we refined a set of 14 Entrepreneurially Minded Learning Objectives (EMLOs) to guide curriculum design and establish common objectives to be used across the college [23, 24]. We also established a "toolkit" of 3C's assessments that consists of a direct and indirect assessment for each of the C's to total six assessments. A goal of establishing this toolkit was to develop attribute-specific direct and indirect assessments such that each attribute could be individually assessed as recommended by the literature [12, 16]. We developed the direct assessments as activities to be completed in or out of class. These activities consist of a question generation prompt to assess Curiosity [25], generation of a concept map to assess Connections [26–28], and a stakeholder value matrix activity to assess Creating Value [29]. As an indirect assessment for Curiosity, we adopted the established and validated Five-Dimensional Curiosity Scale (5DC) from the work of Kashdan et al. that has been used in many contexts including engineering education [30]. To date, these four assessments have been implemented at varying levels into our FYEP, intermediate engineering, and Capstone courses [24, 25, 29] and have provided valuable characterization of students' EM [17, 26].

Given a lack of validated instruments for the 3C's constructs of an EM, we aimed to develop two indirect assessments for the "Connections" and "Creating Value" constructs as defined by

KEEN's EML framework [10]. We developed these instruments in-house as the final two assessments for our 3C's assessment toolkit. Our aim was to investigate and define any underlying structures for Connections and Creating Value to operationalize these two attributes with specific and focused factors (i.e., variables) such that our developed instruments have utility for measuring a students' EM and detecting attribute-specific changes over time. Accordingly, we developed two separate surveys and implemented them in the First-Year Engineering Program honors sequence at our institution. Using those survey data, we employed exploratory factor analysis (EFA) with the 3C's of KEEN's EML framework as the grounding conceptual framework for our exploration of latent variables describing any covariance in survey data [31–33]. With this manuscript we describe the development and implementation of both surveys and our initial EFA results. Based on our factor solutions, we present assessment data acquired at the beginning and end of the 2021–2022 academic year from first-year engineering students.

2. Development of Assessments and Factor Analysis

2.1 Survey Development

Statements were mined for the Connections and Creating Value surveys by pulling from the KEEN EML framework [10] and a set of 14 Entrepreneurial Mindset Learning Objectives that were previously established by a team at OSU [23, 24]. To develop survey statements, wording was first sourced from the EML framework or learning objectives and then converted into "I" statements. For example, "*Connect ideas from more than one domain of knowledge*" was sourced from learning objective 3c [23, 24] and converted to "*I can connect ideas from more than one domain of knowledge*." The initial sourcing of statements was conducted by one researcher and then reviewed independently by two different researchers for initial face validity, one of whom has expert knowledge in research related to EM assessment. This statement mining process resulted in 18 and 22 statements for the Connections and Creating Value surveys, respectively. For implementation, statements were compiled into a survey with a 7-point Likert-type scale to align with the 7-point scale of the 5DC [30]: (1) Does not describe me at all, (2) Barely describes me, (3) Somewhat describes me, (4) Neutral, (5) Generally describes me, (6) Mostly describes me, and (7) Completely describes me.

2.2 Survey Implementation and Data Collection

Both surveys were combined into one Qualtrics survey together with the 25-item 5DC scale [30] that was adopted at our institution as an indirect assessment for Curiosity [17]. Statements were provided sequentially in the order of the 25 5DC items, 18 Connections items, and 22 Creating Value items. The survey was implemented at two time points in the FYEP honors sequence. The first data collection (pre) occurred in week 1 of the Autumn 2021 semester as an individual day 2 preparation (out-of-class) assignment. The second data collection (post) occurred in week 13 of the Spring 2022 semester as a weekly individual journal prompt (out-of-class) assignment.

Informed consent was collected immediately following the first data collection and with Institutional Review Board approval. In total, 244 out of 357 students consented to the study at the time of the first data collection in Autumn 2021. Students came from the population summarized in Table 1; no individual identifiers were collected related to student demographics given that surveys were implemented as a part of routine class work. From the consenting population, there were 215 fully completed and 20 partially completed responses for the Connections statements. For the Creating Value statements, there were 206 fully completed responses, 28 partially completed responses, and 1 completely blank response. A total of 9 responses were removed as duplicates or because students did not reach the end of the survey. These subject population sizes for Connections and Creating Value resulted in subject to item ratios of approximately 13:1 and 11:1, respectively. Subject to item ratios fell above a "gold-standard" ratio of 10:1 [32], and as such, were suitable as a dataset for subsequent EFA. Only data from the first collection time point were used for our initial EFA.

2.3 Exploratory Factor Analysis

We conducted a series of EFAs using IBM SPSS Statistics (Version 28.0.1.1 (14)) [34]. Since the Curiosity indirect assessment is already validated [30], EFAs were only conducted for the Connections and Creating Value datasets. The one instance of a completely blank response in the Creating Value survey was removed from the analysis as person-level missingness. Further item-level missingness in the partially completed responses in both Connections and Creating Value datasets was addressed using a maximum likelihood missing data routine expected maximization algorithm on both data sets, separately [32, 34]. This expected maximization algorithm resulted in a complete data set for each of the Connections and Creating Value data sets that was used in all subsequent analyses.

Associations between the items within each

Table 1. Ethnic, sex, and major demographics of students enrolled in the FYEP honors sequence in Autumn 2021

URM status	**Number**	**Percentage**
Non-URM	305	95.9
URM	13	4.1
Sex	**Number**	**Percentage**
Male	246	77.4
Female	72	22.6
Major	**Number**	**Percentage**
Aerospace Eng	35	11.0
Aviation	4	1.3
Biomedical Eng	42	13.2
Chemical Eng	34	10.7
Civil Eng	4	1.3
Computer Science and Eng	105	33.0
Electrical and Computer Eng	19	6.0
Environmental Eng	7	2.2
Engineering Physics	4	1.3
Food, Agricultural, and Biological Eng	1	0.3
Industrial and Systems Eng	8	2.5
Materials Science and Eng	4	1.3
Mechanical Eng	50	15.7
Welding Eng	1	0.3
Total	**318**	**100.0**

URM: underrepresented minority; URM include African American or Black, Hispanic, American Indian/Alaskan Native, and those who identify as Two or More Races, including at least one of the previous categories. Students are only considered as URM if they are a U.S. citizen or permanent resident.
FYEP: First-Year Engineering Program; Eng: Engineering.

survey were examined with an EFA (principal-axis factoring in SPSS) with an extraction method based on eigenvalues greater than 1. An oblique pro-max rotation was used which assumes that underlying factors are correlated [33, 35]. Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy, and Bartlett's test of sphericity were computed to assess whether each dataset was adequate for EFA. Items with extraction communalities below 0.3 were removed from the analysis. A scree plot analysis was used to determine how many factors to retain and correlation coefficients between extracted factors were affirmed to not exceed 0.8 [34]. Pattern matrix coefficients were used to determine factor loadings, with a 0.3 factor loading determined a priori as an item sufficiently loading onto one factor [34]. A reliability analysis was conducted for the items within each factor by computing the Cronbach's α statistic as a measure of internal consistency of items within a given factor [36, 37]. Finally, we assigned labels to the factors for each survey based on the content of the final factor solutions within the context of KEEN's EML framework.

An unconstrained EFA on the Connections dataset resulted in an acceptable KMO measure ($\geq$0.65) and a statistically significant Barlett's test of sphericity (Table 2) [32, 34]. The analysis returned a four-factor solution that explained 58.4% of the total cumulative variance (Table 2). A four-factor solution was confirmed with the associated scree plot with factor correlation coefficients of ≤ 0.611. All 18 items were retained since all computed communalities were greater than 0.3 and returned factor loadings ≥ 0.339 (Table A1). Cronbach's α ranged from 0.791 to 0.929 (Table A1). The labels given to the factors based on the content of each factor's items were: (1) Integrate Outside Information, (2) Consider Social, Economic, and Environmental Factors, (3) Define Connections, and (4) Make Connections within Engineering Design (Table 3).

Table 2. KMO, Bartlett's Test, and variance explained by factor for final EFA outputs of each survey

	Connections	**Creating Value**
Kaiser-Meyer-Olkin measure	0.889	0.935
Bartlett's test of sphericity	$p < 0.0001$	$p < 0.0001$
	variance explained (%)	
Factor 1	38.394	42.230
Factor 2	8.080	4.095
Factor 3	6.714	2.956
Factor 4	5.177	–
Total	58.365	49.281

Table 3. Factors for the *Connections* survey resulting from Exploratory Factor Analysis

Factor 1: Integrate Outside Information	
Item	**Statement**
7	I can apply a given set of user needs as part of the design process.
8	I can develop a list of user needs using either primary or secondary research.
9	I consistently refine user and stakeholder needs through iterative cycles of iteration and feedback.
10	I consistently use resources and expertise to advance an element of a solution.
11	I can identify needed resources or expertise to fill an identified knowledge gap.
12	I can identify a knowledge gap related to a specific topic.
Factor 2: Consider Social, Economic, and Environmental Factors	
Item	**Statement**
4	I can evaluate the social, economic, and environmental costs of a proposed solution to a problem.
5	I can evaluate the social, economic, and environmental risks of a proposed solution to a problem.
6	I can evaluate the social, economic, and environmental benefits of a proposed solution to a problem.
Factor 3: Define Connections	
Item	**Statement**
1	I can synthesize ideas from a wide variety of sources to discover something new.
2	I can connect ideas from more than one domain of knowledge.
3	I can connect ideas from the same domain of knowledge.
Factor 4: Make Connections within Engineering Design	
Item	**Statement**
13	I frequently mentally integrate technical topics, relating one to another.
14	I frequently think about the potential unintended consequences of my work.
15	I tend to plan for decisions associated with increasing scale or production when designing a solution.
16	I habitually assess "What if?" regarding connections between aspects of my design.
17	I frequently investigate the intersection of seemingly disparate ideas.
18	I tend to use current affairs in discussions of technical solutions.

The initial unconstrained EFA on the Creating Value dataset returned a communality below 0.3 for one item on the survey (Item 5: "*I often reflect on previous personal or team failures.*"), so this item was removed from the analysis [32]. We then tested a three-factor solution since the scree plot of an unconstrained EFA with Item 5 removed suggested a three-factor solution. The three-factor solution passed both KMO and Bartlett's tests (Table 2). This final three-factor solution explained 49.3% of the total cumulative variance (Table 2) with factor correlation coefficients of ≤ 0.721 and factor loadings of ≥ 0.347 aside from Item 1 (Table A2). Item 1 ("*I can discuss social, economic, and environmental values in relation to a proposed solution to a problem.*") cross-loaded onto all factors which was confirmed with a comparison of squared factor loadings. We identified similarities in content between Item 1 and the Items 19 and 20 in the third extracted factor (e.g., context words relating to societal value and human flourishing), and the reliability test for these three items returned a Cronbach's α of 0.665. Given that a Cronbach's α between 0.6 and 0.7 is regarded as acceptable [13, 37], we assigned Item 1 to the third extracted factor. Cronbach's α for the other two factors were 0.909 and 0.856 (Table A2). The labels given to the three factors in this final solution were: (1) Create Value within Engineering Design, (2) Attitude and Approach Toward Value Creation, and (3) Create Value for Others (Table 4).

3. Analyses of Student Responses

3.1 Context

The First-Year Engineering Program honors sequence in which the two surveys were implemented is a two-semester Fundamentals of Engineering I and II sequence that is offered to University Honors-designated engineering students. The FYEP honors sequence teaches basic engineering skills to prepare students for advanced courses, internships, and careers in engineering at an accelerated pace. Fundamentals of Engineering I, offered in Autumn, introduces students to engineering problem solving utilizing computational tools such as Excel, MATLAB, algorithm development, C++ programming, and hands-on experimentation. Fundamentals of Engineering II, offered in the Spring, introduces 3D visualization with computer-aided design and consists of a full-semester team design or research project. Three project options are offered: a robot design-build project, a nanotechnology research project, and an integrated

Table 4. Factors for the *Creating Value* survey resulting from Exploratory Factor Analysis

Factor 1: Create Value within Engineering Design	
Item	**Statement**
2	I can describe the features of an identified opportunity.
3	Given a broad description of an opportunity, I can refine the opportunity based on research.
4	I can justify that a proposed opportunity to create a product, process, or service can be developed to create value using research from multiple sources.
8	I can provide benefits to a variety of stakeholders who may have broad interests in financial, social, and environmental outcomes.
11	I regularly ask questions that reveal authentic demand.
12	I regularly develop archetype users of engineering solutions.
13	I usually test novel ideas with others to obtain formative feedback.
18	I think about the benefits and drawbacks of a market-based view of value.
21	I tend to support a problem whose solution will create value within the identified opportunity with research and stakeholder input.
22	I can identify a problem whose solution will create value within the identified opportunity using either primary research, secondary research, or by engaging stakeholders.
Factor 2: Attitude and Approach Toward Value Creation	
Item	**Statement**
6	I often use lessons learned from failures to improve a solution.
7	I can identify a failure or area of improvement in a submission, project, or team environment.
9	I consider myself an empathetic ethnographer or observer of unmet needs.
10	I habitually reframe problems as opportunities.
14	I can create value from underutilized resources.
15	I tend to extend existing solutions to new situations.
16	I habitually identify unexpected opportunities to create extraordinary value.
17	I seek out opportunities to determine what is valuable to others.
Factor 3: Create Value for Others	
Item	**Statement**
1	I can discuss social, economic, and environmental values in relation to a proposed solution to a problem.
19	I spend time thinking about what engineering solutions are good for individuals versus society.
20	I spend time thinking about how the value of my work is connected to human flourishing and well-being.

business and engineering honors option. Topics of ethics, teamwork, and written and oral communications are integrated throughout the curriculum in both semesters and across project options. EML is also integrated across both semesters and all project options. The most prominent EML components include a Software Design Project at the end of the first semester and integration throughout the second semester design project. In the 2021–2022 academic year, a notable EML addition included a 3C's workshop at the end of the second semester. Given the day 2 integration of our surveys in Autumn 2021 (the pre time point), students had experienced only an introduction to the course syllabus. However, the post collection point in week 13 of the Spring 2022 semester occurred near the end of the semester project following students' exposure to a majority of the year's curriculum.

3.2 Data Analysis

To assess survey results by factor for the Connections and Creating Value surveys, we extracted a subset of survey data from both acquisition time points (Autumn 2021 and Spring 2022). To allow for matched pairs comparisons, this subset consisted of consenting students who had fully completed pre *and* post surveys. This population selection resulted in a subset of 101 complete and paired survey responses. To quantify factor scores, Likert-type scale responses from 1–7 for each item (i.e., statement) were averaged for each factor, separately for each survey. Factor averages were computed separately for each student's responses in the pre and post surveys. Descriptive statistics were calculated for each factor and normality was tested using a custom MATLAB script (R2021b). Since all datasets were found to be non-normal, a paired Wilcoxon Rank Sum test was used to compare pre and post factor averages for each of the two surveys, with $\alpha = 0.05$.

3.3 Results

On average, students responded above Neutral (4) regardless of factor or time point and those responses consistently increased from the beginning to the end of the academic year with increases across some factors being statistically significant (Fig. 1). On the Connections survey, students' views on their believed ability to "Integrate Outside Information (Factor 1)" and "Make Connections within Engineering Design (Factor 4)" increased significantly ($p<0.05$) and by over half a scale point (Fig. 1). Their views on abilities to "Consider Social, Economic, and Environmental Factors (Factor 2)" and "Define Connections (Factor 3)" did not change significantly (Fig. 1). On the Creating Value survey, students perceived that their views of value creation increased significantly ($p < 0.05$) across all three factors (Fig. 1).

4. Discussion

EFA revealed underlying structures for both surveys explored in this study, with higher magnitude factor loadings for the Connections survey. This notion is supported by all 18 items in the Connections survey loading onto only one factor in our initial unconstrained EFA (Table A1). The first Connections factor, accounting for nearly 40% of the covariance (Table 2), contains words such as *user needs*, *stakeholder needs*, *resources, expertise, and knowledge gap*. We interpreted these words as a student looking to external sources of information and accordingly named this factor "Integrate Outside Information." There is clear parallel language in the statements contained in the second factor, "Consider Social, Economic, and Environmental Factors," with only one word (costs, risks, or benefits) changed between statements (Table 3), and thus it is not surprising that these items loaded onto the same factor. The third factor, "Define Connections," was named for its similarity to an educational outcome defined in KEEN's EML framework: "Integrate information from many sources to gain insight" [10]. Our label for the fourth factor, "Make Connections within Engineering Design," was chosen for several instances of *technical solutions/topics* and references to a *solution / my work / my design*, yet we found the fourth factor least cohesive in its item content. For example, item 18 refers to *current affairs* which more closely aligns to the first factor (Table 3).

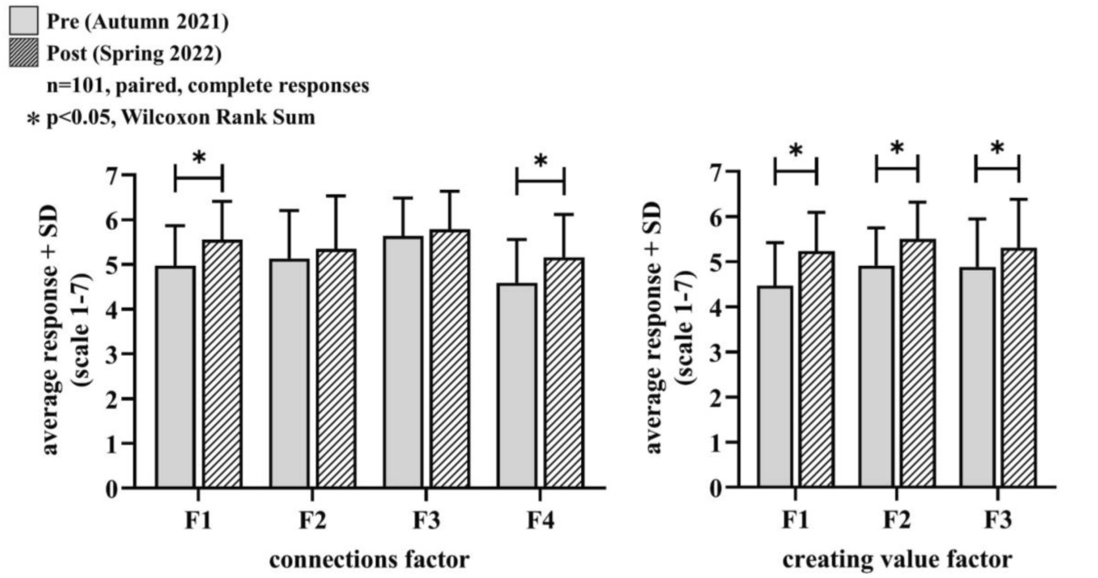
Despite our factor solution for the Creating Value survey passing all quantitative measures for a stable solution (Table 2), the cohesion of the content within the factors is less clear than the Connections factor solution. The first factor was named "Create Value within Engineering Design" due to our observation that many of the factor's statements mapped to the Engineering Design Process that first-year students learn in our department (Table 4). For example, words such as *opportunity, stakeholders, users, test*, and *market* correspond to steps in the Engineering Design Process as we present it in our context at OSU. Interestingly, there are several words that have the potential for more negative connotations in the second factor, including *failure, underutilized*, and *unexpected*. Items 9 and 10 also connect to one's *empathy* and ability to *reframe problems*. For these reasons we named this factor, "Attitude and Approach Toward Value Creation," yet given the range of content in the statements we expect that this factor may be further resolved with future EFA iteration. Nonetheless, the Cronbach's α suggests a high reliability in the second factor solution (Table A2). Finally, the third factor "Create Value for Others" includes language about society across all items yet Item 1 cross-loaded onto multiple factors and had overall low factor loadings (Table A2), which may indicate that Item 1 may be removed from the solution if further EFA is performed on future data sets. Moreover, given the size of factors one and two, it is possible that some statements could be combined and/or condensed.

We assert that the factors solutions we propose improve upon previous wholistic EM self-report instruments by characterizing the individual EM constructs of Connections and Creating Value. For example, a specific goal of the ESEMA survey was to clearly define and operationalize the 3C's through existing literature. While the authors found that 4 of the 7 emergent factors map to one of the 3C's, the 2 largest factors, "Ideation" and "Open-Mindedness" contain content across more than one of the C's. For example, "Open-Mindedness" aligns with Connections and Curiosity content, consequently measuring the intersection of the two constructs [14]. Measuring the intersection of concepts no doubt has utility in numerous applications yet adds complexity when applying separate EM constructs within a curriculum grounded in the 3C's. At the same time, the content within our first Connections factor, "Integrate Outside Information" and our third Creating Value factor, "Create Value for Others," align strongly with the smaller factors of "Help-Seeking" and "Altruism" in the ESEMA, respectively [14]. Taken together, this alignment begins to reveal where our language could be improved for content validity considering the broader literature. For example, since the "Create Value for Others" factor contains only 3 statements with a low factor loading for Item 1 (Table A2), a future iteration of our survey may consider pulling from the "Altruism" content in the ESEMA.

Although most of the proposed factors contain 6 or more items (Tables 3 and 4), we argue that the breadth of the factors begins to address the criticism that two item factors in broader EM instruments are conceptually problematic due to the inherent complexity of assessing a mindset [12, 16]. This notion is supported by mapping the content of smaller factors in the wholistic EM survey by Li et al. to the emerging factors we present in this study. Unlike the ESEMA, the wholistic EM survey by Li et al. was designed with the secondary KEEN learning outcomes of Collaboration, Communication, and Character [13]. Although the authors do not map their findings to the 3C's, we observe that some of the smaller factors in this survey contain content that redistributes well to either the Connections or Creating Value factors proposed here. For example, the content items of "identify potential stakeholders" and "address stakeholder interests" in Li's factor of "Emerging Stakeholders" align with our factors of "Connections within Engineering Design" and "Creating Value within Engineering Design," respectively.

Students report significantly higher scores in two Connections factors and all Creating Value factors from the beginning to the end of their academic year (Fig. 1), suggesting that the two instruments are sensitive enough to detect changes in self-reported student data over time. Furthermore, these results reveal areas in which students are, and are not, experiencing significant growth. Collectively, our results suggest that our first-year curriculum is excelling in teaching students how to integrate outside information in the context of engineering design yet falling short in delivering information about EML's definition of making connections and considering social, economic, and environmental factors (Fig. 1). For Creating Value, however, students experience growth for all factors (Fig. 1), implying that our formal learning efforts are succeeding in meeting learning objectives in the Creating Value domain.

The Connections and Creating Value surveys presented in this study are a part of a larger institutional initiative to assess the 3C's directly and indirectly. Accordingly, the assessment data presented here (Fig. 1) can be integrated with direct 3C's assessments to better compare how students self-report EM attributes (on indirect instruments) and how they demonstrate those same EM attributes (on direct instruments). For example, concept map scores from our direct assessment for Connections did *not* change from the pre to post time points in this same student cohort, suggesting a disconnect between how students perceive their ability to make connections (Fig. 1) and their concurrent demonstration of this skill. Alternatively, these contradictory findings may suggest that concept maps or our method of scoring them are not effective in



Factor	Connections	Factor	Creating Value
1	Integrate Outside Information	1	Create Value within Engineering Design
2	Consider Social, Economic, and Environmental Factors	2	Attitude and Approach Toward Value Creation
3	Define Connections	3	Create Value for Others
4	Make Connections within Engineering Design		

Fig. 1. Factor averages for *Connections* and *Creating Value* surveys for first-year engineering students. Students' responses increase significantly ($p < 0.05$) for *Connections* factors 1 and 4 (F1 and F4) and for all 3 *Creating Value* factors (F1, F2, and F3) from the beginning (pre) to the end (post) of the academic year.

detecting differences that may exist. Direct assessment data from our assessment for Creating Value, however, increase significantly and thus support the growth in students views on value creation that they self-report (Fig. 1).

4.1 Limitations

There are several limitations associated with our study. This study was implemented using a Qualtrics survey with statements for Curiosity, Connections, and Creating Value presented sequentially. We observed that statements loaded onto factors sequentially for the Connections survey (Table 3), which may be confounded by the sequential statement presentation in Qualtrics. To address this possibility, we randomized statements within each of the 3C's items in subsequent survey implementations. As a preliminary analysis to test for differences in factor averages with the original and randomized surveys, we compared results from the Autumn 2022 semester to those from Autumn 2021 with unpaired t-tests by factor. Those results showed no significant differences between Autumn 2021 and Autumn 2022 first-year engineering cohorts suggesting that randomization may not alter factor loadings and that the two first-year student cohorts demonstrate similar beliefs in their Connections and Creating Value abilities. However, an EFA with the Autumn 2022 data set or Confirmatory Factor Analysis (CFA) is necessary to conclude that factor loadings remain consistent. The length of the survey may have also led to fatigue whereby the later statements, particularly the Creating Value items, were ignored or answered without consideration [38].

Survey data used for the EFA came from a specific student population cohort (Table 1) and these results cannot be assumed to be extrapolated to other types of student cohorts (for example, senior engineering students) nor the broader population. Moreover, the EFA solutions presented here were computed with survey data from primarily male and non-Underrepresented Minority students (Table 1). Future empirical studies and subsequent EFA in different academic settings and with more diverse student groups are necessary to apply the present factor solutions in different contexts. For example, the 5DC is widely accepted as a validated instrument following multiple iterations with three populations of 508, 403, and 3,000 adults [30]. Given the goal that these instruments become validated instruments across KEEN institutions, immediate next steps are to collect data from other KEEN institutions as well as our entire FYEP to capture responses from a broader student group.

Finally, with any EFA, it is critical to emphasize the *exploratory* component of the analysis approach and that results do not prove or disprove any hypothesis or theory [32]. Consequently, we do not aim to draw substantive conclusions from our exploratory analysis but rather to present our results as a first step in creating validated tools to measure EM attributes.

4.2 Future Work

Next steps for this work include further validating both surveys with content and face validity approaches as we refine the items in both surveys. Face validity approaches may include focus groups and/or think-aloud approaches with undergraduate engineering students in our program [14, 39], as initial validity measures focused on expert researcher perspectives. We aim to perform iterative EFAs on subsequent data sets within the FYEP as we refine survey items and then a CFA once we have completed the iteration process. The next step in establishing these indirect assessments as gold-standards for measuring EM attributes is to validate these instruments in a variety of contexts such that they can be utilized by KEEN broadly and consistently. CFA will be necessary to answer the question of whether these instruments have the same structure across different populations or sub-groups of populations.

In our context at OSU, our approach is to implement the Connections and Creating Value indirect assessments more widely within our own institution and in other institutions across KEEN. With this broader dataset, we will validate the proposed instruments such that they can be as widely used as the 5DC assessment for Curiosity [40–42]. We will also test if our surveys reveal differences between groups and how results compare to reported significant differences in self-report survey data using the ESEMA (engineering students and practicing engineers) and survey by Li, et al. (freshman and senior engineering students) [14].

Ongoing work also includes exploring individual student assessment data across the 3C's assessments to investigate the "wholistic EM" of a given student. We anticipate that this approach will reveal different subsets of student who may score highly in some of the "C's" but low in others. Moreover, there is an opportunity to compare results from our surveys to individual factor results from wholistic EM survey that map to specific C's. For examples, Brunhaver et al. posit that some factors in their ESEMA survey overlap strongly with a single "C" [14]. Our future work will expand on prior studies of wholistic EM surveys by adding higher resolution measurements of EM attributes.

5. Conclusions

With the increasing emphasis on EML in undergraduate engineering, there is a parallel need for validated assessment instruments that are specific to the nuanced constructs that make up the complex EM. This work presents the initial development, implementation, and preliminary results of two surveys for the indirect assessment of the EM constructs of Connections and Creating Value. EFA results suggest that each construct can be apportioned into distinct factors that describe variance in data collected from a first-year engineering student population. We believe that analyzing student responses by factor will provide utility in targeting curricular EML initiatives for construct development. Moreover, we show the presented surveys detect differences over time in a first-year engineering student population. Future work is required to fully validate these psychometric instruments for assessing students' ability to form Connections and Create Value. Ultimately, these tools will allow instructors to measure the impact of their EML initiatives on students' EM such that they can iterate and adapt their approaches to consistently improve their approach to EML and the 3C's. Creation of validated instruments will provide a common language for quantitative comparison across institutions that will facilitate cohesion and collaboration across KEEN and EML implementation.

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Appendix Tables

Table A1. Pattern matrix for the *Connections* survey resulting from Exploratory Factor Analysis

Item	Statement	1	2	3	4
8	I can develop a list of user needs using either primary or secondary research.	0.938	0.041	–0.123	–0.170
9	I consistently refine user and stakeholder needs through iterative cycles of iteration and feedback.	0.869	0.036	–0.223	0.008
10	I consistently use resources and expertise to advance an element of a solution.	0.755	0.034	0.007	0.089
7	I can apply a given set of user needs as part of the design process.	0.705	0.035	0.023	–0.079
12	I can identify a knowledge gap related to a specific topic.	0.589	–0.074	0.267	–0.014
11	I can identify needed resources or expertise to fill an identified knowledge gap.	0.578	–0.021	0.175	0.064
	Cronbach's α	***0.879***			
4	I can evaluate the social, economic, and environmental costs of a proposed solution to a problem.	0.032	0.911	–0.006	–0.004
5	I can evaluate the social, economic, and environmental risks of a proposed solution to a problem.	0.015	0.833	–0.006	0.125
6	I can evaluate the social, economic, and environmental benefits of a proposed solution to a problem.	0.026	0.807	0.160	–0.032
	Cronbach's α		***0.929***		
2	I can connect ideas from more than one domain of knowledge.	–0.083	0.020	0.920	–0.069
3	I can connect ideas from the same domain of knowledge.	–0.045	0.026	0.847	–0.088
1	I can synthesize ideas from a wide variety of sources to discover something new.	–0.001	0.127	0.642	0.048
	Cronbach's α			***0.829***	
14	I frequently think about the potential unintended consequences of my work.	–0.215	0.029	–0.087	0.741
17	I frequently investigate the intersection of seemingly disparate ideas.	0.091	–0.188	0.100	0.722
15	I tend to plan for decisions associated with increasing scale or production when designing a solution.	–0.010	0.115	–0.049	0.641
18	I tend to use current affairs in discussions of technical solutions.	–0.008	0.174	–0.130	0.586
16	I habitually assess "What if?" regarding connections between aspects of my design.	0.162	0.044	0.025	0.455
13	I frequently mentally integrate technical topics, relating one to another.	0.267	–0.097	0.283	0.339
	Cronbach's α				***0.791***

Table A2. Pattern matrix for the *Creating Value* survey resulting from Exploratory Factor Analysis

Item	Statement	1	2	3
12	I regularly develop archetype users of engineering solutions.	0.946	–0.116	–0.116
22	I can identify a problem whose solution will create value within the identified opportunity using either primary research, secondary research, or by engaging stakeholders.	0.786	–0.080	0.171
11	I regularly ask questions that reveal authentic demand.	0.728	–0.103	0.037
3	Given a broad description of an opportunity, I can refine the opportunity based on research.	0.678	0.087	0.042
8	I can provide benefits to a variety of stakeholders who may have broad interests in financial, social, and environmental outcomes.	0.663	0.149	0.001
21	I tend to support a problem whose solution will create value within the identified opportunity with research and stakeholder input.	0.588	–0.139	0.357
13	I usually test novel ideas with others to obtain formative feedback.	0.507	0.145	–0.114
4	I can justify that a proposed opportunity to create a product, process, or service can be developed to create value using research from multiple sources.	0.500	0.114	0.174
18	I think about the benefits and drawbacks of a market-based view of value.	0.489	–0.045	0.257
2	I can describe the features of an identified opportunity.	0.478	0.343	–0.077
	Cronbach's α	***0.909***		
6	I often use lessons learned from failures to improve a solution.	–0.191	0.742	0.044
14	I can create value from underutilized resources.	0.241	0.737	–0.172
7	I can identify a failure or area of improvement in a submission, project, or team environment.	–0.173	0.636	0.141
16	I habitually identify unexpected opportunities to create extraordinary value.	0.311	0.510	0.006
10	I habitually reframe problems as opportunities.	0.070	0.503	0.147
15	I tend to extend existing solutions to new situations.	0.373	0.452	–0.120
17	I seek out opportunities to determine what is valuable to others.	0.085	0.428	0.182
9	I consider myself an empathetic ethnographer or observer of unmet needs.	0.068	0.347	0.235
	Cronbach's α		***0.856***	
1	I can discuss social, economic, and environmental values in relation to a proposed solution to a problem.	*0.224*	*0.252*	*0.197*
20	I spend time thinking about how the value of my work is connected to human flourishing and well-being.	–0.090	0.190	0.711
19	I spend time thinking about what engineering solutions are good for individuals versus society.	0.042	–0.008	0.588
	Cronbach's α			***0.665***