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Work in Progress: A Strategy for Assessing Learning Through Reflecting on Doing

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Integrated Realization of Engineered Materials and Products

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Work in Progress - A Strategy for Assessing Learning through Reflecting on Doing

Abstract

How can self-assessment instruments be used to understand student learning in design, build, and test engineering design courses? We contend that current assessment methods, which focus on design artifact performance, often fail to fully characterize student learning. We contend that student learning outcomes, related to principles of design, in courses involving design, build, and test projects are improved when instructors de-emphasize design performance and instead focus on promoting the learning acquired through reflection on doing as embodied in Kolb's experiential learning construct. The incorporation of experiential learning provides the opportunity to facilitate learning by forcing students to learn through reflection on doing while student self-assessment provides instructors with a method to assess learning. In this paper, we explain how two instruments embodying student self-assessment that we employ in our course, AME4163: Principles of Engineering Design, the learning statement (LS) and the Material Internalization Inventory (MII), are leveraged to understand the progression of student learning and internalization of the Principles of Engineering Design (POED). We report how students value particular lessons over others in terms of near and long-term utility. Of note in our findings are the impact of a post-mortem exercise on student confidence in their design abilities in both the near and long-term and how teams and individuals take away differing lessons from the design process.

1. Frame of reference

At the University of Oklahoma, we offer an engineering design course in the semester preceding their capstone project to expose senior-level mechanical engineering students to the process of design. In the course, AME4163: Principles of Engineering Design, we leverage experiential learning to enable students to internalize the Principles of Engineering Design (POED) and to transition from students to Junior Engineers, who we distinguish from students by their ability to identify new principles to suit their needs. From a research standpoint, we are primarily concerned with improving assessment of student learning in design, build, and test courses. We assert that traditional measures of student success, such as project output, do not adequately enable instructors to assess student internalization of target material. Consequently, we posit the need for improved tools and strategies for understanding student learning. In this paper, we explore the implementation of two 'self-assessment' instruments in our course and discuss how analysis of data from these instruments enables us to better characterize team versus individual learning, how learning changes over the course of a design project, and how confidently students feel they can apply their learning moving forward.

In Section 1, we frame the course structure and the role of our two self-assessment instruments in the course as well as outline our research aims. In Section 2, we justify our pedagogy, assessment instruments, and data gathering and analytical approach via a survey of the relevant literature. In Section 3, we describe how data are collected, processed and analyzed for this paper in order to answer our questions. In Section 4, we outline our results and provide analysis for the patterns and information highlighted. In Section 5, we critically analyze our work in terms of the questions posed in Section 1 and explore our contributions and intentions for future work. We close with acknowledgements in Section 6, our references in Section 7, and a supplementary information in Appendix A.

1.1 Course structure and pedagogy

In AME4163, students form their own teams of four or five to complete a design, buid and test challenge issued by the instructors: two professors and a teaching assistant. Over the course of the design project, we require the teams to complete a series of assignments, each tied to one or more of the five POED, which embody the steps of a structured design process. To ensure exposure to all POED and their subcategories, we provide students with *Figure 1*, in which we map the POED to the assignments. We provide instruction through lectures which we tie to the assignments to enable further internalization of the POED. Moreover, we provide context and additional tools through the lectures that the students can leverage in their projects and beyond. We map the progression of the course through assignments, lectures, and major course milestones in the timeline presented in *Figure 2*. Teams use the assignments to complete the design problem titled "Project POP: Prospect or Perish," a project and context borrowed from Mistree et al. [1]. In the vignette, the fictional inhabitants of the planet Vayu need an autonomous mobile device capable of navigating rough terrain to prospect and drill for subterranean natural resources. Given the problem context, we require that the students form teams, frame the problem requirements, design and test a device capable of traversing a course of our own construction, and finally perform a post-mortem reflection on their design experience. In addition to the problem context, we create further constraints in terms of device size, weight, cost, and safety. We present additional features of AME4163 in the Appendix A.1.

POED		Assignment / POED Description	1	2	3	4	5
		Assignment Description	***Given:*** Story, Team Contract ***Provide:*** Problem Statement, Plan of Action, House of Quality, Requirements List, Learning Statements	***Given:*** Problem Statement, HOQ, Req. List. ***Provide:*** Function Structure, Morphological Chart, 6 Configuration, Plus/Minus/ Interesting, Failure, LS	***Given:*** Configurations, PMI, Failure ***Provide:*** Go/No-Go Analysis from 6 to 2 concepts, Bill of Materials, Recommendation, LS	***Given:*** Chosen Concept ***Provide:*** Geometry analysis, CAD model, Refined Bill of Materials, Buildability analysis, Report, LS	Post-mortem report
POED		**POED Description**					
1. Planning a Design Process	1a	Forming a team	✗				
	1b	Accepting and executing a team contract	✗				
	1c	Understanding the problem	✗				
	1d	Proposing a plan of action	✗	✗	✗	✗	
2. Preliminary Design	2a	Ideation: generating concepts		✗			
	2b	Developing concepts (ensure feasibility and realizability)		✗			
	2c	Evaluating concepts; identifying most likely to succeed		✗			
3. Embodiment Design	3a	Refining/modifying most likely to succeed concept			✗	✗	
	3b	Stipulating a Bill of Materials			✗	✗	
	3c	Ensuring functional and technical feasibility, safety, etc.				✗	
4. Prototyping, Testing, and Post-mortem Analysis	4a	Bill of Materials as built; understand all components					✗
	4b	Ensuring built device meets performance requirements					✗
	4c	Critical analysis of device; causes of success and failure					✗
5. Learning through Doing, Reflecting, and Articulating	5a	Critically evaluating the design, build, and test process					
	5b	Articulating internalized POED via learning statements	✗	✗	✗	✗	✗
	5c	Carrying lessons to future: capstone and other ventures					

Figure 1: Description of all POED and mapping of each POED subcategory to the five assignments addressed in this paper.

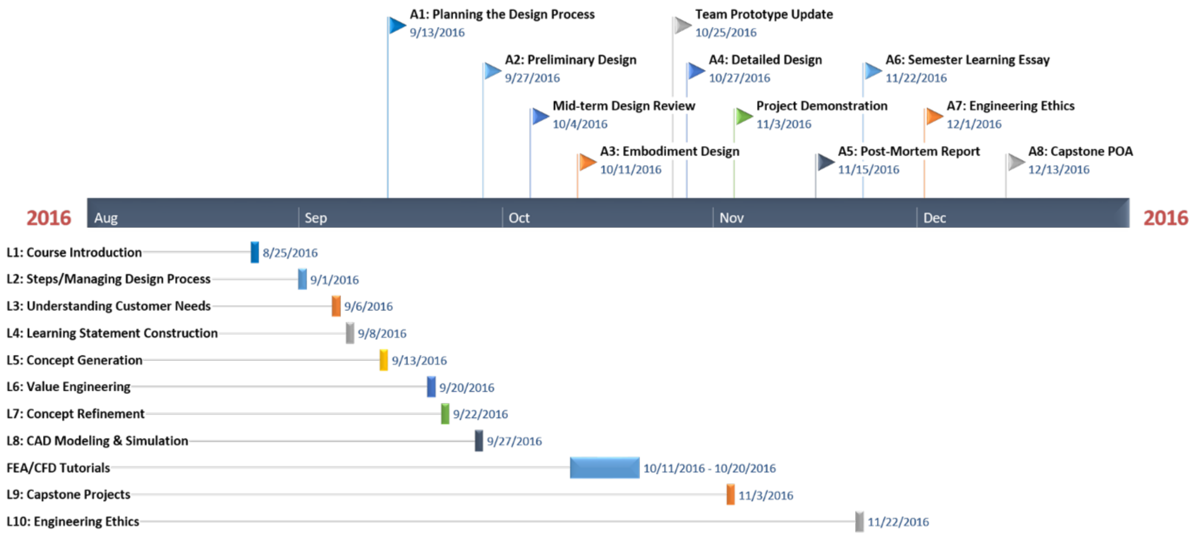


Figure 2: Detail schedule of the course lectures, assignments, and major milestones for the design project.

In AME4163, we integrate David Kolb's experiential learning cycle [2] into a design, build, and test course. It is our belief that the structure of an open design problem provides unique opportunities to enable students to reflect and articulate their own learning. To enable this reflection, we expose students to two self-assessment instruments. First, we require students in lectures and in each assignment to write learning statement (LS), in which they describe the utility of lessons acquired through experience. Second, our students must complete five surveys, titled the Material Internalization Inventory (MII), in which they reflect on their confidence in their ability to apply knowledge in the short- and long-term. In keeping with our interest in assessing learning through reflection on doing, we deemphasize to the students the importance of project output, which is reflected in the course grading rubric, reproduced in the Appendix, Section A.2.

1.2 The learning statement

As stated in Section 1.1, our course pedagogy is anchored in the experiential learning cycle of David Kolb [2]. To that end, we employ a student self-assessment instrument called the learning statement (LS) to enable students to engage with the steps embodied in the cycle: have an experience, reflect on it, abstract learning, and integrate the new knowledge. Over the course of the design project, in both assignments and lectures, students and teams are required to write LS which express their learning in the context of particular experiences. We insist on the structure, outlined in *Figure 3*, of the LS and explain its purpose in early lectures. During lectures, we encourage students to tie their learning to value related to their later work as Junior Engineers. For LS submitted with assignments, we encourage the students to explore the value of their learning in terms of their internalization of the POED. We further do not specify or require a particular number of LS in each assignment, only that each team member write at least one and that the team as a whole write at least one.

Over the course of a semester, our approximately 150 students and their teams generate between eight and ten thousand LS. In this paper, we draw our data set from only one section of the course (seventy-six students) and further, only from Assignments 1-5, a sample size of approximately three thousand LS. During the course, we evaluate the LS and provide feedback to the students in order to encourage deeper reflection and wider exploration of the utility of their learning. For our analytical purposes, we have also developed a two-pronged evaluation method for the LS. The first portion of our evaluation of each LS involves identifying the primary associated POED of the learning expressed in each statement, labelling each LS with a POED sub-category such as '1a' or '4c' (see *Figure 1*). In the second portion of our evaluation, we endeavor to categorize each LS's 'insightfulness.' In reading each LS, rating it using our two-pronged method, and providing individual feedback to students, we find that a grader can spend between five and ten hours grading the LS from a single assignment from one section of the course. We have included the rubric for assessing a LS's level of insight in the Appendix, Section A.3. We also include the Appendix, Section A.5, in which we provide the POED and 'insight' breakdown for team and individual LS in Assignments 1-5.

Experience x	**Learning y**	**Value/Utility z**
Through x (From x, By doing x, …)	I learned y	
I did not consider x initially	I realized y	Value/Utility z in future of learning y
I thought (expected) x before/initially	I found out y	
	I discovered y	
	I became conscious of y	
Value (Lectures) = Help you transition from a student to a junior engineer and gain insight into how to do the assignments Value (Assignments) = Principles of Engineering Design		

Figure 3: This information is provided to the students both through reading materials made available through the course website as well as through in-class lectures.

1.3 The material internalization inventory

The second self-assessment instrument which we employ in our course takes a very different form from the LS. We have developed a series of five surveys, titled the 'Material Internalization Inventory' (MII), which are comprised of two sections designed to assess student confidence in their abilities to leverage knowledge in the short and long-term. The first section, which we call '*Current Status*,' allows us to assess the short-term applicability of particular lessons, tied to the POED. We provide a preamble to the students to prompt them to think of the applicability of their knowledge in the short term and ask them to rate a series of statements using a five-point interval scale, where '1' represents strongly disagree with the statement and '5' represents strongly agree with the statement for the student. As we tie the '*Current Status*' section to short-term applicability of their knowledge, the assessed statements change from survey to survey. The statements in this section of the MII are listed in *Figure 4* with the bold phrase following each serving as the question shorthand for use in charts.

Survey	**'*Current Status*' MII Questions**
(All)	1. I understand what is being asked of me in the most recent assignment and how that material is connected to the previous work in the course **(connectivity)** 2. I know why previous feedback has been provided to me and/or my team regarding the work that we have completed and how that feedback fits into the overall intention of the assignment **(feedback)**
1	3. I understand the importance of forming a team in order to complete Assignment 1 (POED 1a) **(team)** 4. I understand the utility to team management of the team contract in order to complete Assignment 1 (POED 1b) **(management)** 5. I recognize the role of forming a team understanding of the problem in order to complete Assignment 1 (POED 1c) **(problem)**
2	3. I understand the importance of forming a team in order to complete Assignment 1 (POED 1a) **(team)**

	4. I understand the utility to team management of the team contract in order to complete Assignment 1 (POED 1b) **(management)** 5. I recognize the role of forming a team understanding of the problem in order to complete Assignment 1 (POED 1c) **(problem)** 6. I understand the utility of proposing a plan of action in the design process (POED 1d) **(plan)** 7. I understand the importance of the morphological chart in the process of concept generation as seen in Assignment 2 (POED 2a) **(morph.chart)** 8. I understand the importance of ensuring concept functional feasibility via Plus, Minus, Interesting in Assignment 2 (POED 2b) **(plus-minus-interesting)** 9. I understand the importance of evaluating concepts to determine the most likely to succeed concept in the design process (POED 2c) **(concept-eval.)**
3	3. I understand the utility of proposing a plan of action for the design process (POED 1d) **(plan)** 4. I understand the importance of technical evaluation of concepts (analysis, experimentation, thought exercises) in order to refine them such as through the Go/No-Go matrix in Assignment 3 (POED 3a) **(go/no-no)** 5. I understand the need to stipulate a Bill of Materials during the concept refinement phase of the design process (POED 3b) **(bill-of-materials)** 6. I understand the need to ensure functional feasibility, safety, and buildability in the design process (POED 3c) **(concept-feas.)**
4	3. I understand the importance of technical evaluation of concepts (analysis, experimentation, thought exercises) in order to refine them in the design process (POED 3a) **(concept-refine)** 4. I understand the importance of having a Bill of Materials (as built) and knowledge of the limitation of chosen components in the design process (POED 4a) **(component-choice)** 5. I understand the importance of ensuring that the device (as built) meets target requirements for the design process (POED 4b) **(requirements-met)** 6. I understand the importance of critically evaluating the performance of the prototype in the design process (POED 4c) **(perform.-eval.)**
5	3. I understand the importance of critically evaluating the entire design process (POED 5a) **(process-eval.)** 4. I understand the importance of learning statements and articulating my learning to others in the design process (POED 5b) **(learning-statement)** 5. I understand the importance of carrying lessons from the design process forward into other ventures (POED 5c) **(carry-forward)**

Figure 4: Table outlining the changing questions asked in the 'Current Status' *section of the MII surveys. In each question, linked to a particular POED, we assess student confidence in the utility of that POED in the short-term.*

In the second section of the survey, we ask students to rate agreement as it applies to them individually, of ten statements tied to particular knowledge of design using the same five-point Likert scale as the first section. As in the first section of the survey, a preamble prompts the students completing this section to consider how their knowledge may be applied in the long-term (capstone, their careers, etcetera). Unlike in the first section, however, these ten statements do not change from survey to survey. The ten statements that we employ in this section of the survey are listed in *Figure 5* with the bold phrase following each serving as the question shorthand for use in charts.

Question	'*Moving Forward*' MII Questions
1	Based on what I have learned so far, I feel that I am prepared to move from a student to a junior engineer working in a design-related field (industry, graduate school, academia, etc.) **(junior-eng.)**
2	I understand how to effectively form and manage a team in the context of designing a system **(manage-team)**
3	I know how to diagram engineering design problems and write a problem statement **(state-problem)**
4	I understand how to develop system concepts that are consistent with the project requirements as I understand them **(develop-concepts)**
5	I am able to effectively evaluate concepts by leveraging engineering principles to analyze technical function, manufacturing feasibility, and functional feasibility of concept sub-systems **(evaluate-concepts)**

6	I am capable of refining and modifying concepts using analytical techniques until I find a solution to the problem **(refine-concepts)**
7	I know how to identify which aspects of selected concepts are likely to succeed from a functional and technical feasibility and buildability standpoint **(concept-feas.)**
8	I am capable of constructing models and prototypes of my concepts in order to communicate my design concepts to other team members and customers **(prototype)**
9	I know how to analyze my own work critically and plan a way forward as needed **(self-analyze)**
10	I understand how to communicate to others my ideas and learning in the design process **(communicate)**

*Figure 5: Table outlining the questions asked in the '*Moving Forward*' section of the MII surveys. In each question we assess student confidence that the sentiment expressed will provide them long-term value.*

We administer the five MII at key points throughout the course: MII: I before completion of Assignment 1, MII: II following completion of Assignments 1 and 2, MII: III following completion of assignment 3, MII: IV following completion of Assignment 4, and MII: V following completion of the student device demonstrations and Assignment 5, which is a post-mortem exercise. By tying the survey dates to milestones in the course, we are able to then view our survey responses in the context of student course experiences.

1.4 Research questions addressed

In this paper, we document the strategies, including two assessment methods, which we used in the Fall 2016 iteration of AME4163. Data are collected from student responses to the two assessment instruments over the course of a design project (specifically, Assignments 1-5) and analyzed for overall statistical trends and comparisons between team and individual responses. The two assessment instruments we employ are used to measure fundamentally different aspects of student learning. Analyzing LS, we assess what POED students preferentially explore. Analyzing the MII, we assess how confident students feel in applying their knowledge. We seek to answer the following primary question: how can the two self-assessment instruments (LS and MII) be leveraged to improve AME4163 via an improved understanding of student learning in design, build, and test courses? In order to address this, we pose three questions and identify the instruments used to address them in *Figure 6*.

2. Survey of the relevant literature

In the following section, we highlight the relevant literature on which we form the pedagogical foundations of the course, our understanding of assessment in engineering design courses, and our methods for data gathering and analysis.

2.1 Pedagogical foundations of the course

As we state in Section 1.1, our course structure and the assessment instruments we have developed are anchored in the experiential learning cycle of David Kolb [2]. We further draw from the work of Dym et al. [3], who establish not only the important role that project-based learning (PBL) frameworks have in enabling students to acquire necessary engineering design competencies but also conclude that such courses may serve as an opportunity for education researchers to perform pedagogical studies to improve engineering design education in general. Our work in this paper represents one such effort. We find that others have used this approach. We draw our project challenge and vignette from Mistree et al. [1] while Balmer [4] provides us a framework for modifying engineering design courses based on assessment data. Similarly, we incorporate lessons from our previous work [5], in which we use LS data gathered from the Fall

2015 iteration of AME4163 to demonstrate that student learning in design courses is not significantly tied to project output.

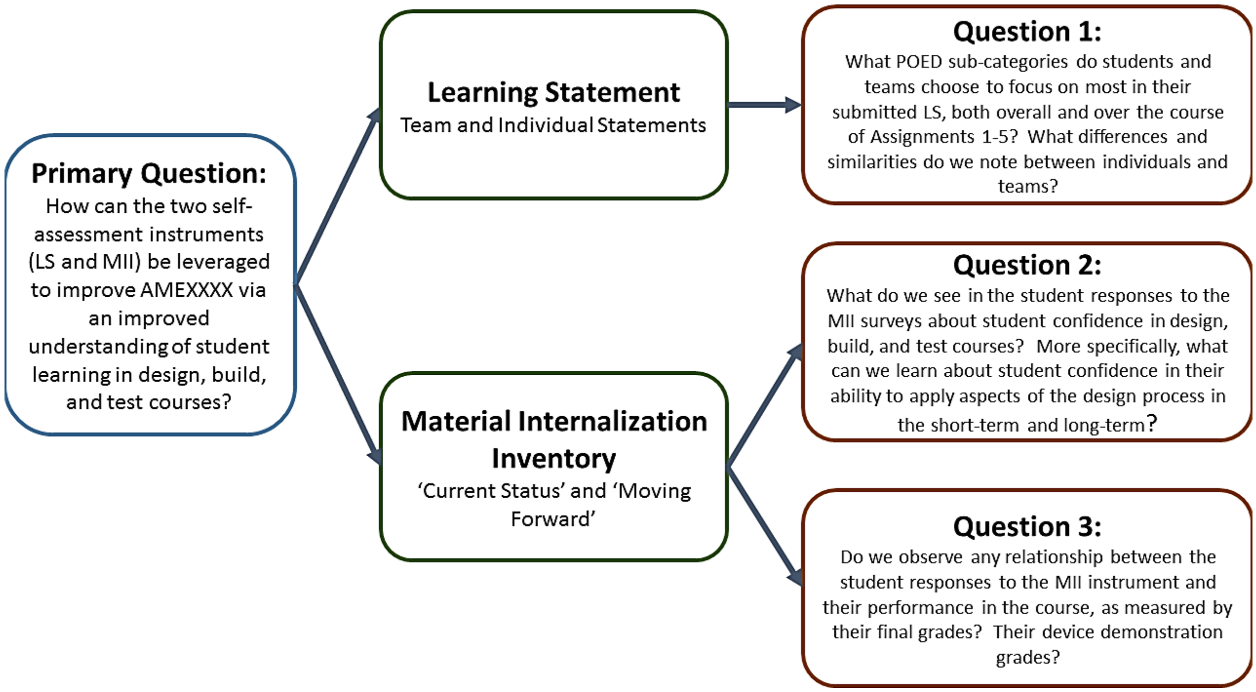


Figure 6: Relationship between paper questions and AME4163 self-assessment instruments.

Mistree [6], in an editorial for the Journal of Mechanical Design, identifies the need for improved methods of assessment in engineering design courses. He argues that educators must educate engineers to be critical of their experiences to foster continuous learning. Although no longer our primary focus, much of the course structure is based on earlier efforts to incorporate target competencies into PBL engineering design courses. In this respect, we draw from ABET [7], Eggert [8], and others [9-13], who have identified competencies foundational to modern engineering practice. Consequently, we cite the work of Todd et al. [14] who outline a model for organizing an engineering design course around a 'structured' design process in order to produce engineering graduates capable of working in modern industry.

2.2 Assessment in engineering design courses

We observe in much of the literature on assessment in engineering design courses that self-assessment is becoming more widely-accepted as a supplement to traditional forms of student evaluation. As already noted in Section 2.2, in prior work [5], we utilize a self-assessment instrument to identify discrepancies between student self-assessed learning and instructor evaluation. We note that student learning and growth is evident even in students who do fail to meet their design challenge. Smith et al. [15] associate self-assessment with improved design student outcomes and also demonstrate how such instruments can be used to better understand the process of student learning in design courses. Segers and Dochy [16] demonstrate that some self-assessment instruments in PBL-based courses succeed at prompting students to critically evaluate their own learning, though they note that this outcome requires that educators align the course goals with the purpose of self-assessment. Finally, Olds et al. [17] inventory common approaches to assessment in engineering education, noting the need for improved communication between education researchers and educators to improve engineering curricula. Additionally, they note the that surveys can provide instructors valuable information about student attitudes to their learning, provided the surveys are constructed carefully.

2.3 Data analysis

We now seek to identify in the literature techniques for analyzing survey data. We find abundant justification for the correlation matrix method we employ in this paper. Specifically, we employ Spearman's rank coefficient and correlation matrices. We cite Mendenhall and Sincich [18] for our calculation method of Spearman's coefficient, r_s. Ramachandran and Siddique [19] provide us with a framework for interpreting survey response data using bivariate correlational analysis. Excepting our use of the Spearman correlation coefficient in place of the Pearson coefficient, we also largely follow the method for using correlation matrices to establish inter-correlations between surveys using Likert style responses outlined by Sterzinger [20]. We also use, as reference, the methods employed by education researchers Kim et al. [21] and social science researcher Wahn [22].

3. Data analysis methods

In this section, we outline the data acquisition and analysis methods employed in this research. Evaluating written work so as to produce quantifiable data is a time consuming process, but integral to our effort to understand student learning. We will explore the methods employed before moving on to our analysis of the data in Section 4.

3.1 Data collection and organization

As we stated in Section 1.2 and 1.3, LS and MII data are collected from students over the course of the design project. Both team and individual LS data are submitted with each assignment. In this paper, we look only at data collected from Assignments 1-5. Similarly, the data that we collect from the MII are taken from surveys taken from one section of AME4163 over the course of Assignments 1-5. Both the LS and MII data are stored in the course website, Desire2Learn. LS data are collected from the digital assignment submissions and moved to spreadsheets, where they are evaluated using the method outlined in Section 1.2. Similarly, we simply download survey response spreadsheets from the course website and reorganize the responses to particular questions to make reading the responses easier. We then remove data collected from students who did not complete all surveys.

3.2 Analysis of ls data

In this paper, we use the LS data primarily to address Question 1, presented in *Figure 6*. Specifically, we use the LS data to identify notable patterns in the topics chosen by students to write about, both overall and from assignment to assignment. Further, we wish to understand how individuals and teams differ in their characterization of their learning. Having evaluated each LS to determine the most closely associated POED to the learning expressed, we first simply sort the data by POED. As individual and team LS data are stored in separate CSV files, we can then simply form stacked bar charts outlining the number of POED in each primary and sub-category. We thus essentially form a histogram with bins equivalent to POED 1, 2, 3, 4, and 5 (though with each bin further sub-divided by category). Color coordinating the bar chart by POED and POED sub-category further enables us to illustrate patterns. Following this approach, we then reorganize the data by assignment and produce pie charts of the POED breakdown for each assignment. Utilizing the same color scheme from the bar charts allows us to improve readability of the data.

3.3 Analysis of mii data

We analyze the MII data in this paper to address Questions 2 and 3, which ask how student confidence in their ability to apply their knowledge in the short and long-term changes during the design project. We first separate out student responses to the two separate sections of the survey: '*Current Status*' and '*Moving Forward*.' To analyze the '*Current Status*' data, we plot mean student responses to the survey questions which appear on multiple surveys. Questions 1 and 2 from these quizzes are used consistently in all five surveys and pertain to broad enough subjects (understanding of 'most recent' assignment material and instructor feedback, respectively) to enable us to assess student confidence in applying knowledge in the short-term over the course of the project. In addition, we look at the ten, unchanging questions in the '*Moving Forward*' section to identify patterns in student confidence in their abilities to apply knowledge moving into capstone and their professional careers. Using radar plots, we can both visualize how individual mean question responses change from quiz to quiz, and also identify general trends in each survey. Finally, we employ correlation matrices to test whether responses to the '*Moving Forward*' section on each survey are correlated with any other questions, as measured using Spearman's correlation coefficient, r_s. This allows us to identify patterns in student confidence throughout the design project. To address Question 3, we employ the same method to identify correlations between responses to the ten questions on all five MII with the students' final course grades and device performance grades.

4. Results and discussion

In this section, we outline the work that has been completed and analyze the results of the LS and MII data over the course of the design project. Principally, we are concerned with data taken from students during Assignments 1-5, which begins with team formation and understanding the design problem in Assignment 1 and ends with the post-mortem assessment of the design artifact in Assignment 5.

In the first part of our analysis, we seek to understand how student learning embodied in the LS is explored over the course of the design project. As we would like to get an overall picture of the areas of the POED that students are focused on their writings, we provide *Figure 7*. In *Figure 7(a)*, we observe the total breakdown of all individual student LS submitted in Assignments 1-5, broken down in terms of the POED explored in each statement. We further sub-divide each POED bar into their sub-categories, coordinated by color (e.g. POED 1a is light green and 1d is dark green). Within each section of each bar, we include a POED sub-category label and the number of LS in that category. The boxed number at the far right of each bar is the sum of all LS in each POED's sub-categories. We employ the same approach for the team LS and illustrate them in *Figure 7(b)*.

For the individual LS in *Figure 7(a)*, we observe that POED 1 and POED 4 are largely the focus of individual LS. POED 1, which deals with team formation, planning the design process, and understanding the problem, are a continuing focus for students throughout the semester. Many students report throughout the design process that only at later stages do they see how valuable ensuring teams are responsibly formed and organized from the beginning can be to later success. Similarly, throughout the project many individuals identify how key forming a proper “plan of action” is to managing the uncertainty of time and effort. Student writing LS tied to POED 4, which deals with prototyping and post-mortem analysis, largely focus on POED 4a, which refers to the role of the Bill of Materials and understanding prototype components. Students writing these statements often explore how components which were purchased at the last minute or without full understanding of their limitations contribute to struggles during the device testing and demonstration. Interestingly, though POED 2 is only the third most explored POED overall, POED 2a is the second largest sub-category written about by individuals. Students writing LS tied to POED 2a, which deals with concept generation, largely write about how the systematization of ideation (through tools like the Function Structure and Morphological Chart in Assignment 2) is useful in generating a variety of useful concepts, as opposed to a more intuitive, unstructured approach.

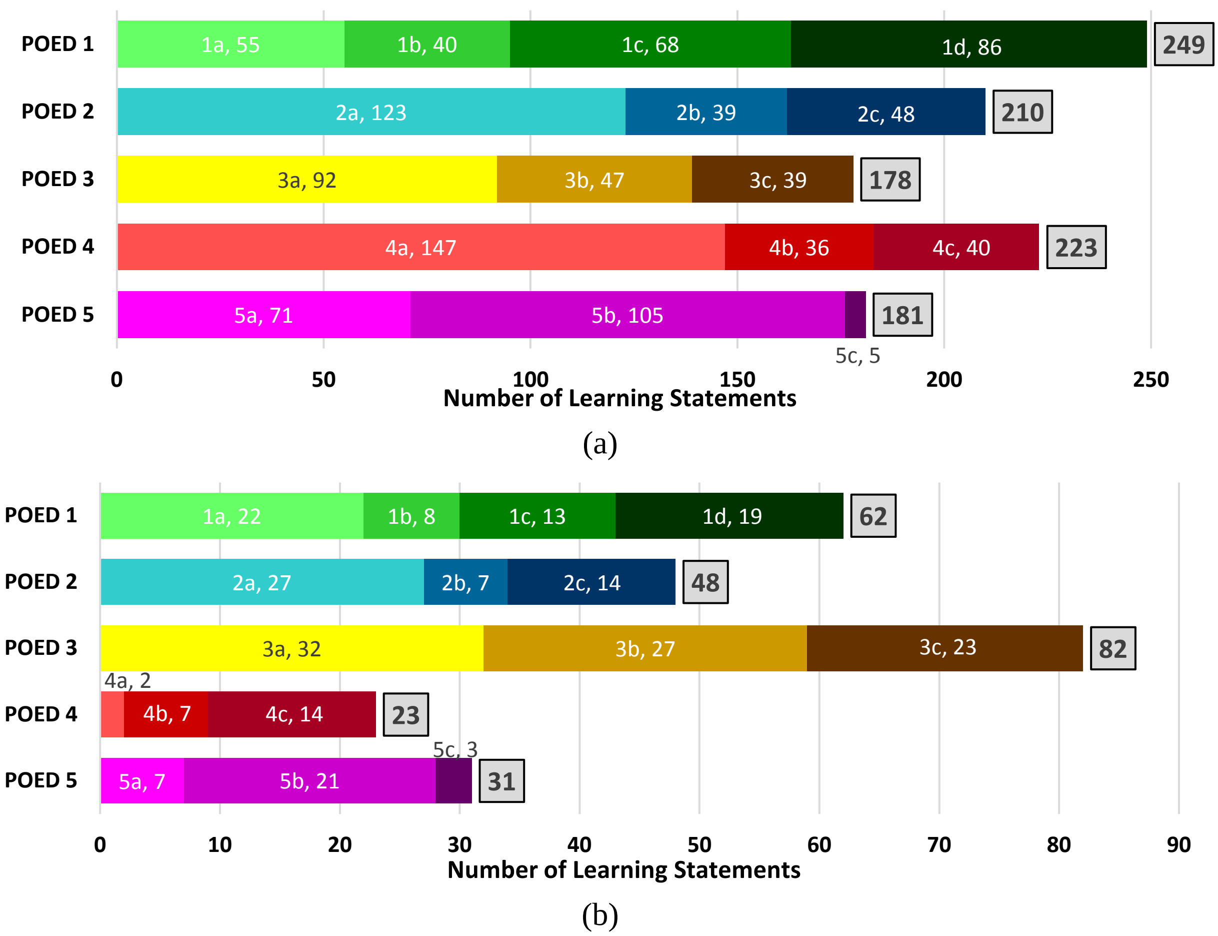


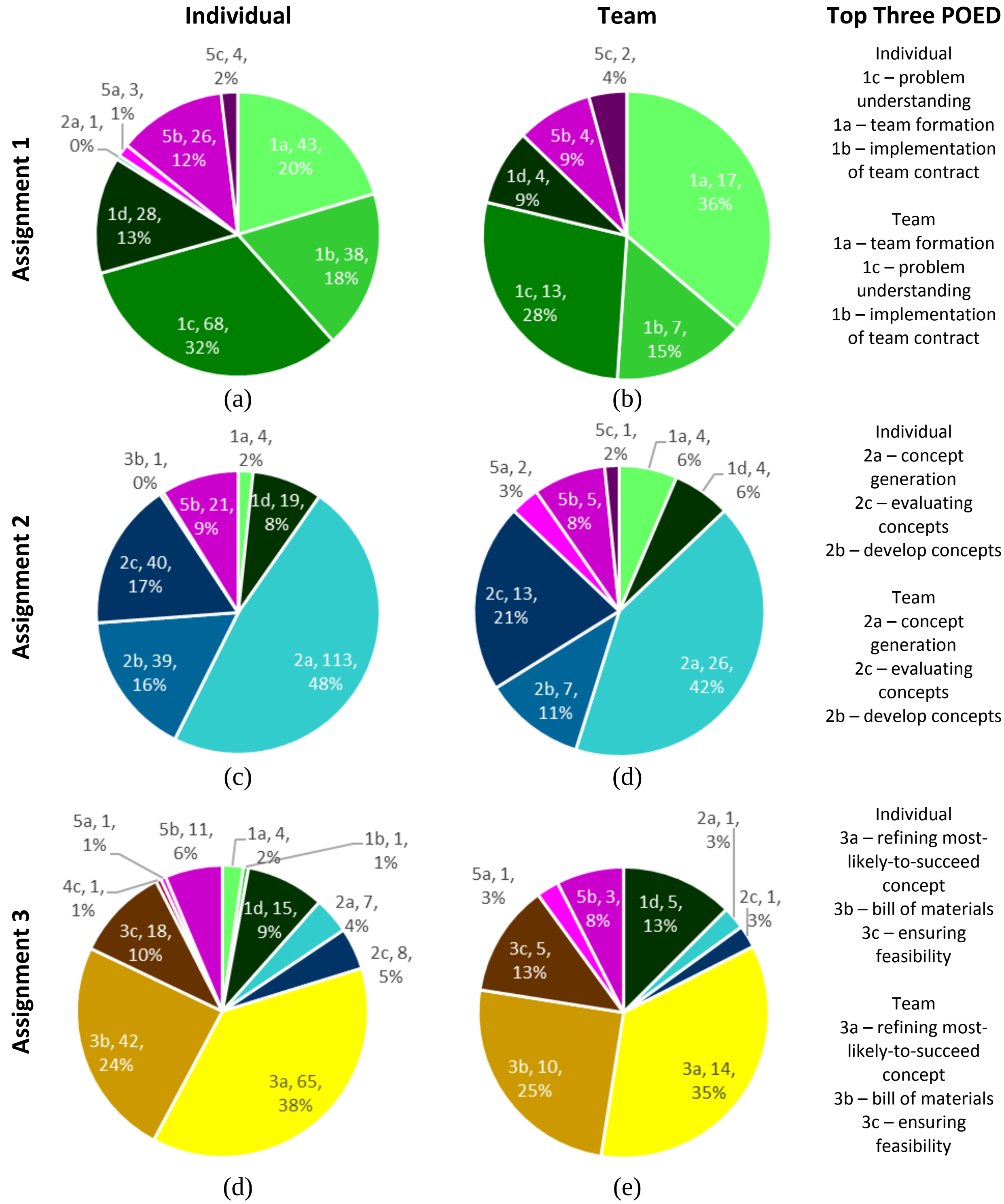
Figure 7: (a)Overall breakdown of individual LS for Assignments 1-5 by POED category; (b)Overall breakdown of team LS for assignments 1-5 by POED category.

For the team LS we present in *Figure 7(b)*, there appears to be similar patterns of subject matter explored but with several notable differences. First, as in *Figure 7(a)*, we observe that teams are largely concerned with both team formation (POED 1a) and proposing the plan of action (POED 1d). However, relatively speaking, we observe that, unsurprisingly, teams write a higher percentage of their LS about POED 1a than 1d, indicating that teams continually revisit the process by which they had organized and collaborated in their team formation. Another similarity we observe between the two figures is that POED 2a is well represented among the team LS, once again being the second largest category written about (though tied for that position in this case). Student teams throughout the design process revisit the role of the concept generation phase on their current progress or difficulties. Perhaps the largest difference between teams and individuals, and rather surprisingly so, is that we observe in *Figure 7(b)* that statements exploring POED 3 are by far the largest block of LS written by teams. We suspect that POED 3, which deals with concept refinement and elimination, forming a preliminary Bill of Materials, and ensuring concept feasibility, is so well represented among team LS because the process of narrowing down concepts to two (primary and a backup concept) and refining the primary concept until it meets all identified requirements is anchored in several, labor-intensive tools. That is, we require teams at this stage to perform a series of structured analyses that they likely perform as a team (rather than delegating to individuals) due to the fact that said analyses cannot be easily broken up into discrete tasks and necessitate the input of all team members. Therefore, we conclude that students drafting the team LS find the design work embodied by POED 3 to be an area well understood by all team members. This may also account for the representation of POED 1 and 2 (work more easily done as a team) and the relatively weak representation of POED 4 and 5 (work can be more easily divided among individuals).

Having broken down the POED explored in the LS for teams and individuals in Assignments 1 through 5, we now further breakdown this data by assignment. *In Figure 8*, we demonstrate the POED breakdown of both team and individual LS for each assignment in order to better understand how the chosen subject matter of student and team LS changes over time. One of the more interesting patterns that we note from the data we present in *Figure 8* is how consistent the POED breakdown is between teams and individuals for Assignments 1-3. We suspect that this may be due to the fact that, until Assignment 4, all of the design work is included in the assignments. Around the time of Assignment 4, students begin to construct their devices. We do not have an assignment which addresses this phase of the design process; it is the only unstructured part of the design process. As a result, individuals, around the time of Assignment 4, may be working on tasks separate from Assignment 4 itself and therefore may find these experiences more relevant to write about. The fact that we observe similar LS breakdowns between teams and individuals in Assignment 5 lends credibility to that hypothesis. We do note slight differences, however, in Assignments 1-3; for example, in *Figure 8(a)* and *Figure 8(b)* (Assignment 1), we observe that teams, unsurprisingly, devote more relative LS than do individuals toward POED 1a, dealing with team formation. However, despite slight variation in the breakdown of POED sub-categories in Assignments 1-3, the differences between team and individual LS are relatively slight. As anticipated, both teams and individuals focus on POED 1 in Assignment 1, POED 2 in Assignment 2, and POED 3 in Assignment 3, mapping extremely well to the target assignment POED table presented here as *Figure 1*.

Despite how well the POED breakdown in *Figure 8(a-e)* maps to that presented in *Figure 1*, we observe that in *Figure 8(f-i)*, these trends no longer hold true. In particular, we note that in Assignment 4, individuals largely write about POED 4 (particularly POED 4a), as we intend from our assignment targets, whereas teams focus almost exclusively on the areas of concept evaluation and refinement embodied by POED 3. We have suggested earlier in this section that teams may be focusing on ‘Embodiment Design’ (POED 3) as the work associated with this

POED is more team-driven (or at least, less able to be distributed as individual tasks) than that of other POED. Another confounding factor may be that at the time that Assignment 4 is being drafted, many teams are beginning to purchase real components for the device. As we do not require LS to be written about any particular experience, it may be the case that individuals are beginning to focus more on prototyping and testing (POED 4) than the team as a whole.



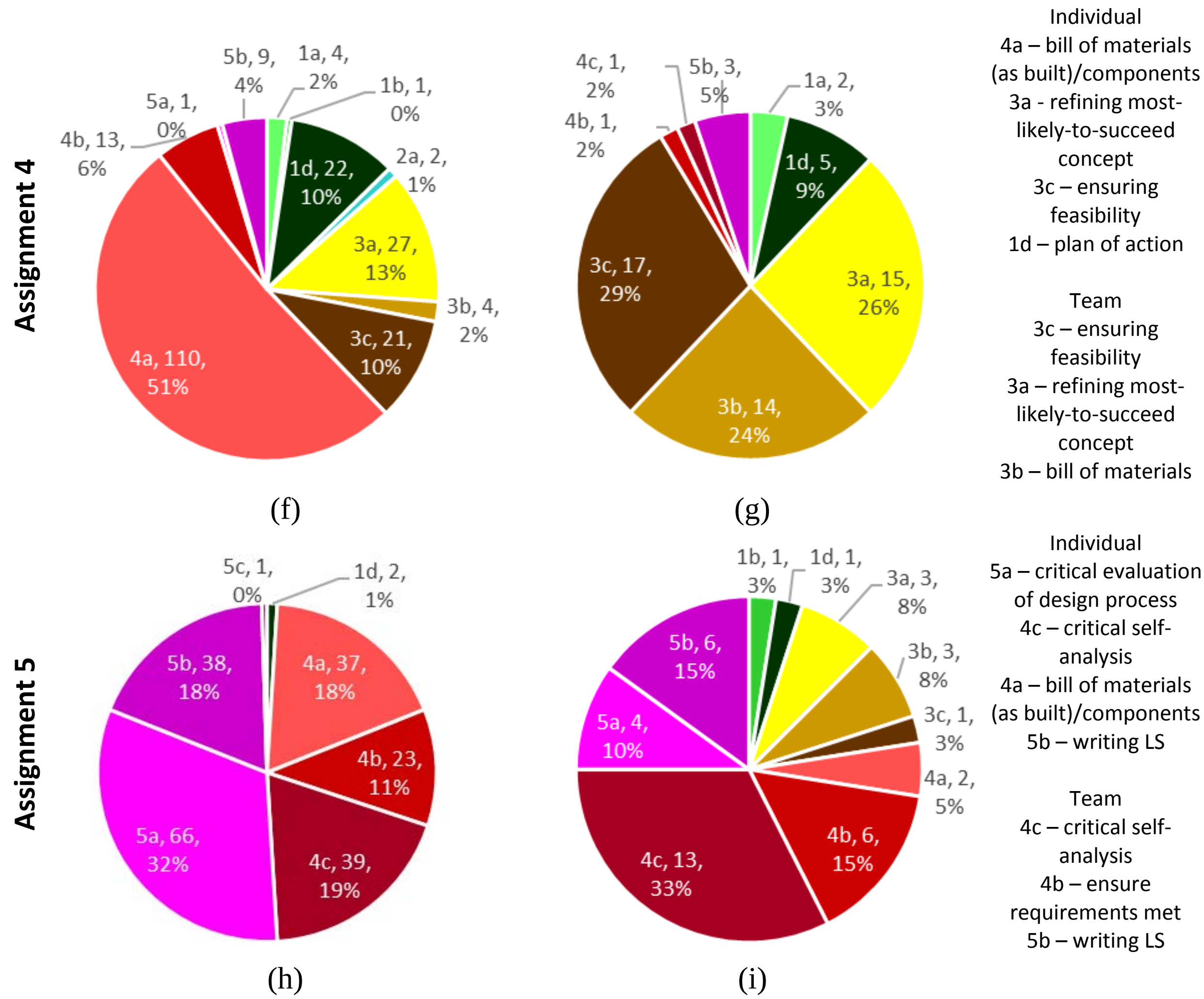
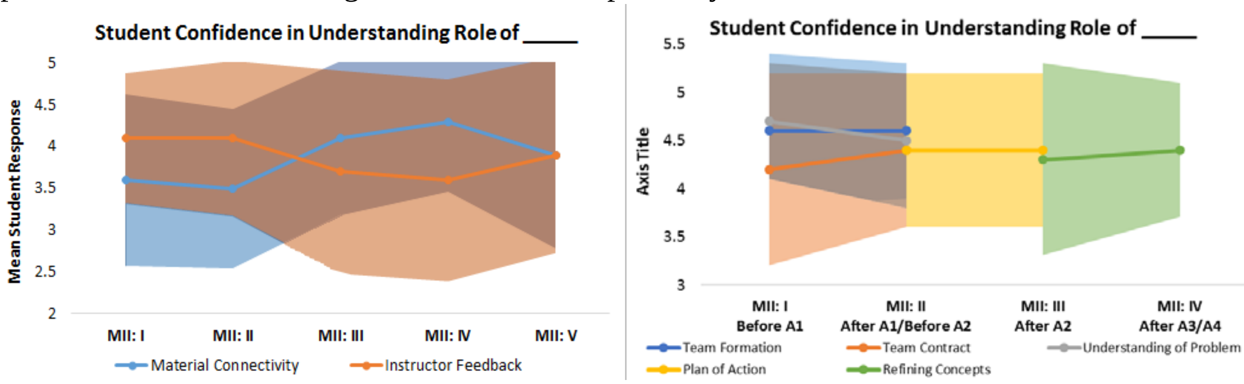


Figure 8: Pie charts depicting LS POED categorization for teams and individuals for each of Assignments 1 through 5. The left column reflects statements written by individuals for each assignment and the right reflects statements from teams, with each row a different assignment. Colors for each POED sub-category are consistent with those in Figure 7.

We now turn our attention to the MII instrument. As we state in Section 1.3, the MII is principally divided into two sections. We seek to separately gauge how confident students are in applying their learning in the short-term ('*Current Status*') and the long-term ('*Moving Forward*'). Questions in '*Current Status*' (see *Figure 4*) differ from survey to survey (with some overlap), whereas our questions in '*Moving Forward*' are the same between surveys. We present the mean response to questions in '*Current Status*' which appear in multiple surveys in *Figure 9.* The first two questions of '*Current Status*' appear in all five surveys. The first question asks students to rate their confidence in understanding what is required in the most recent assignment and how that work connects to the rest of the course. The second question asks students to rate their confidence in how well they understand why recent feedback on their work was provided. In addition to these two questions, five other questions appear on two surveys. In each we ask students to express how confidently they feel that they understand one of the items associated with POED 1a, 1b, 1c, 1d, or 3a, which deal with team formation, implementation of a team contract, forming an understanding of the problem, developing a plan of action, and refining generated concepts, respectively. The questions pertaining to POED 1a, 1b, 1c, and 1d appear on MII: I and MII: II, which take place before and after Assignment 1, respectively. The question pertaining to POED 1d appears on MII: II and MII: III, which occur before and after Assignment 2, respectively. The question pertaining to POED 3a appears on MII: III and MII: IV, taking place before and after Assignments 3 and 4, respectively.



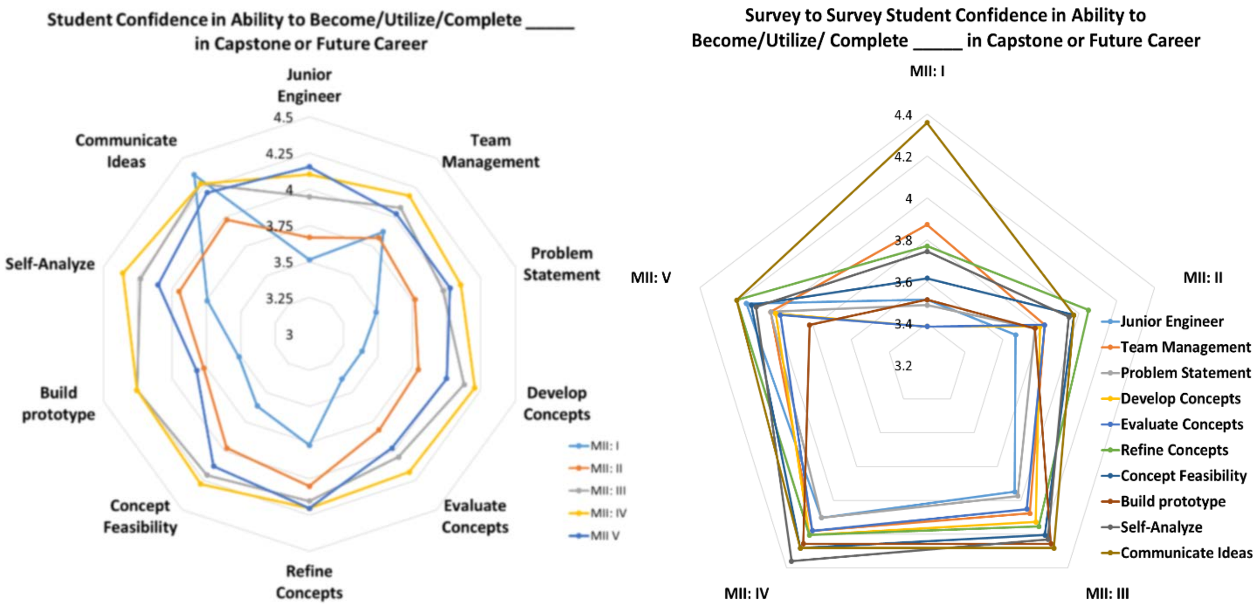
(a) (b)

Figure 9: (a)Change in student response to 'Current Status' *Questions 1 and 2, which remained constant for all surveys; (b)Change in response for questions dealing with POED 1a, 1b, 1c, and 1d between surveys in which the question appears in each. The shaded bands in each figure represent the variation about the mean respons.*

We observe in *Figure 9(a)* that the trends in mean student response to Question 1 and Question 2 are almost perfect mirrors to one another, converging at almost the same level of confidence. Between MII: I and MII: II, students do not significantly change in how confident they report they feel about what is being asked of them in the most recent assignment. However, between MII: II, III, and IV, students are substantially more confident in what is being asked of them and how the material connects to previous work, before dropping in confidence again in MII: V. This suggests that the students are quite comfortable with the assignments which call heavily on their technical skills; in Assignment 3 they narrow generated concepts down to two through technical analysis and in Assignment 4 they develop their chosen concept through technical analysis such as Computer-Aided Design. Assignment 5 however, turned in shortly before MII: V, is a post-mortem exercise, encouraging students to critically reflect on the design process and the team's successes and failures. We observe that this is relatively more challenging to the student, as their confidence in understanding the purpose of Assignment 5 declines. In contrast, student confidence in their understanding of instructor feedback drops from MII: II to III and from MII: III to IV, before rising again after MII: V. Once again, the effect we highlight seems to be prompted by the assignments in which students favorably leverage their technical skills. This suggests that students may value feedback less in technical domains, areas which, as seniors, they likely feel more confident in. Of note also the relatively high mean confidence expressed in general; in fact, in all five surveys, students expressed confidence of three or less only slightly more than twenty percent of the time. Overall, we observe that senior-level design students are, on balance, firmly confident in their short term ability to apply knowledge acquired.

In *Figure 9(b)*, we note that most students do not significantly change their responses to questions which appear on successive surveys. Questions in which we assess student confidence in the importance of team formation and forming a plan of action did not change at all across two assignments dealing heavily with those topics. Questions in which we assess student confidence in the importance of implementing the team contract and evaluating concepts only rose by .2 and .1 points, respectively, across the assignments dealing with those topics while the question in which we assess student confidence in the importance of understanding the problem actually *fell* by .2. Given these small shifts, we identify that student confidence in the importance of various POED to the design process are not significantly affected by single assignments. However, recalling the LS POED breakdown in *Figure 8*, we do note that the student focus is shifting over time. Further, from *Figure 9(a)*, we know that on average students increasingly see the connections between each step of the design process as that process moves forward. From this seeming contradiction, we postulate that as students move forward in the design process, though they may identify the value in distinct steps of the design process, they might be coming to see each step as *relatively* less important in the grand scheme of the project.

We now shift our focus to the section of the survey in which we assess student confidence in applying their knowledge to future endeavors (capstone, industry). In this section of the survey, titled '*Moving Forward*,' we pose the ten questions outlined in *Figure 5*. We plot the data from this portion of the survey in *Figure 10(a)* and *Figure 10b)*. We provide both versions of the radar plot of the mean student responses to Questions 1-10 of the '*Moving Forward*' section on all five surveys to illustrate different points. Immediately, from both plots, we observe that mean student confidence never falls below 3 nor greater than 4.5 across all five surveys, with response variance ranging from .85 to 1.0. We note that the average student taking our course appears confident in their ability to apply the identified skill or knowledge to capstone or their career.



(a) (b)

Figure 10: (a)Radar plot of the mean student responses from question to question on each survey; (b)Radar plot of the mean student response for each question from survey to survey.

From *Figure 10(a)*, we observe first that, overall, between MII: I and MII: V, mean student confidence in each question rose for all but Q10. In Q10, we ask students to assess confidence in their ability to communicate their ideas and learning. At first, we observe that students start off fairly confident in this area (MII: I), their confidence then drops (MII: II), and then rises and converges at around 4.25 (MII: III-V). Given that students complete MII: I before submitting their first assignment, we postulate that their initial experience with the assignments reveals to the students shortfalls in their communication skills that they had not anticipated but that the exercise of writing and submitting assignments grows their confidence over time. In *Figure 10(b)*, we observe another interesting phenomenon in the responses to the surveys over times. Excepting Q10, we observe that not only do students become more confident in their ability to apply the skills embodied in Q1-9 over time, but that their response variation *between* questions converges over time until MII: IV, before becoming slightly more varied in MII: V. We attribute this phenomenon to the fact that MII: V takes place after the completion of the post-mortem exercise in Assignment 5. The post-mortem exercise is a reflective one; the students are now looking back at their project through the lens of the success or failure of their device. Going into the prototyping phase (MII: IV), most teams have gained confidence in most design areas, but many are disappointed by the performance of their device during the demonstration. We therefore see in the slight downward trend in confidence from MII: IV to MII: V evidence that students are critically examining their abilities after Assignment 5.

Given the overall trends we observe in *Figures 10(a)* and *10(b)*, we now seek to identify any bivariate relationships between the responses to the individual survey responses. As we explore in Section 3.3, we have opted to analyze the survey responses using correlation matrices, in which we check for monotonic correlations between all survey responses for all questions in the '*Moving Forward*' section of the five surveys. We illustrate these matrices in *Figure 11*. We observe in *Figure 11(a)-(e)* that interrelationships between the survey responses appear to strengthen over time. Given our analysis of the mean responses in *Figure 10*, we observe that the strengthening of the correlations between all survey questions over time is largely explained by the convergence of question responses. We note relatively few strong correlations, which we define as an r_s value greater than .55, between pairs of questions over the course of all surveys. In fact, we only observe six in total, four of which involve the question dealing with student confidence in their ability to identify concepts likely to succeed ('ConceptFeasibility').

We plot the question pairs which exhibit a Spearman rank correlation coefficient greater than .55 for all five surveys in *Figure 11(f)*. We observe that six pairs of questions meet this criterion. However, while the change in r_s for question pairs over the course of the five MII is generally upward, we see that at least one correlation ('ConceptFeasibility-EvaluateConcepts') actually fell between MII: I and V, though the change was very slight. The three sets of question pairs which concluded with the strongest correlations all involved the students' confidence in their ability to develop system concepts consistent with the identified requirements. The pairs, which ended with correlations all above .75 for p-value less than .01, were 'DevelopConcepts-StateProblem,' 'ConceptFeasibility-DevelopConcepts,' and 'EvaluateConcepts-DevelopConcepts.' We observe also that, of six question pairs identified as both statistically significant and with strong correlations, four of them involved 'ConceptFeasibility.' From these results, we posit that a strong relationship exists between both student confidence in their ability to identify likely to succeed concepts and their ability to develop system concepts and student confidence in many other areas. The interconnectedness of the most correlated question pairs suggests that our bivariate approach may not enable us to fully assess the relationship between student confidence in multiple areas. We may need to investigate identifying a multivariate model to characterize these patterns in future work.

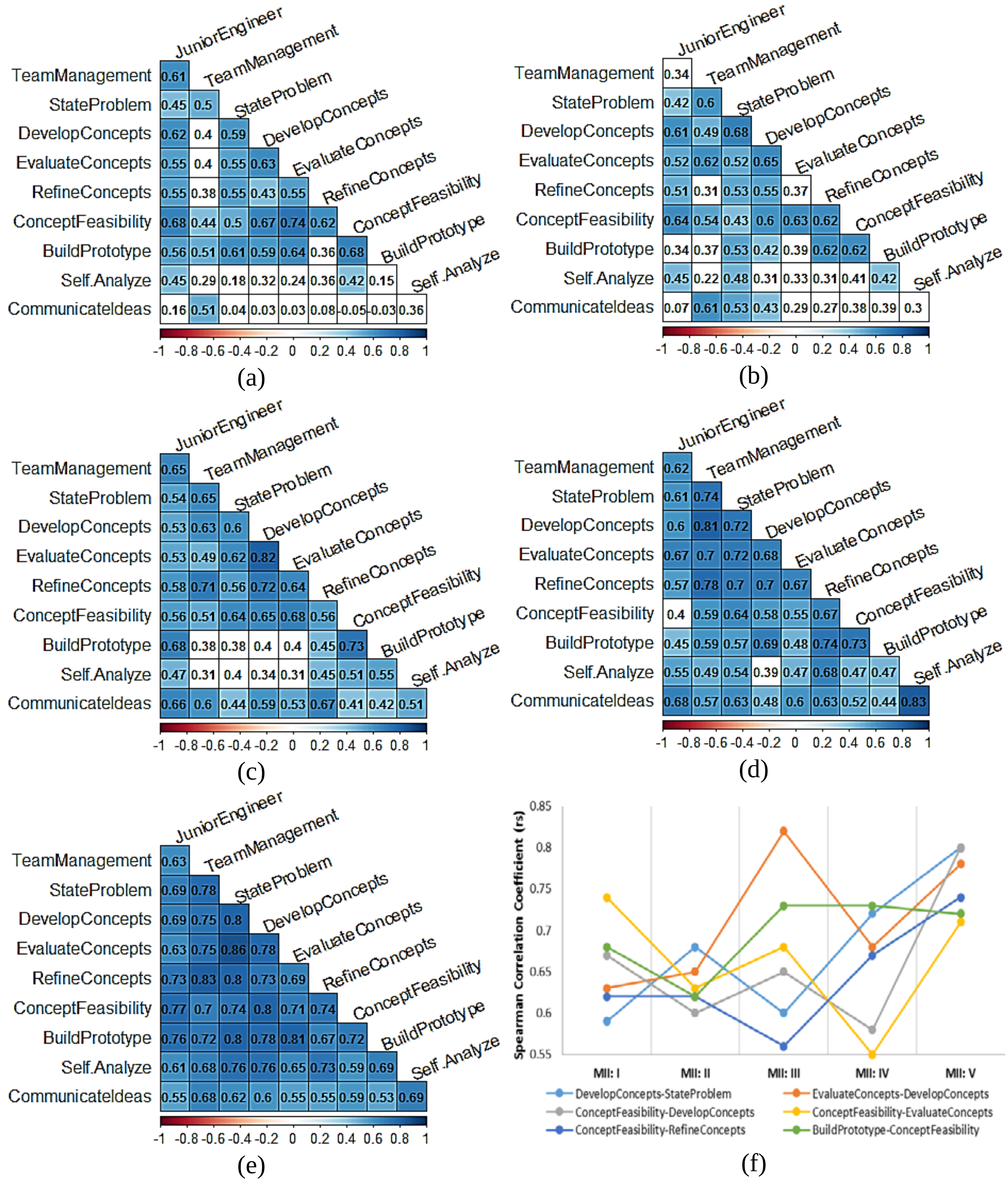


Figure 11: Correlation matrices between 'Moving Forward' *survey Questions 1-10 for MII: I-V; each survey corresponds to letters (a)-(e). Correlation coefficients are shaded if deemed statistically significant (p<.01) and darker shades correspond to stronger correlations. (f)Plot of changes to r_s coefficient value for Question pairs with correlation coefficient value greater than or equal to .55 in all five MII.*

In the final portion of our analysis, we seek to identify possible patterns between student grades and the confidence they express in the surveys. We focus in particular on two relevant grades commonly used to assess design students: device demonstration grade and final course grade. As in the prior analysis, we utilize correlation matrices to compare each student's response to the ten questions in the '*Moving Forward*' section for all five surveys with their competition grade and final grade. We note no strong correlation (r_s value greater than .55) between the student grades in either the device demonstration or the final grade for the course. In fact, we find no correlation coefficient greater than .36 and none met our statistical significance criterion (p-value less than .01). This finding is consistent with our previous work [4], in which we note that comparisons between other self-assessment instruments (such as the LS) appear to show no link between student self-assessed learning and course performance as measured by instructor evaluation. We include the results of this analysis as supplementary information in Appendix, Section A4.

5. Closing remarks

In Section 1.4, we pose a set of questions that we answer using the results presented in this paper. Principally, we are concerned with the primary question: *how can the two self-assessment instruments (LS and MII) be leveraged to improve AME4163 via an improved understanding of student learning in design, build, and test courses?* In order to address this question, we pose three associated questions and, in Section 5.1, we reflect critically on our responses.

5.1 Critical review of the work

In Question 1, we ask, *what POED sub-categories do students and teams choose to focus on most in their submitted LS, both overall and over the course of Assignments 1-5? What differences and similarities do we note between individuals and teams?* To answer this, we look at the student and team LS in two ways. First, we provide an overall breakdown of all submitted individual LS in *Figure 7*. What we observe in these charts is that both students and individuals largely focus on subjects tied to POED 1, which pertains to planning the design process. Specifically, individuals primarily focus on developing a plan of action while teams, unsurprisingly, focus on team formation. In addition, both teams and individuals focused a large portion of their respective LS on POED 2a, which deals with ideation and concept generation, and 5b, which deals with internalization of the POED through writing LS. Where we note divergence, however, is in the widely differing exploration of POED 4 and, to a lesser degree, POED 3. Specifically, we observe that teams focus a large portion of their statements on POED 3, dealing with evaluating, modifying, and refining concepts. We note one possible reason why by looking at *Figure 8*, which shows the LS POED breakdown for teams and individuals in Assignments 1-5. We observe that, until Assignment 4, both teams and individuals largely focus on similar subject areas. During Assignment 4 however, individuals begin focusing on POED 4 (particularly 4a, dealing with the Bill of Materials and component analysis) while the teams remain focused on POED 3. We suggest that the discrepancy results from the fact that Assignment 4, which is completed as a team, is tied to POED 3 while many individuals have begun to focus on individualized tasks related to prototyping, which is tied to POED 4.

In Question 2, we ask, *what do we see in the student responses to the MII surveys about student confidence in design, build, and test courses? Specifically, what can we learn about student confidence in their ability to apply aspects of the design process in the short-term and long-term?* To address this, we have analyzed the student responses from two sections of the survey, '*Current Status*' and '*Moving Forward,*' which are focused on these two domains. In *Figure 9*, we illustrate student responses to questions in '*Current Status*' which appear on more than one survey. Notably, we find that, over the course of the five MII, student confidence in their understanding of recent assignment material and their understanding of instructor feedback appears to change starkly between assignments. More specifically, between Assignments 1 and 2, which bookend MII: I and II, student confidence in their ability to understand the recent assignments and instructor feedback does not significantly change. However, between MII: III and IV, we observe that students are, on average, more confident in their understanding of assignment material while growing less confident in their understanding of instructor feedback on previous assignments. We observe that these trends then sharply pivot in MII: V, which takes place after the post-mortem exercise. We suspect that what we are seeing here is that, as the students begin to understand the design process more holistically, their confidence in their design abilities increases (and their patience for negative feedback correspondingly going down) until they demonstrate their devices and many are disheartened by their underperformance. We thus frame the critical self-reflection involved in Assignment 5 as the reason for the reversal of trends we observe in both question responses. Additionally, we do not observe significant change between surveys in other questions in '*Current Status*' which appear on multiple MII. We suspect this may be a result of students, on average, beginning to see particular POED sub-categories as important, but not relatively more so, over time.

To complete our answer to Question 2, we further address the MII '*Moving Forward*' data presented in *Figure 10* and *Figure 11*. From *Figure 10(a)*, we observe that the only question in this survey in which student responses did not increase between MII: I and V is the students' confidence in their ability to communicate their ideas to others in future projects. We suspect that most senior level students feel strongly about their ability to communicate, perhaps more so than any other design related skill. However, what they come to realize over the course of the project is that communicating engineering design information rigorously is a different skill set than that required, for example, in a technical report or lab write-up. We observe that their confidence in this skill does rise between MII: II and V, but not to their 'pre-design-experience' levels. Overall, we also see that students start off and stay relatively confident in all assessed skills; we observe relative change, but within a somewhat narrow band. Though we must point out the relatively large variance we see in the data. Interestingly, though they start highly confident, on average, the single largest change is a decrease in confidence for all questions which occurs from MII: I to II. As Assignment 1 is submitted and reviewed before completion of MII: II, we suspect that student confidence is severely challenged by their first completed assignment. Also of note is that we observe a drop in confidence for Questions 1-9 (see *Figure 5*) between MII: IV and V, suggesting that the critical self-reflection in the fifth survey appears to enable students to more humbly self-assess their ability to take their skills forward into the future.

We now utilize correlation matrices to identify potential relationships between student responses to the questions in the '*Moving Forward*' section in each survey. We find that overall, inter-question correlations strengthen over time as responses converge to a narrow band of responses. However, we note relatively few strong correlations (r_s greater than or equal to .55) across MII: I-V. For all question-pair correlations, only five strong correlations with calculated statistical significance become more strongly correlated throughout the semester. Of those pairs, three are tied to student confidence in their ability to identify feasible system concepts and three are tied to student confidence in their ability to develop concepts consistent with the requirements list. We hypothesize that student confidence in their ability to develop concepts and identify feasibly concepts are metrics which are closely tied to student opinions of their own design-related competencies. However, we recognize that the limitations of the bivariate approach employed here may not permit us to see the entire picture.

In Question 3, we ask, *do we observe any relationship between the student responses to the MII instrument and their performance in the course, as measured by their final grades? Their device demonstration grades?* We have attempted to find correlations between student responses to the '*Moving Forward*' section of the surveys with two important grades that each student received during the semester: their final course grade and their device performance grade. We illustrate these results in the Appendix, Section A.4. Using the same correlation matrix approach as used in the prior analysis, we compared our set of student responses to those same students' two grades for each of the ten '*Moving Forward*' questions. We find our results in agreement with our earlier findings [4], in which we find that student self-assessment does not correlate with either design project outputs or course performance. Our approach here differs from our prior approach in that we compare the confidence assessed in a series of surveys with the student grades whereas before we compared grades to the LS.

5.2 Contributions and future work

One of the areas in which we have made an important stride is in understanding the process of learning as it relates to both teams and individuals. We have, in this paper, marked several notable differences between how individuals frame their learning compared to teams. We find it interesting that, individually, students tend to focus more on the effort to build and test their physical prototypes, whereas the teams remain more steadfastly analytical toward the concept refinement, modification, and reality check steps. We are also interested to note how individuals and teams focus on similar subjects once again following the post-mortem exercise.

In addition, we highlight several important phenomena regarding student confidence in their ability to apply their learning in the short and long term. Specifically, we note that, in the short term, the post-mortem exercise appears to serve as important moment for students, forcing them to pause and reflect in a more critical manner. Sudden reversals in the patterns of two questions assessing confidence in understanding of assignment material and understanding instructor feedback occurred in the survey immediately following the fifth survey, which followed the post-mortem exercise. Of note also is that we find that the design, build, and test experience appears to challenge student preconceptions of their abilities in several areas. Most notable is the marked shift between student confidence in their ability to communicate their ideas to others experienced from MII: I to II and from II to V. In addition, we observe that, in the '*Moving Forward*' section of the surveys we see the effects of the post-mortem assignment on student self-assessment. In *Figure 9*, we observe that student confidence, which had grown steadily for almost all questions between MII: I and MII: IV, noticeably fell from MII: IV to V.

Primarily, we are interested in following up on the role that the post-mortem exercise serves in student self-assessment. It appears that this exercise represents a watershed moment among a variety of metrics using multiple assessment instruments. This finding is consistent with our course pedagogy, anchored as it is in the work of David Kolb [2]. In future, we will look closely at another purely reflective exercise following the conclusion of the design process, the Semester Learning Essay, which we employ in the course but do not address in this paper. We intend with this work to provide other instructors a set of assessment instruments which they might be able to leverage in design, build, and test courses to complement more traditional measures of assessment. The work we present here will be used to modify our course going forward and we hope others might follow up by exploring similar approaches to engineering design education. We have found that, though initially resistant, students over time come to appreciate our emphasis on critical self-reflection and find the approach rewarding. Further, we contend that our analysis justifies the utility of such exercises in engineering design education.

In addition, much work remains to be done with our existing data. First, in this paper we deal with only with data fromone section of our course from Fall 2016. Future efforts must involve comparing the analysis results from this data set with those of the second section. Further, we have noted that our bivariate approach used to identify correlations between survey responses may be too limiting. We must now follow up by using multivariate models to identify more complex relationships. Finally, we state in Section 1 that our course aim is to enable senior-level engineering students to transition to Junior Engineers, a label which we define as engineers capable of identifying new principles of engineering design in response to emerging challenges. To assess the degree to which we are able to do this in AME4163, we must follow up with students who follow our course with their capstone design experience. We are currently in the process of collecting that data. It is our hope that this information will enable us to develop a framework for education researchers to explore the utility of experimental pedagogy in producing successful Junior Engineers capable of meeting modern challenges.

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Appendix A

We include this supplementary appendix to provide additional context for our study and the course that our work is anchored in. We deem this information not critical to answering the research questions but believe it to be relevant to those wishing to implement our approach.

A.1 AME4163 course characteristics

For reference, we provide our relevant course features in the following figure.

Feature	Measure
Course Title	*AME4163: Principles of Engineering Design*
Credit Hours	3
Presence in Curriculum	Offered every Fall semester (August-December); must be completed before enrollment in Capstone Design Practicum
Course Prerequisites	Interactive Engineering Design Graphics, Dynamics, and Design of Mechanical Components
Available Sections	Two sections: 001 and 002 (Maximum section enrollment: 90)
Fall 2016 Enrollment	Section 001: 76; Section 002: 82
Majors of Students	Mechanical Engineering: >95% Petroleum or Aerospace Engineering: <5%
Instructors	Each section has one primary instructor, who also acts as a secondary instructor for the other section. The primary instructor grades team assignments for their section while the secondary instructor teaches some lectures to either section. One Graduate Teaching Assistant manages the project for both sections.
Project Management	The instructors and GTA also serve as project advisors for each team. This includes assessing team progress during a Mid-Term Design Review and a Prototype Review (one month before demonstration)
Course Management	Assignments are submitted to the course website, which also hosts the MII for individual students. The course website also serves as a repository for course documents, rubrics, handouts, and announcements.

A.2 AME4163 course grading rubric

In AME4163, we attempt to deemphasize the importance of the design project output and focus on enabling students to internalize the POED and becoming more reflective learners. In service to that goal, we provide the course grading rubric for reference. Using this rubric, we have placed the project output at only thirteen percent, which is only slightly higher than the average assignment point value. This rubric is provided to all students in the course booklet at the beginning of the semester and we discuss with the students our goals for the course.

Grade Item	Grade (%)
A1: Planning a Design Process	10%
A2: Preliminary Design	10%
A3: Embodiment Design, Pt. I	10%
A4: Embodiment Design, Pt. II	10%
Project Demonstration and Reviews	
Mid-term Design Review	1%
Prototype Update	1%
Project Demonstration	13%
A5: Post-Mortem Analysis	10%
A6: Semester Learning Essay	10%
A7: Engineering Ethics	10%
A8: Capstone Plan of Action (New Teams)	7%
Participation and Attendance	3%
Short Assignments	
Material Internalization Inventory (Or substitute)	3.5%
FEA Short Exercise	1.5%
Total	100%

A.3 Learning statement 'insight' assessment rubric

The LS rating scale is a four-point scale for categorizing insight, which, for our purposes, is defined as how well the student is able to express internalization of the material and connect their learning to a wider context. Our rubric for the scale is as follows:

1. Zero points: Statements earn a rating of zero if the LS is not written to conform to the structure illustrated in *Figure 3.*
    a. Example: "*Projects tend to be extremely overwhelming when viewed in the holistic sense, but when a plan of attack is proposed that breaks down the project into smaller tasks, the project becomes more conceivable and therefore more manageable.*" – AME4163 student, Fall 2016
    b. Regardless of a lesson expressed, the student fails to put the learning in the context of an experience and therefore is not a learning statement.
2. One point: Statements receive a rating of one point if the structure is present but the insight is trivial or obvious.
    a. Example: "*Through Assignment 1, I have realized that communication protocols are crucial for a team to work together to complete a goal.*" – AME4163 student, Fall 2016
    b. The student both states something obviously true and neglects to explore any deeper relevance that the learning might have.
3. Two points: Statements receive a rating of two points if in the LS the student demonstrates a connection between their learning and something not explicit to the experience such as a novel circumstance in which the lesson might be applied.

a. Example: *"Through considering the customer requirements in greater depth individually, this has taught us more about the entire breadth of the problem and what needs to be taken into account in producing a successful end product, this has a value of allowing us to tailor the device to the end customer more effectively."* – AME4163 student, Fall 2016
b. The student expresses learning in terms of an experience and then connects that to a future scenario involving a later stage of the design process.

4. Three points: Statements merit a rating of three points if the student exhibits a deeper understanding of the lesson learned and relates its utility to a wider context. Additionally, statements which embody any of the Principles of Design merit this rating.
   a. Example: *"By developing an assembly of our future device, I have learned that preparing a plan of action for assembling it piece by piece in a logical order by stepping through the functions will lead to a better resultant vehicle, more so than just assembling it without regard to the order in which it should be done, which will lead to fewer mistakes in the future when sizing and manufacturing parts and will save our team money and time by eliminating errors and allowing focus to be kept on the completion of the project."* – AME4163 student, Fall 2016
   b. The student draws connections while demonstrating a more generalizable lesson learned. The student takes the learning beyond the obvious and directly relates to the fourth POED, which involves manufacturability.

A.4 Correlation matrices for survey data and course grades

In the following figure we display Spearman rank correlation coefficients between the 'Moving Forward' question responses on MII: I-V and (a) the students' device performance grades from the competition and (b) the students' grades for the device demonstration, also referred to as the competition. Though the tables are formatted to show strength of correlation for statistically significant correlations (p-value<.01) using darker shading for stronger correlations, none of the calculated correlations were deemed statistically significant and all table entries are therefore left unshaded.

Moving Forward v. Final Grade					
	MII: I	MII: II	MII: III	MII: IV	MII: V
JuniorEngineer	.16	.12	.12	.09	-.03
TeamManagement	.07	.10	.19	.06	-.21
StateProblem	.07	-.01	.16	.12	.02
DevelopConcept	.23	.03	.22	.20	-.08
EvaluateConcept	.04	.09	.18	.03	-.05
RefineConcept	-.08	.08	.36	.16	-.02
ConceptFeasibility	.14	.05	.08	.04	-.17
BuildPrototype	.17	.27	-.10	.21	-.08
SelfAnalyze	.06	.27	.09	.13	.08
CommunicateIdeas	-.02	.08	.14	.10	-.05

(a)

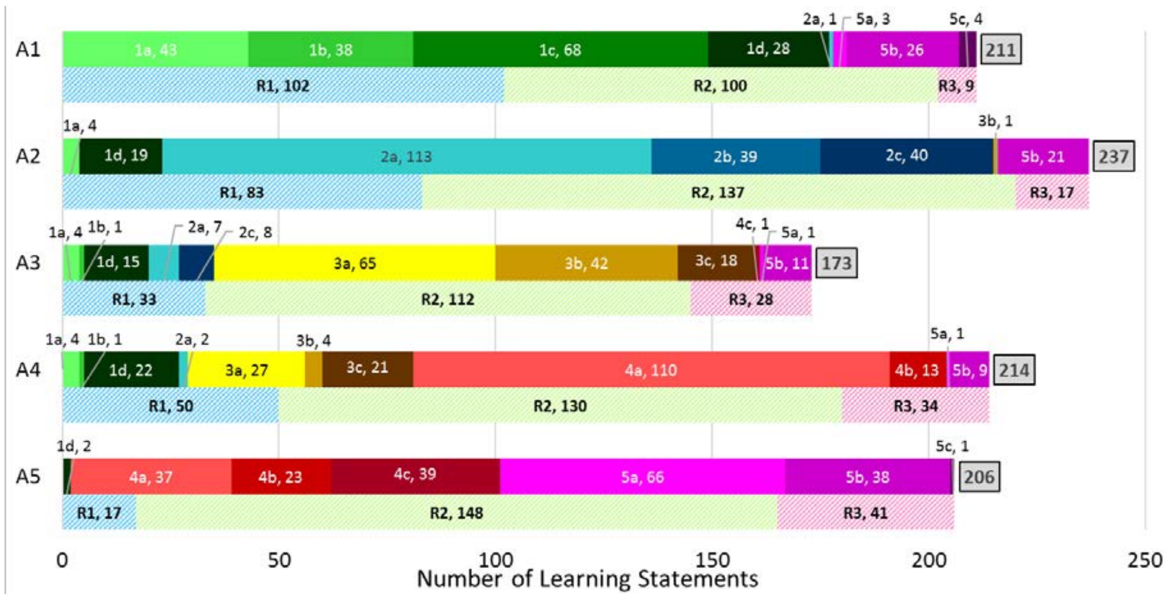
Moving Forward v. Competition Grade					
	MII: I	MII: II	MII: III	MII: IV	MII: V
JuniorEngineer	.12	.20	.03	.00	-.01
TeamManagement	.18	-.04	.09	.13	.06
StateProblem	.16	-.01	.15	.24	.04
DevelopConcept	.03	.28	-.05	.14	.10
EvaluateConcept	.17	.08	.09	.05	-.02
RefineConcept	.05	.14	.17	.23	.18
ConceptFeasibility	.05	.17	.06	.12	.09
BuildPrototype	.17	.12	-.04	.14	-.06
SelfAnalyze	.02	.12	-.05	.11	-.04
CommunicateIdeas	.09	.06	.01	.08	-.07

(b)

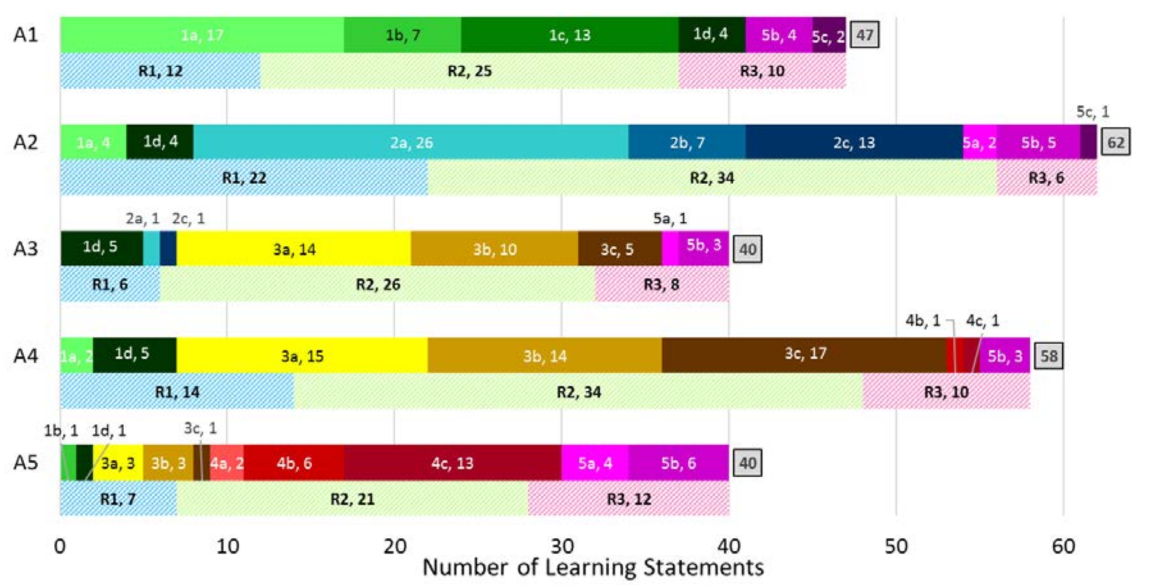
In addition to the fact that all of our calculated correlation coefficients were deemed statistically insignificant, we observe in the table that, even had our results met the significance criterion, the results we show do not reveal any strong correlations whatsoever. In fact, for both the correlations with the final grades and the competition grades, the strongest observed Spearman correlation coefficient, r_s, is .36, which we see in (a) is for the correlation between the students' final grade and the MII: III response to the question assessing confidence in the students' ability to refine concepts. We conclude that student self-assessment is not a reliable indicator of student performance in design, build, and test courses.

A.5 Learning statements organized by 'insight' rating

In the figure below, we highlight the breakdown of (a) individual and (b) team LS by assignment. For both figures, the top bar for each assignment depicts the POED breakdown with an interior label for the POED sub-category and number of LS in that subcategory. The bottom bar for each assignment represents the number of LS rated as R1 = one point, R2 = two points, and R3 = three points. We see that, in general insightful statements (R3) grew as a proportion of each assignments' total LS over time, though the trend is more pronounced for individual LS. Likewise, we observe that weak statements decrease as a proportion of total LS over time.



(a)



(b)