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Progress of Student Competencies from Cornerstone to Capstone Design: A Longitudinal Study*

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Using a rubric which measures student design competencies from pre-engineer to professional engineer levels, we assessed 104 cornerstone, 96 mid-program and 97 capstone final design projects over a five-year period to monitor student performance. The competencies chosen were System Design, Implementation, Project Management and Documentation. Each competency mapped to a separate ABET student outcome. The results showed a marked improvement as students progressed through the curriculum. The greatest improvement was shown in the System Design competency, followed by the Implementation, Project Management and Documentation competencies. The results provide an overview of evolution in design skills from cornerstone to capstone design and help identify areas of improvement within the design curriculum. The data also show that over the academic years 2016–2017 and 2017–2018, the 58 students who completed all three design courses and whose final design projects were assessed, scored consistently higher in each of the competencies on the assessment rubric than the 81 students who took only the cornerstone design course or the 38 students who took just the cornerstone and mid-program design courses. This suggests that those who scored higher marks in the cornerstone design course had a higher probability of passing the capstone design course and successfully graduating from the program.

Keywords: design based learning; rubric; assessment tools

1. Introduction

Learning design is an integral part of engineering education. Determining the level at which a student attains the necessary design skills depends on a careful and thorough assessment of those skills. ABET requires that accredited engineering programs have a culminating design experience in their curriculum [1], and these courses are often used to assess and evaluate some of the required student outcomes [2].

A move to a more rigorous, universal approach to design education began in the 1990s. Dym et al. [3, 4] held two workshops to discuss the future of teaching design. They brought together educators and practitioners to discuss cornerstone (first-year) and capstone (final-year) courses, discipline-based and cross-disciplinary design courses, pedagogy, technology and assessment in design education. Some of the conclusions of the workshop included a recommendation to implement design courses throughout the engineering curricula and to involve both assessment and continuous improvement in the design program.

To measure effectiveness of design in student learning, assessments have been developed which evaluate various skills and competencies in student learning. Trevisan et al. [5] piloted a program to determine the engineering design competencies of community college students continuing their four-year degrees within the state of Washington. They used a multiple-choice assessment, a team design performance assessment and an essay to cover important design-related outcomes expected of junior-level students. Davis et al. [6] recognized the challenges associated with a systematic assessment of design, so they instituted a process to support effective transfer of design credits, feedback for improvement of design education and an evaluation of program success. They presented scoring standards to make performance comparisons within and among programs. Dym et al. [7] studied the project-based learning model and investigated assessment data to determine its success. They found that project-based learning courses improve retention, student satisfaction, diversity, and learning.

A rigorous assessment of a students' design process knowledge is essential for understanding the best learning environments. Bailey and Szabo [8] acknowledge the difficulty of developing appropriate assessment tools to measure the necessary knowledge, and developed an instrument based on Bloom's taxonomy, including: remembering; understanding; applying; analyzing; evaluating; and creating. Kim and Gurocak [9] developed a design panel tool to assess courses with substantial project components. The panels consisted of faculty, industrial representatives, alumni and graduate students to evaluate student design pro-

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jects. Plumley and Wilczynski [10] used design portfolios, similar to those used by artists, to document student work. They gave a template which could be shown to broad audience, including administrators, institutional benefactors, politicians, industry representatives and parents. The student perception of design can change as a student moves through the curriculum, and Facciol, et al. [11] developed an instrument to evaluate student understanding of design. The data gathered from this instrument assisted faculty to develop cross-disciplinary courses. While most course evaluations are faculty-centric, Livesay et al. [12] developed a student-centric evaluation to assess student actions and attitudes related to their design experience. They found a statistically significant improvement in self-reported practices and attitudes as student cohorts progressed through design projects. Kellam et al. [13] developed a Synthesis and Design Studio to integrate design learning into all four years of the curriculum. They give an account of student reflections and focus group analysis to understand student learning in the Studio model. Using Likert Scale items and multiple-choice questions related to design scenarios, Osgood and Johnston [14] piloted a design ability technique. The abilities included defining a problem, evaluating alternatives, communicating their design and ethical awareness. A rubric to evaluate and promote the integration of stakeholder considerations into the engineering design process was developed by Coso and Pritchett [15]. They discussed how rubrics can be used as a formative assessment to identify and describe key aspects of the design process to account for stakeholder considerations. Atwood et al. [16] used a standards-based grading tool which ties assessment throughout the course learning objectives. Students reported a higher value than cost in traditional scoring schemes and reported a higher self-efficacy in the design-based objectives of the course. Chandrasekaran and Al-Ameri [17] evaluated students' experiences of assessment practices in a cohort of third- and fourth-year undergraduates. They described how students began to understand the importance of project/design-based learning and prepared themselves for their final year in this learning mode.

The Transferable Integrated Design Engineering Education (TIDEE) project, in consultation with academic and industrial practitioners developed a number of competencies which engineering students are expected to hold prior to entering the workforce [18–20]. They identified broad performance areas including Personal Capacity, Teamwork, Design Process and Solution Assets. Within these performance areas are common phases, processes and products of design including Problem Definition, Concept Generation, Detail Design, Documentation and Communication, and Implementation. From these areas we chose a set which we felt were important for undergraduate engineering students and represented a broad set of skills. We decided on the System Design and Implementation competencies to assess technical skills, the Project Management competency to assess a team's ability to plan, budget, and manage their project, and the Documentation competency to monitor a students' ability to write and communicate. Our competencies aligned with the Engineering Competency Model [21], the professional skills identified by Shahbazi et al. [22], and the National Association of Colleges and Employers (NACE) career readiness competencies [23], which were published after our rubric was developed.

The literature survey provides a general overview which confirms the importance of design in engineering education, how design skills can be assessed and which skills should be assessed. However, there is a dearth of literature discussing how student performance improves throughout the curriculum. Hence, the objective of this study was to use a single rubric to assess student progress from the first-year, cornerstone design course, through a mid-program sophomore design course to the fourth-year two-semester capstone sequence to measure student improvement in those competencies.

2. Courses

2.1 Cornerstone Design

A first-year engineering design course, or cornerstone design, is an excellent way to introduce engineering principles to new university students. It is also a good opportunity for program faculty to become acquainted with these students as they begin their engineering studies. First-year design courses have been implemented at a number of different schools [24, 25] with good student outcomes. Different practices have been implemented to teach these courses, including studio methods [26], flipped classrooms [27] and forming learning communities with high school students [28]. Including open-ended design experiences in a first-year engineering course has been shown to improve retention rates and increase overall student satisfaction [29, 30]. A key aspect in understanding student achievement in cornerstone design classes is a rigorous assessment plan [31–34].

In our program, the first-year design course introduces students to the engineering design process, analysis methods, problem-solving skills, economic decision making, teamwork concepts and documentation skills. The course serves as a way for students

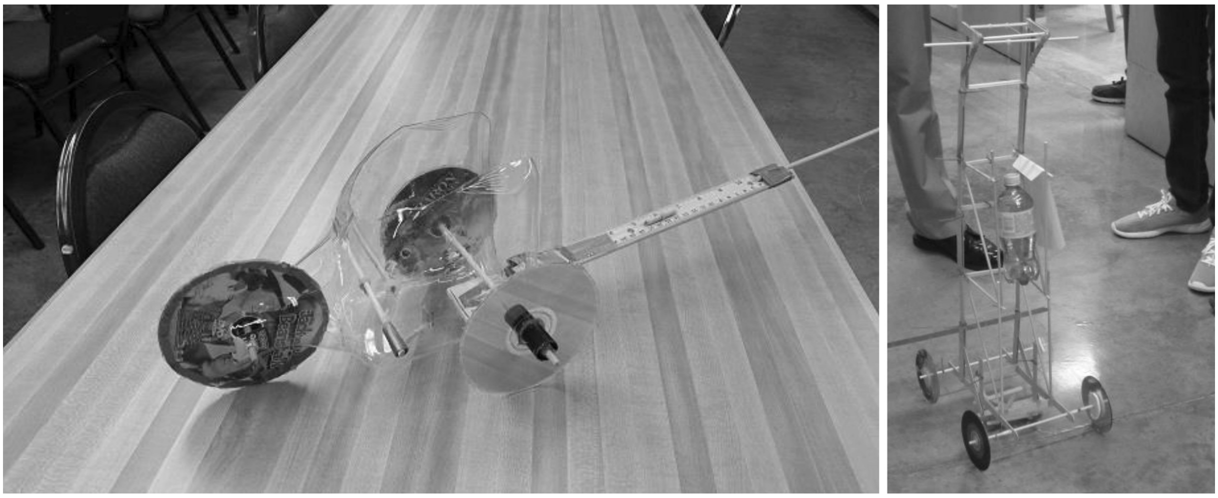

Fig. 1. Two examples of first-year, cornerstone design projects. Left: Mousetrap powered car. The challenge was to use the mousetrap to propel and brake the vehicle. Right: Potential energy to kinetic energy converter car. Here, student teams were tasked to use a falling weight to propel a car over a prescribed distance.

to become familiar with the expectations of university courses and to give them an idea for what mechanical engineering students do. Students work in a team environment on laboratory projects and open-ended design projects where they incorporate elementary engineering design methodologies to design some device within certain constraints. Students meet in a formal laboratory section once a week, and also meet outside of class to brainstorm ideas, build and test prototypes and refine their final designs. The design experience culminates in a final project that lasts approximately five weeks. Teams typically had three or four members and were formed by the instructor to include a range of higher to lower performing students. The final projects varied each semester and have included rubber-band powered cars, catapults that launch ping-pong balls at targets and vehicles that transform potential energy to kinetic energy by dropping a weight. Fig. 1 shows two different projects.

2.2 Mid-Program Design

A mid-program design project provides a good opportunity to assess student design skills along the educational journey. It also provides feedback to the faculty about student performance before they begin capstone design. Our curriculum has a design course which is usually taken in the second year. Mid-program design courses serve to integrate design learning throughout the curriculum, improve retention rates, solidify design process concepts and improve teamwork and design communication skills [35–37].

This course represents a significant step forward in complexity and design sophistication. It is more focused on the engineering design process, and students have a year of college-level engineering courses under their belt. Students develop computer programming skills and simple control systems, become proficient at developing and applying mathematical models to analyze design parameters and predict the performance of their design. They also learn to outline and identify the product development process and where and when business decisions are made. The design projects are open-ended and team-based, with three to five members per team, and the project lasts about half of the semester. Teams were formed by the instructor. Some semesters students were grouped with a random distribution of higher and lower performing students, and at other times the teams were comprised of students with similar performance. Unlike the cornerstone design course, student teams decide on the project they wish to realize. As a team they come up with an idea then discuss it with the faculty member to ensure that it is at a sufficiently high level for the course. In these projects, students had to incorporate an Arduino control system, a three-dimensional printed part, mechanical components and a mathematical model of their design. Logbooks were also required. Examples of projects include color pencil sorters, automated terrariums, externally sensitive lighting systems and secure door locking devices. Two examples of student projects are shown in Fig. 2. Students documented their designs using a binder-based portfolio until the 2020/2021 academic year when students built webpages to document their design processes.

2.3 Capstone Design

ABET requires that accredited engineering programs have a culminating design experience in their curriculum. These capstone design courses are ideal for assessing many of the ABET student

Fig. 2. Examples of mid-program design projects. Left: A motion following camera using a smartphone. The team developed a camera system to track a moving person at the front of a room. Right: Doorknob sanitizing device, inspired by the Covid-19 pandemic. After the door handle was touched a sensor sent a signal to spray disinfectant onto the handle.

outcomes [38–44]. In the mechanical engineering program at the University of Idaho, the capstone experience is a two-semester long, interdisciplinary course where students work on industry- or faculty-sponsored projects. Team sizes are typically three to five members and often involve students from multiple engineering disciplines as well as computer science. Students choose from a list of projects their top five preferences, then the instructors assign students based on those preferences. Students are expected to design, build and test their prototypes and present their work to judges and the public at-large. The project must meet engineering specifications as given by the customer; students meet with their customers on a regular basis for progress reports, get feedback on their design and map out a path forward. The student design teams meet with each other on a regular basis to go over design ideas and solutions. During team meetings, students track their budget, schedule, work assignments and project quality. Each team member has a set of responsibilities and students are accountable to each other to ensure that the project is moving forward on a timely basis with specific objectives achieved on time. Students maintain an engineering logbook which documents project learning, design decisions, and discuss lessons learned. At the end of the capstone course, students are expected to deliver reliable and robust physical prototypes that meet the needs of their client. The projects must be described on their publicly available course wiki page. Fig. 3 shows examples of typical senior design projects.

3. Assessment Rubric

3.1 Rubric Purpose and Structure

A primary goal of this project was to utilize a single rubric to assess student improvement in key design competencies from cornerstone to capstone design courses. The notion of monitoring differences in student design skills has been applied previously including comparing freshman and senior engineering design practices [45, 46], threading a common design project across the curriculum [47, 48], and linking first-year and senior design teams [49]. Using a common rubric for all the design courses meant that using common rubric rankings such as *Exceeds Expectations, Meets Expectations, Does Not Meet Expectations* would be problematic. For example, a project that met expectations for a cornerstone class would likely not meet expectations for a capstone course. Rankings with judgmental titles such as *Marginal, Acceptable and Exemplary* were also avoided for similar reasons. The authors felt that an absolute scale would give a better measure of skills progress. We chose rankings with the following designations: *Pre-Engineer* (1 point), *Trainee* (2 points), *Intern* (3 points), *Entry-Level* (4 points), and *Professional* (5 points). A description of the evolution of this rubric and a presentation of preliminary results was given previously [50].

We chose four competencies which incorporated a broad set of skills expected of engineering students. The four competencies were: System Design, Implementation, Project Management, and Docu-

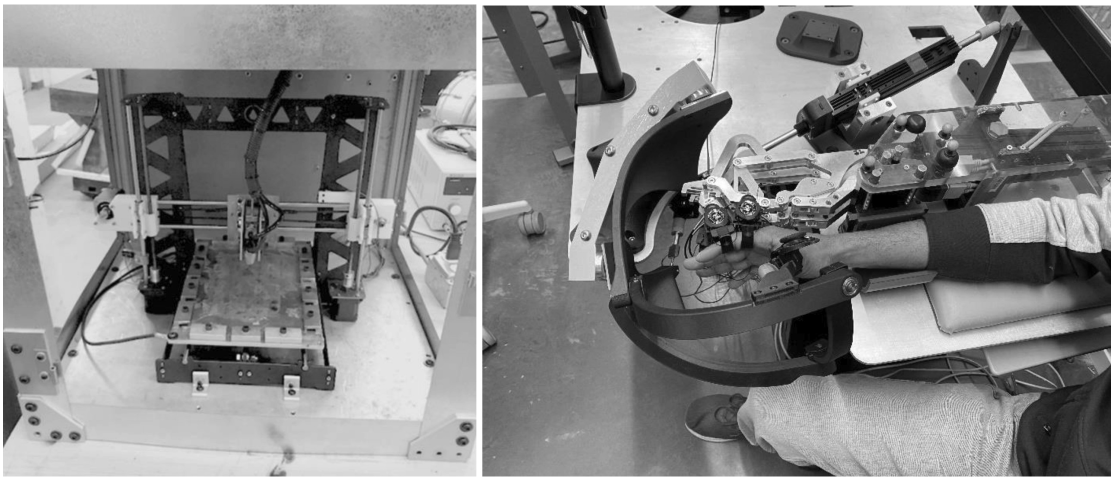

Fig. 3. Examples of capstone design projects. Left: Three-dimensional metal printer. The team integrated a variety of off-the-shelf and custom parts to realize the device. Right: Thumb rehabilitation robot. The team developed a robot to help stroke victims regain strength and motion in the thumb.

Table 1. Design assessment rubric to assess skills progress through the curriculum

Team: ________________ Course: ______________ Date: _____________ Evaluator's Name: ________________________________

Competency	**Pre-Engineer 1 point**	**Trainee 2 points**	**Intern 3 points**	**Entry-Level 4 points**	**Professional 5 points**	**Score**
System Design	No overall system architecture and lack of system integration. Minimal consideration of design constraints.*	Partial consideration given to system-architecture and integration. Some consideration of design constraints.*	Broad concept of a design with an adequate consideration of system integration while meeting many design constraints.*	Refined and thoughtful integration of subsystems and meets most design constraints.*	Well-integrated system which meets all design constraints.*	
Implementation	Inappropriate selection of materials; undisciplined fabrication; no manufacturing plan; rarely functioning system.	Arbitrary selection of materials; minimal consideration of manufacturing; intermittent system functionality.	Suitable materials identified; some consideration given to manufactur-ability; system usually functions.	Standard selection of materials; complete manufacturing plan; system functions reliably.	Purposeful selection of materials; optimization of manufacturing and system functionality; high system reliability.	
Project Management	Unorganized and lacks direction; team members unaware of responsibilities; no accountability.	Minimally organized and planned; team members somewhat aware or responsible; some accountability.	Moderate organization and planning; team members aware of responsibilities and held accountable.	Well organized and planned; team members are responsible and willingly accountable.	Thoroughly organized; team members are highly responsible and hold each other accountable.	
Documentation	Poor clarity, minimally descriptive; lacks organization and consistency; poor use of figures and graphs.	Minimal clarity, partially descriptive; some organization and consistency; mild use of figures and graphs;	Some clarity, moderately descriptive; organized and consistent with minor errors; moderate use of figures and graphs.	Nice clarity, solidly descriptive; well-organized and consistent; good use of figures and graphs.	Very clear and descriptive; highly organized and consistent; excellent use of figures and graphs.	

* Design constraints include a consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors

Notes/Comments:

mentation. Table 1 shows the rubric used in the project. These competencies also map to ABET student outcomes so that the results of the project can be used to partially satisfy ABET Criterion 4 to "evaluate the extent to which the student outcomes are being attained." [1] Table 2 lists the design competency and its corresponding ABET student outcome.

While the rubric was used in mechanical engineering design courses, its structure and wording were intentionally broad so that it could be used to assess design projects in other disciplines. The

Table 2. Mapping of design competencies to ABET student outcomes

Competency	ABET Student Outcome
System Design	(2) An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.
Implementation	(1) An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.
Project Management	(5) An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.
Documentation	(3) An ability to communicate effectively with a range of audiences.

rankings and competencies are applicable to any field of engineering.

3.2 Using the Rubric

Using this framework, all of the projects, from cornerstone through capstone were assessed based on how, in the view of the faculty evaluators, a professional engineer would realize the design. Similar comparisons to expert practitioners have been made previously [51, 52].

In all courses, the final designs were assessed at an end-of-course design exposition. Students in the cornerstone course presented their designs briefly in a poster-session style event then competed against other teams during the assigned challenge. Students in the mid-program design course participated in an hour-long professional exposition-style demonstration of their designs. Seniors presented their work to the broader public at a half-day long exposition event.

The team compositions were not assigned by gender or underserved population status; therefore demographics were not considered in this study. The assessment tool was only designed to evaluate team performance. However, the three design courses described in the paper are all required classes, so the demographics of the department are naturally reflected in the demographics of each course. Approximately 13% of the students in the department were women.

All of the raters were mechanical engineering faculty with either industrial design experience, experience in teaching one of the design courses or both. Not every rater was able to visit with every team, but there were at least three raters per team. During the first two semesters of this assessment project, four raters participated, then three new faculty joined the project and were trained on using the rubric.

Individually, the faculty raters would discuss the design with representatives from each student team, ask questions related to the design process and project management, observe the design and its functionality, then privately record their assessment. The raters then read the design reports which were usually available a week or two after the final design presentations. Using the rubric, the raters then entered their score in increments of one-half point for each competency. Essentially, the scores were scaled based on how the raters felt a professional engineering team would design the particular project. The competency score for each rater was averaged giving the overall team score. The team scores for each course were then averaged and the standard deviation calculated giving the overall value for the course in a particular semester.

The Mann-Whitney-Wilcoxon [53] test for unpaired data was used to determine if data sets were from different populations, thereby determining a statistically significant difference in the scores. The test returns a p-value, where $p \leq 0.05$ is indicative of samples from different populations. The test was run for all scores in-aggregate from a design course for a particular competency and compared to the aggregated scores from the subsequent design course for the same competency. This was accomplished using the Matlab function *mwwtest* by Cardillo [54]. We assume that if samples from the entire population are distinct, that each individual semester is as well and then omit that calculation.

Krippendorff's alpha, α [55,56], a measure of inter-rater reliability, was calculated for each set of teams and competencies within a particular course. We used the function *kriAlpha* by Eggink [57]. Positive values of α indicate better reliability than chance, and negative values indicate worse agreement than chance. A value of $\alpha = 1$ indicated perfect agreement between raters assigning a score.

4. Results and Discussion

4.1 Assessing Student Competencies

Fig. 4 shows the data for each of the competencies on a semester-by-semester basis beginning with the fall 2016 semester. Due to logistical issues, no assessments were completed for the documentation competency during that semester. Because of the Covid-19 pandemic, face-to-face course delivery was cancelled just as the spring 2020 cornerstone and mid-program design projects were beginning. This prevented students from working in teams to

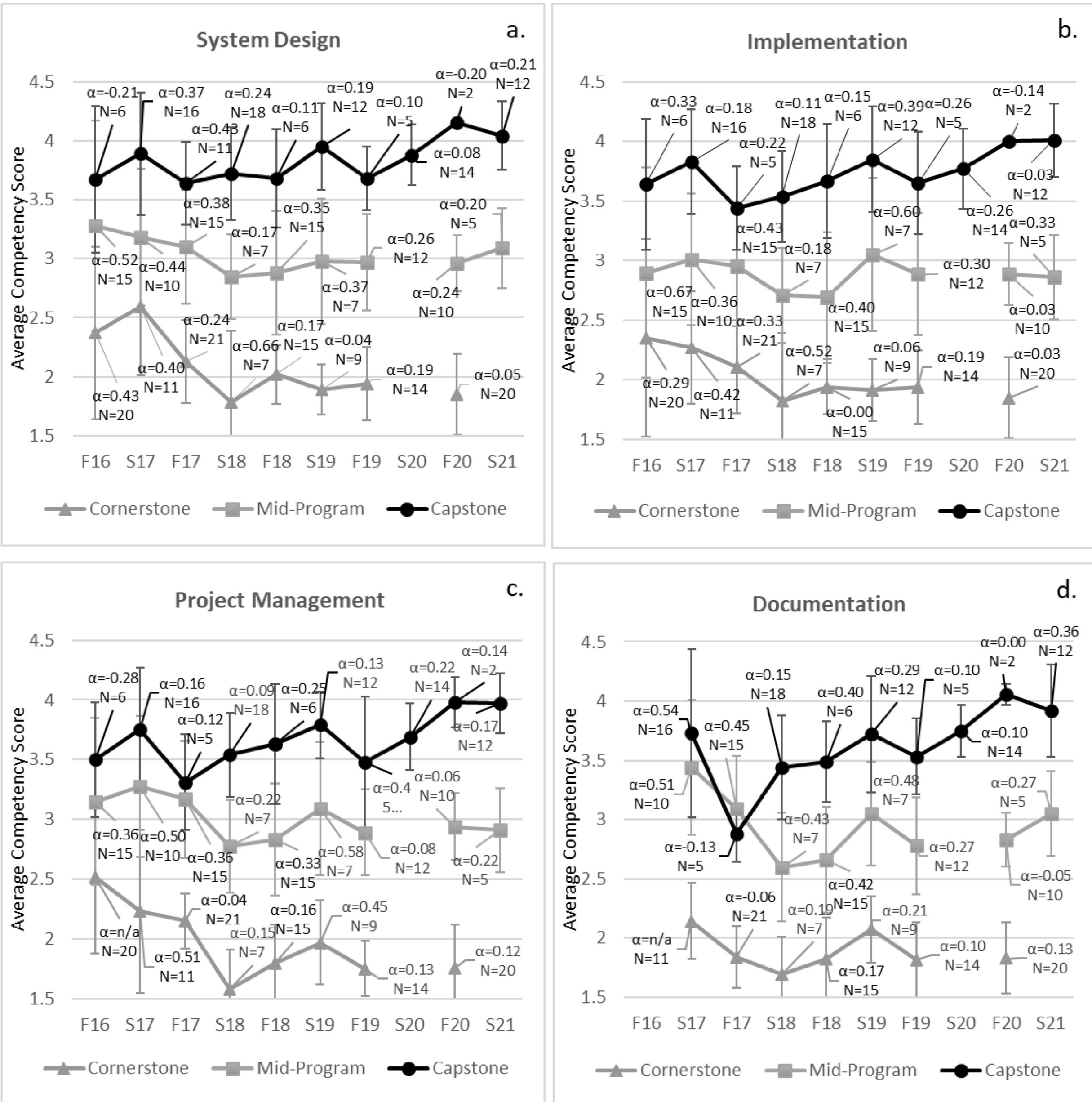

Fig. 4. Average competency scores, standard deviations and Krippendorff's alpha for assessments of each design competency using the rubric in Table 1 for each semester beginning with fall 2016. Fig. (a) System Design; (b) Implementation; (c) Project Management; (d) Documentation. Scoring is based on 1 – Pre-Engineer; 2 – Trainee; 3 – Intern; 4 – Entry-Level; 5 – Professional. For each data point, α represents Krippendorff's alpha (inter-rater reliability) and N the number of teams assessed.

complete their projects, so consequently no assessments were performed for these two courses during that semester. However, at the time the pandemic began, the capstone design course was approximately 75% complete so students were able to finish their projects. These students gave presentations via Zoom with live interactions with judges, faculty and other participants. The cornerstone design course was not offered during the spring 2021 semester.

An overall view of student performance shows a consistent improvement in each of the competencies from cornerstone to capstone design. The data correlate with the increase of sophistication in the projects as seen in Figs. 1–3. The number of teams (N) is also shown. The variations of the scores reflect the relative strength of the students in the particular semester. Fig. 5 presents the data by academic year. It shows that the variation in the results is attenuated compared to the semester-by-semester data and reveals clear improvement from cornerstone to capstone design. As previously mentioned, Swenty et al. [48] assessed student performance on the same project as students progressed through a civil engineering program. They observed that the most knowledge was gained and retained

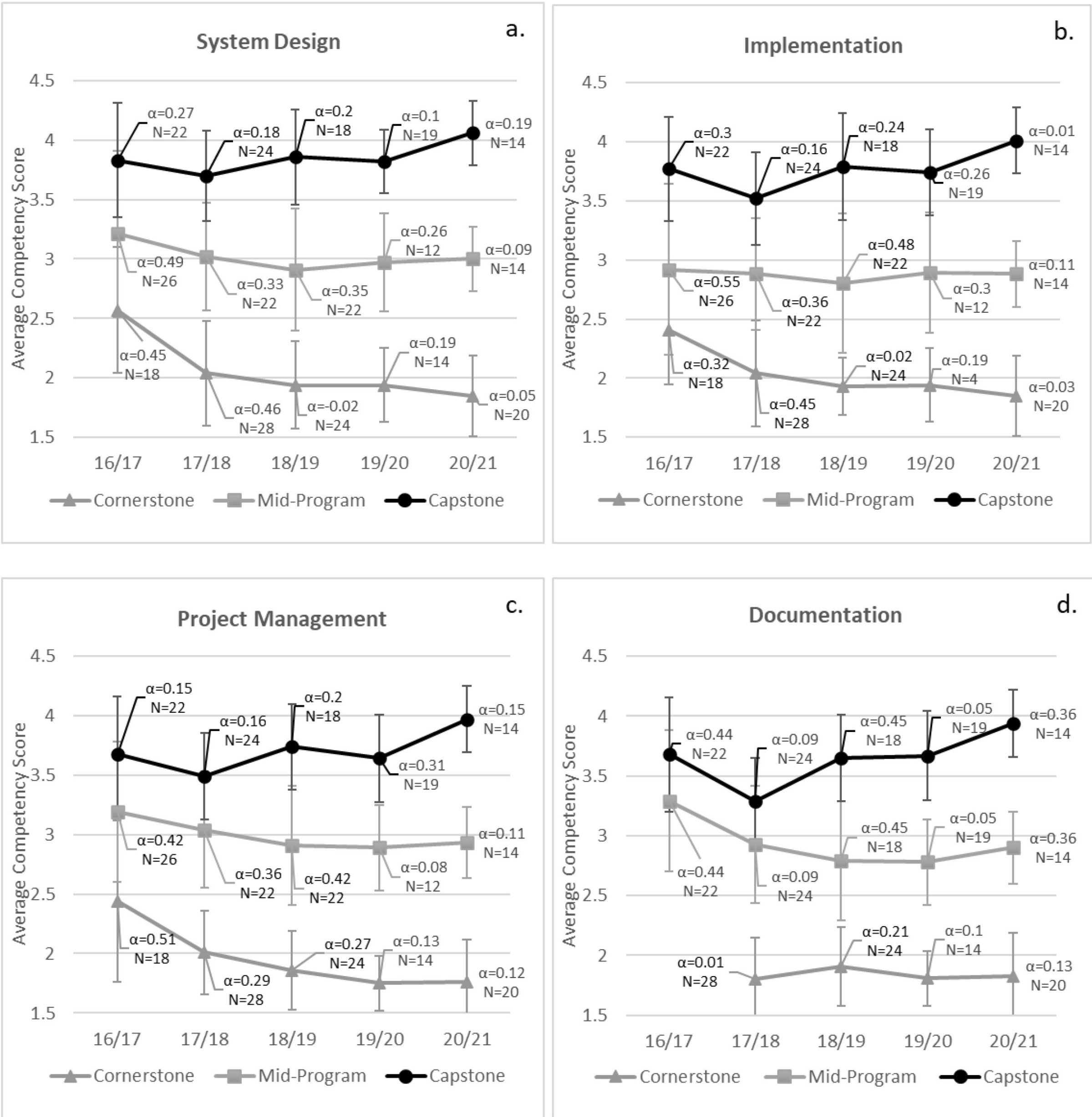

Fig. 5. Average competency scores, standard deviations and Krippendorff's alpha for assessments of each design competency using the rubric in Table 1 averaged over each academic year beginning with AY 2016–17. Fig. (a) System Design; (b) Implementation; (c) Project Management; (d) Documentation. Scoring is based on 1 – Pre-Engineer; 2 – Trainee; 3 – Intern; 4 – Entry-Level; 5 – Professional. For each data point, α represents Krippendorff's alpha (inter-rater reliability) and N the number of teams assessed.

the first time conducting the project. Our observations were similar. Student performance increased the most between cornerstone and mid-program design courses. Capstone students in-general demonstrated the highest scores overall. Qualitatively the evaluation team found that capstone students were able to describe more completely the benefits, tradeoffs, and alternatives in their designs than any of the other groups. Seniors also demonstrated this superiority of design skills in the study by Atman et al. [45]. Fig. 6 shows the results averaged over all five years of the project. The data show that graduating seniors are prepared to enter the workforce with the broad skills necessary to contribute meaningfully to the profession.

The assessment data were also used to investigate how individual students performed. We tracked the scores of all 236 students who took the cornerstone design course in the academic years 2016/2017 and 2017/2018 through the time that they graduated or left the mechanical engineering program. During this time period, cornerstone design was offered all four semesters by two different instructors. Because of the team-based nature of the assessment, scores

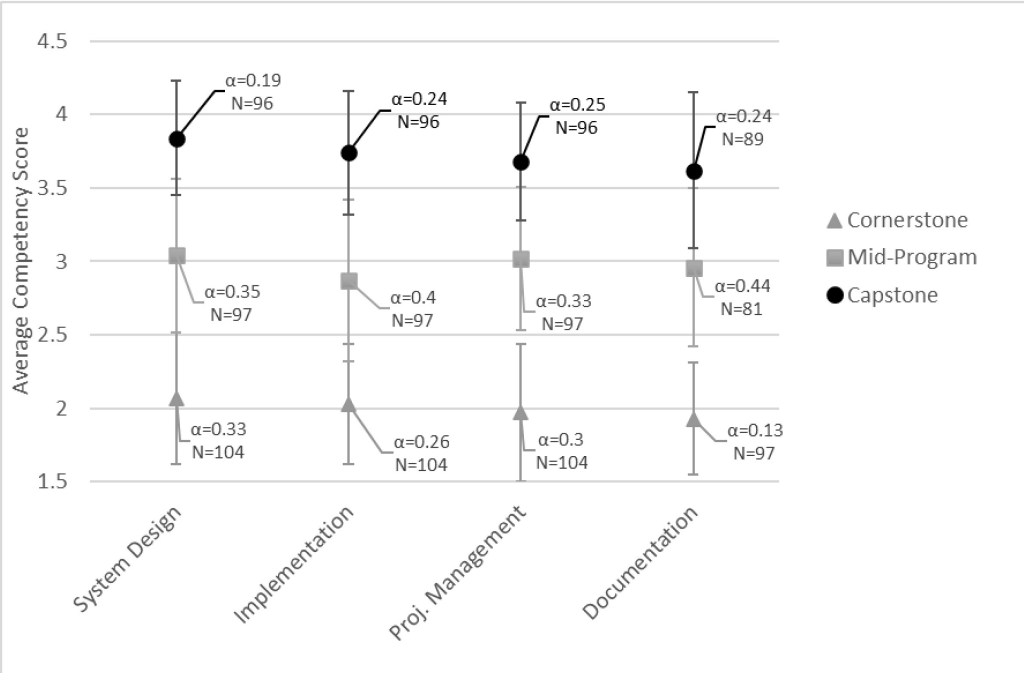

Fig. 6. Average competency scores, standard deviations and Krippendorff's alpha for assessments of each design competency using the rubric in Table 1 averaged over all semesters of the project. Scoring is based on 1 – Pre-Engineer; 2 – Trainee; 3 – Intern; 4 – Entry-Level; 5 – Professional. For each data point, α represents Krippendorff's alpha (inter-rater reliability) and N the number of teams assessed.

for each team project were necessarily mapped to each student from the team. We note that ascribing team scores to individual students does not necessarily correlate perfectly with the skill level of that particular student, but the results show a reasonable trend which will be addressed here. From the group of 236 students, 81 left the program by either changing majors or leaving the university. The remaining students took the mid-program design course, and of that group, 38 students either changed majors or left the university. Those 117 students who continued in the program after the mid-program design course either graduated or were still in the program. We were able to assess the capstone projects of 58 of the students who graduated. Table 3 shows the competency scores for each of those groups. The students who only took cornerstone design had consistently lower scores, except in the documentation competency, than those who took the mid-program design course, and lower than the students who finished all three design courses. The average competency scores of the students who took the cornerstone and mid-program courses were lower than the scores of the students who completed all three design classes. This indicates that cornerstone students, on average, who scored lower in the competencies were likelier to leave the program. While not a precise indicator of success in the program, since strong students were on weak teams, and weak students were on strong teams, the overall scores give a rough measure of who has the greatest chance of completing the program.

4.2 Statistical Significance and Evaluator Reliability

The standard deviations of the scores are shown as error bars in Figs. 4–6. Generally, the error bars do not overlap; however, in certain cases the cohort of one student group performed better than the corresponding more advanced course in a particular competency. The Mann-Whitney-Wilcoxson two-tailed test results in all cases were returned at $p = 0$, leading to the conclusion that there is a very high confidence in a statistically significant difference between the cornerstone, mid-program and capstone competency scores.

The Krippendorff's α values are consistently positive as shown in Figs. 4–6, indicating better than chance agreement among the raters. The scores of the raters did not get more consistent with time, indicating that bias was not a concern. Regarding the magnitude of acceptable α values, Krippendorff [55] writes that the minimum reliability should be chosen based on the "validity requirements imposed on the research results, specifically to the costs of drawing the wrong conclusions." Our alpha values fell generally in the range of $0.2 \leq \alpha \leq 0.5$, which is below the generally accepted minimum value of 0.667. It was not uncommon that a faculty evaluator would observe

Table 3. Assessment scores and standard deviations from cohorts of students who began with cornerstone design in AY 2016–17 and 2017–18. The left-hand column indicates the number of students who only took cornerstone design (N = 81), those who only took cornerstone and mid-program design (N = 38) and those who took all three design courses (N = 58)

	System Design	Implementation	Project Management	Documentation
Cornerstone only N = 81				
Cornerstone scores	2.15, $\sigma = 0.68$	2.09, $\sigma = 0.63$	2.12, $\sigma = 0.54$	1.90, $\sigma = 0.35$
Cornerstone and Mid-Program only N = 38				
Cornerstone Scores	2.26, $\sigma = 0.71$	2.25, $\sigma = 0.78$	2.31, $\sigma = 0.63$	1.86, $\sigma = 0.34$
Mid-Program Scores	2.79, $\sigma = 0.45$	2.64, $\sigma = 0.49$	2.82, $\sigma = 0.45$	2.67, $\sigma = 0.46$
Cornerstone, Mid-Program and Capstone N = 58				
Cornerstone Scores	2.34, $\sigma = 0.5$	2.24, $\sigma = 0.54$	2.31, $\sigma = 0.61$	2.07, $\sigma = 0.49$
Mid-Program Scores	3.13, $\sigma = 0.46$	2.95, $\sigma = 0.45$	3.12, $\sigma = 0.46$	3.03, $\sigma = 0.49$
Capstone Scores	3.95, $\sigma = 0.28$	3.86, $\sigma = 0.37$	3.82, $\sigma = 0.33$	3.84, $\sigma = 0.3$

a team's design in operation, then something would malfunction when the next faculty evaluator visited with the team. Rather than omit these findings, we would like to highlight and emphasize the difficulty in obtaining consistent assessment scores, submitted by many faculty, while evaluating such competencies as system design or project management despite the rubric training that the group received.

4.3 Program Improvement

The expectation of any curriculum is that student's skills progress throughout and that their knowledge expands. Unlike the instrument developed by Facciol et al. [11], which focuses on student perceptions of the design process, the student performance data from this study can be used to identify strong and weak skills in the design curriculum. For example, our data indicated a relative weakness in documentation skills in the capstone students when the assessment project began. Consequently, additional effort was directed toward improving those skills. This included the use of additional discussion, assignments, and templates implemented in the capstone course over an approximately two-year period. The data indicated that capstone-level student documentation skills improved over this time. Our overall goal for graduates is that they earn a mean score of four across all of the competencies. The data indicate that we are nearing this benchmark.

One consequence of having a skills-focused evaluation rubric is that it is not targeted at students' understanding of design, but rather evaluators must infer that students who perform highly in the competency areas understand the design process. This is a valid assumption since our evaluation team discussed the project directly with students and did not notice any major discrepancies between student scores and the ability of students to thoughtfully discuss their designs. In the future, however, students' understanding and perception of the design process could be evaluated with focus groups or surveys.

4.4 Lessons Learned

Throughout the five-year period working with the assessment rubric, we have learned some valuable lessons about its implementation. Here we will share some of the most important ones so that others may benefit. First, there are some lessons on the mechanics of implementing such an assessment. We found that it is useful to have a coordinator to keep track of dates, evaluator assignments, and other important items like video conference links that are important to the evaluators. The coordinator serves an important function to keep the team organized, share information, and limit duplicate work. Such an evaluation requires a commitment from faculty, so it is wise to acknowledge this up front and take steps to avoid a situation where evaluators feel overburdened. An overburdened situation could be prevented by engaging more evaluators and limiting the number of teams each evaluator is required to assess. Increasing the number of competencies evaluated increases the amount of time required, but not unreasonably. Four or five competencies seemed like a good number to our team. Fewer may not provide good resolution and more could require too much of an assessor's time.

We also found value in working together at the beginning of the assessment period for a training session on how to use the rubric. As outlined previously, our approach was to use an absolute scale, where all students were assessed relative to a professional engineer. The training session (we actually had several throughout the project), was a great time to create mindshare around this concept and share best practices that faculty evaluators were using. As a team, and before starting the project, we discussed together exemplars to train and calibrate the team, but once the project began, evaluators relied upon their own concept of what performance a professional engineer would achieve given the constraints of the projects. Training sessions should improve inter-rater reliability since all evaluators will be working with a common strategy. Our evaluation group consisted of a core group of faculty, with several joining and some leaving (hence some additional training sessions). We felt this was a good model but are intrigued by the idea of a rotating set of evaluators to allow time to recharge and prevent stagnation or bias in scoring. One of the evaluators commented that this project helped them develop ideas for their non-design related courses and that inviting other faculty members to participate in the process could provide a similar opportunity.

From a strategic standpoint, a team beginning an evaluation of their own should choose competencies of strategic importance to their program. It is beneficial to choose competencies that align with ABET assessment criteria, or where it is desired, to augment existing assessment methods. We found that we gained considerable insight into the performance of our entire cohort of students with a manageable effort from the evaluation team. In our program, we identified a weakness in documentation skills and were able affect a positive change in the level of student competence.

One limitation of a skills assessment rubric is related to our approach in discussing the design with students. As with any team, members will make different contributions and have different levels of understanding of the design process. For example, our assessment of project management skills relied upon discussions with team members regarding scheduling, planning, resource allocation, etc. Variability in which a team member was available for discussion was inherent to the exposition style format and some students more effectively communicated the team's processes than others. A benefit of having multiple evaluators is that in-aggregate this affect could be mitigated but at the expense of more evaluation effort. The three other competencies besides project management relied less upon team member discussion, focusing instead on observable design products. Assessors should consider this effect and whether it would be detrimental to their project goals as they choose to develop competency categories of their own.

5. Conclusions

We have shown that a single rubric can be used to track design skills in four competencies. The descriptive headings in the rubric rate student competencies from Pre-Engineer to Trainee, Intern, Entry-Level and Professional abilities. The rubric gives a method to gauge student progress based on comparing final design projects with how a professional engineer would realize such a project. The results show that student design competencies improve from the cornerstone design course, through mid-program design to capstone design and that students who successfully complete the capstone design class are prepared to enter the workforce with key design skills.

When the team design scores are mapped to individual students, the data indicate that students who complete the capstone design course score higher than students who only take the cornerstone design course or just cornerstone and mid-program design courses. This suggests that students who have higher assessment scores in the cornerstone course are more likely to successfully complete capstone design and graduate from the program.

While the rubric was used in mechanical engineering design courses, there is nothing in the structure or wording which would preclude its implementation in other engineering disciplines.

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