Development and Implementation of a Longitudinal Design Assessment

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After graduating from Oregon State University with a B.S. in Mechanical Engineering in 1999, I immediately pursued a career in industry, quickly excelling and continuously accepting roles of increasing responsibility. The first five years, I worked at GK Machine, Inc., a small company south of Portland, designing customized agricultural equipment. Next, I worked at Hyster-Yale Material Handling, most recently as the Direction of Product Development for the Counterbalanced Electric Truck product line while introducing 8 new products into production between 2009-2013. Although each new role was challenging and rewarding, they progressively drew me further away from science and engineering, and more towards business administration. With this gradual shift, each position demanded more focus on company profits, and allowed less opportunity for me to mentor younger employees in the science and engineering involved in product development. As a result, I decided to relinquish my industry career to pursue a Ph.D. with the specific goal to fulfill my passion for teaching and mentoring young engineers as a university professor.

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Abstract

An assessment tool has been developed to measure and track student design skills longitudinally through the curriculum. The rubric assesses competencies in system design, implementation, project management and documentation. Each competency is evaluated on a 1 to 5 scale, representing skill levels associated with a Pre-Engineer, Trainee, Intern, Entry-Level Engineer and Professional, respectively. The competencies were assessed using freshman, sophomore and senior capstone design courses in the Department of Mechanical Engineering at the University of Idaho. The data show that the scores improved consistently from freshman to senior years, with the largest increase in system design skills, followed by implementation, project management, and then documentation. The data provide an overview of the changes in design skills through the curriculum, helping to identify weaknesses within the design courses that can be improved. While the tool was used in mechanical engineering courses, it is designed to be used in courses within any engineering discipline.

1. Introduction

The genesis of this project lay in the desire of design faculty members to monitor and quantify the evolution of four design competencies of students from the freshman through senior years. The curriculum in the Department of Mechanical Engineering at the University of Idaho has freshman and sophomore design classes to prepare students for the senior capstone design sequence. There are many design rubrics available, but our goal is to develop a single rubric which could be used in freshman design courses as well as capstone courses, and that the rubric could be applied in courses in many engineering disciplines.

Literature Survey

The accreditation organization, ABET [1] and the National Academy of Engineers [2] have taken the lead to ensure that engineering design and its attendant skills are important parts of engineering curricula. Technical societies such as the American Society of Mechanical Engineers [3] and the American Society of Civil Engineers [4] have encouraged programs within their disciplines to integrate open-ended problems and design principles [5] into course offerings.

To gauge the effectiveness of design courses on student learning, a number of assessments have been formulated. Some of the first assessments of engineering design competencies were developed by Trevison et al. [6]. Later, Davis, et al. [7] developed a design team assessment which covered design process, teamwork and design communication skills using their Design Team Readiness Assessment tool. Subsequent studies have investigated design process knowledge [8,9], design creativity [10] and student conceptions of modeling in design [11].

To develop a strong curriculum for introductory design courses, key design competencies need to be identified. These competencies include teamwork, information gathering, problem definition, idea generation, evaluation and decision making, implementation and communication [12]. From these competencies, materials can be developed to meet the learning outcomes of the particular programs. Many schools have developed introductory courses to help first-year students begin to think and function as engineers, and to help them gain a better understanding of what it means to be an engineer. Some institutions have designed introductory courses that combine all engineering disciplines [13,14] and others have developed separate introductory courses for each discipline [15,16]. Additionally, integrating courses such as physics, calculus, chemistry and English, using active and cooperative learning methods has been shown to increase the retention rate of first-year engineering students and increase the percentage of students passing physics and calculus [17]. Involving instructors from chemistry, physics and mathematics in the introductory engineering courses has also been shown to improve learning [18].

ABET mandates that students have a “major design experience” [1] as part of the university engineering curriculum. This experience usually consists of a capstone design course (or courses). These courses are often used to assess the achievement of student outcomes, and a number of methodologies and rubrics have been developed for this purpose [19-24]. Within the context of design skill assessment, specific traits have been studied, including professionalism [25], ethics [26], teamwork [27] and life-long learning [28].

Despite the amount of work devoted to assessing design at certain points of student development, typically in introductory and capstone design courses, relatively little exists to measure the change (and hopefully improvement) of design skills from the time a student begins engineering studies until graduation. The differences in the design processes between high school engineering students and expert engineers have been explored [29]. High school students tend to spend less time determining the feasibility of their ideas, evaluating alternative ideas and decision making than expert engineers.

Comparative, or longitudinal, studies have proven beneficial in showing the progress of design skills and indicating which skills should be focused on early in the curriculum. Researchers [30] compared design skills between student and professional engineers, and showed that the professional teams were more likely to outline an overall design philosophy and not overlook detailed specifications while students were more likely to engage in generating ideas and testing throughout the design process. In another study, freshman and senior design teams were given the same design project and their approaches were compared [31]. The study showed that seniors tended to gather more information and consider a wider range of solutions. The School of Civil Engineering and Environmental Science at the University of Oklahoma [32] implemented a unique program where incoming freshman were given a hypothetical plot of land to develop. The project lasted the full four years of the curriculum so that students could apply knowledge gained semester by semester. In another longitudinal study [33], researchers showed that there is a strong correlation between learning design and process skills in a collaborative environment early in the curriculum and student performance in design courses taken later on. They also found that teaming skills developed early on have a strong, positive influence on student performance in design courses taken later in the program.

The primary purpose of the research presented in this paper was to develop and implement a single instrument which could gauge student design performance at any level of the curriculum, then compare the change in performance through the curriculum. This tool helped monitor the progression of key design skills and aided faculty to better understand their pedagogical processes and identify areas of concern. As an additional benefit, the results from the project were used to monitor student outcomes in courses that had not previously been assessed.

We will present an outline of the three courses that were used during this project, to provide a broader context for the development of the rubric. Following that, the rubric will be discussed and presented, and then the results of the application of the rubric will be given.

2. The Courses

Freshman Design

The freshman design course introduces students to the engineering design process and analysis techniques, including problem-solving skills, development of software learning skills, data analysis, economic decision making, documentation skills, and the use of structured programming concepts. It is offered fall and spring semesters with the largest enrollments coming in the fall. The course serves as a way for students to become familiar with the expectations of college classes and to give them an idea of what mechanical engineering students do. Students work in a team environment once a week on laboratory projects and open-ended mini-design projects where they incorporate elementary engineering design methodologies to design some device within certain constraints. Once students begin working on their final design projects, they meet outside of class to brainstorm ideas, build and test prototypes, and refine their final designs. The final project typically lasts five weeks. Due to budgetary constraints, students construct their project out of common scrap/recycled materials. The final projects vary by semester and have included rubber-band powered cars that are required to travel certain distances or stop at prescribed locations, catapults that launch ping-pong balls at targets, and vehicles that transform potential energy into kinetic energy by dropping some weight and converting that drop into forward motion. Figure 1 below shows an example of a vehicle powered by a mousetrap. These vehicles had to meet two challenges. The first was to travel the farthest distance and the second was to travel a specified distance between 10 and 20 feet. The exact distance the vehicle had to travel was not given until the time of the competition.

Figure 1. An example of a mousetrap-powered vehicle, one of the final design projects in the introductory design course.

Sophomore Design

The sophomore design course represents a significant step forward in complexity and design sophistication. The course is more focused on the engineering design process, and by this time in the curriculum students have completed a year of college-level engineering, mathematics and physics courses. It is also offered both semesters, during which the largest enrollments are in the fall. They 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. Students also learn to outline and identify the product development process and where and when decisions are made. Again, the design projects are open-ended and team-based, with four or five members per team. The project lasts about half of the semester. While in freshman design, students are given a prescribed project, in sophomore design, student teams choose the project they wish to realize. As a team they come up with an idea and discuss it with the faculty member leading the course to ensure that it is appropriately scoped and meets all requirements of the course project. Examples of projects include color pencil sorters, automated terrariums, externally sensitive lighting systems and secure door-locking systems. In these projects, students must incorporate an Arduino control system and a three-dimensionally printed part in their design. An example of one design project, a motion-sensing camera using a smartphone, is shown in Figure 2 below.

Figure 2. Motion sensitive camera using a smartphone, an example of a sophomore design project incorporating an Arduino and a three-dimensionally printed part.

Senior Capstone Design

The senior capstone design sequence is a two-semester long, interdisciplinary course where students work on industry or faculty sponsored projects. The sequence is offered in a summer-fall or fall-spring semester sequence. The purpose is to prepare students for professional practice as an engineer, working on an entry-level design project. Team sizes are typically four to five students and usually involve students from multiple engineering disciplines including computer science. Students are expected to design, build and test their prototypes and present their work to judges and the public at-large at the year-end Engineering Expo. The project must meet engineering specifications as given by the customer; students meet with their customers on a regular basis for progress reports, to get feedback on their design and to 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 the 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 project must be described on its publicly available course wiki page and fully documented via physical portfolio. Figure 3 below shows an example of a typical senior design project, a three-dimensional metal printer.

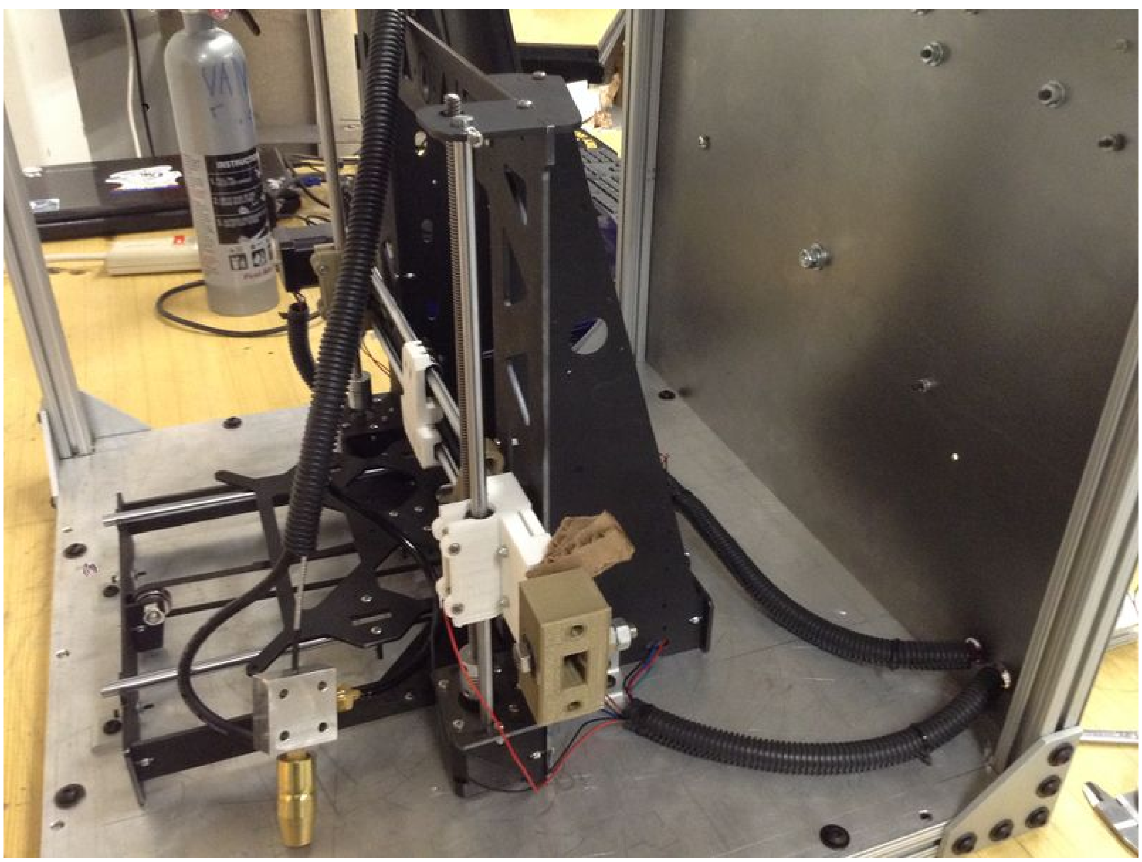

Figure 3. Three-dimensional metal printer, an example of a senior capstone design project incorporating numerical motion control and MIG welding.

3. Assessment Rubric

To measure and track the progress of the design skills of students throughout the curriculum, we began with a rubric used originally for capstone design projects. The capstone rubric has been used for a number of years, and the data it generated has been used to satisfy assessment criteria for various ABET student outcomes. The scoring ranged from 1 to 5, ranking various competencies from Developing (1) through Satisfactory (3) to Exemplary (5). Seven competencies were assessed, including Problem Definition, Concept Development, Proof of Concept, System Design, Implementation, Client Needs and Project Management. We settled on three competencies from this list, System Design, Implementation and Project Management, and these could be mapped to ABET student outcomes. For the capstone design projects, the communications portion was assessed separately, using external judges who visited their assigned projects during the Engineering Expo and scored the oral presentations. We felt it was important to include the Documentation competency, so it was added to the three taken from the capstone design rubric. Table 1 below shows how each competency maps to both the current ABET student outcomes under Criterion 3 and to the student outcomes set to take effect during the 2019-2020 accreditation cycle.

Table 1. Mapping of design competencies to current and future ABET student outcomes

Competency	Current ABET Student Outcomes	2019-2020 Student Outcomes
System Design	(c) An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	(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	(e) An ability to identify, formulate, and solve engineering problems	(1) An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
Project Management	(d) An ability to function on multidisciplinary teams	(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	(g) An ability to communicate effectively	(3) An ability to communicate effectively with a range of audiences

Instead of being used for a single course, this new rubric needed to cover the wide range of skills needed for incoming freshman through graduating seniors. This required modifications to the titles of the scoring range and to the descriptors of performance in each cell to cover the spectrum of students being assessed. A design that might be satisfactory or exemplary for a freshman project would likely not be considered as such for a capstone project. To best match the level of expertise corresponding to a students' position in the curriculum, we decided to use a 1 to 5 scale, beginning at Pre-Engineer, then moving to Trainee, Intern, Entry-level Engineer and Professional levels. These titles also avoided judgmental language (such as marginal, acceptable, exemplary, etc.) when describing the level at which students happened to function. An example of the rubric is presented in Figure 4.

In all courses, the designs were assessed at an end-of-course design exposition. Students in the freshman-level course presented their designs briefly in a poster-session style event then competed against other teams at the assigned challenge. Students in the sophomore-level 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. Individually, the raters would discuss the design with representatives from each student team, ask questions, observe functionality, and then privately record their assessment.

4. Results and Discussion

We deployed the first draft of the assessment rubric during the fall 2016 semester, using four raters. The raters were chosen from the design faculty within the department. Each had industrial experience and taught at least one of the freshman, sophomore, or senior design courses. Not every rater was able to meet with every team, but there were at least three raters per project. Although a form of the rubric had been used on capstone design projects, it had not yet been used on freshman or sophomore projects. Since the new labels for each numbered score had not been used previously, raters needed to be mindful that an excellent freshman project may score low on the rubric, since the highest standard was how a professional engineer would have designed the project. Due to logistical problems, the Documentation competency was not assessed in the fall 2016 semester. After going through the rating process, small adjustments were made to the rubric. These changes, such as minor wording corrections and refinements, enabled the rater team to function more efficiently and comfortably in applying the rubric during spring 2017 semester. The revised rubric is presented in Figure 4. For the fall 2017 semester, three new faculty members joined the rater team and were trained on how to use the rubric. They brought industrial design experience to the project, and each were involved in teaching design courses.

Figure 5 shows the data gathered for each course and the System Design, Implementation and Project Management competencies over three successive semesters. Data for the Documention competency was first gathered in the spring 2017 semester. The error bars for each data point represent the standard deviation, α is Krippendorff's alpha [34,35], a measure of inter-rater reliability, and N is the number of teams assessed for the particular course in that semester.

Assessing the Progress of Student Design Skills Rubric
Final Design Review

Team: ___________________________________Course:__________________________ Date: ___________ Evaluator's Name:__________________

Competency	**Pre-Engineer** **1**	**Trainee** **2**	**Intern** **3**	**Entry-Level** **4**	**Professional** **5**	**Sub-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 manufacturability; 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	Little to no documentation; haphazard organization.	Some documentation included; minimal organization.	Many documents available and largely complete; somewhat organized.	All important documents included and ready for external review; clearly organized.	All important documents included, referenceable by third parties; highly organized.	

Notes/Comments:

Figure 4. Design assessment rubric which can be used at all levels of the curriculum.

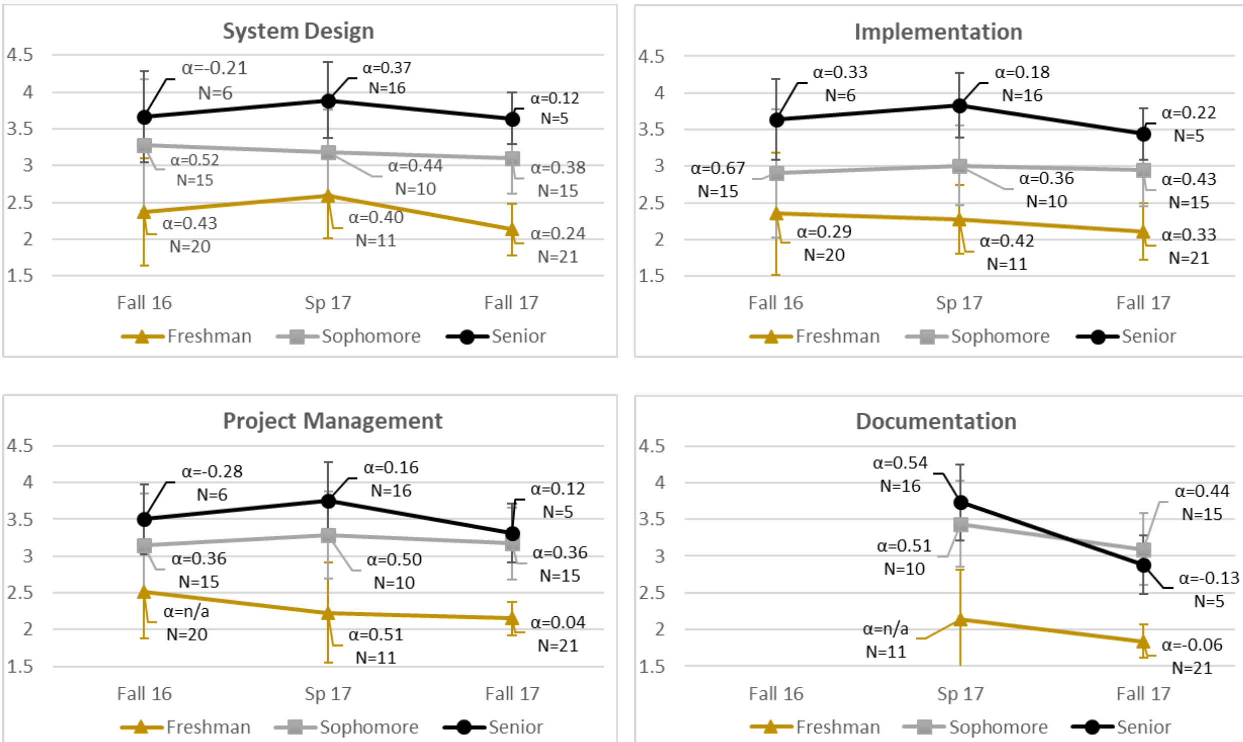

Figure 5. Average results and standard deviations for assessments of each design competency using the rubric of Figure 4. Scoring is based on: 1 – Pre-Engineer; 2 – Trainee; 3 – Intern; 4 - Entry-Level; 5 – Professional. For each data point, α represents Krippendorff's alpha (inter-rater reliability) and *N* the number of teams assessed.

The results presented in Figure 5 show a clear improvement in scores for each competency from the freshman to sophomore year, and from the sophomore to senior year. The jump in scores between the freshman and sophomore years is significant, and the differences can be seen in the complexity and sophistication of the projects. In freshman design, projects are constructed out of cardboard, popsicle sticks, and other common materials (Figure 1). Within one year, Arduinos and three-dimensionally printed parts are used to realize the projects (Figure 2), opening up broad possibilities that can be incorporated into the design. The raters all noted the marked improvement in the designs between the freshman and sophomore years, and this is borne out in the data. By the time students become seniors, they have more experience programming, using more complicated three-dimensionally printed parts and have developed machine shop skills to complete even more sophisticated projects. These observations are also reflected in the data.

Across each course, the data gives relatively constant values from semester-to-semester, and all of the variations are within the standard deviations. While the consistency in these values indicate that the rubric provides an accurate assessment of the competencies, it also shows that improvements can be made. As course improvements are implemented we expect to see the average scores increase. The data also reflects anecdotal observations by the faculty. A number of years ago, the summer-fall capstone sequence was added to the regular fall-spring sequence. This was done to alleviate pressure on limited infrastructure due to large increases in enrollment and to reduce the load in the department machine shop which was very busy during the spring semester as students completed their projects. While this goal was accomplished, an unexpected result was that students who fell behind in their course work used the summer-fall sequence to catch up. The struggling students were teamed together, and faculty observed that in general, the summer-fall projects were of lower quality than the fall-spring projects. This trend is reflected in the data, especially in the Documentation competency score. Similarly, the instructor of the fall 2017 freshman design course noted a few weeks into the semester that this class of students was not as strong as previous classes. Those lower scores are confirmed in the data.

The measure of inter-rater reliability, Krippendorff's alpha, was less conclusive. A value of $\alpha = 1$ indicated perfect reliability, and reliability decreases as α decreases. A negative α value indicates that agreement is worse than what can be expected by chance. The average values of α hovered around 0.36 for the system design and implementation competencies, and about 0.27 for the project management and documentation competencies. These low values indicate the difficulty of assessing these competencies and the wide range of opinion of what constitutes a good design. In most instances, the agreement between raters was a positive α, with plenty of room for improvement. This is evidence of the subjectiveness of what constitutes good design, and individual preferences of the rater. The results were also subject to random variation as some students on the design teams were more capable of describing design features and their teamwork processes than other students. In most cases, a significant number of reviewers assessed the design so the average value is representative of the true value of the student performance level. At the end of each semester, the raters met together to discuss their scores and differences in opinion regarding a team's performance in the competencies.

Given the wide breadth of projects, student abilities, and constraints, it is possible that simpler projects, such as those from freshman design would be interpreted as less professional or complete, simply because of the materials available. The project leads anticipated this effect and in discussions with the raters, instructed them to carefully consider the scale as absolute. For example, while a professional engineer might not normally develop a mouse-trap powered car, the design had they done so should be the result that would earn students a score of five on the rubric. In this way, the materials for the project should not have an artificial effect on the tabulated scores since the materials used are simply another constraint on the design. The mantra "Imagine yourself solving these challenges" or "I imagine myself in their shoes," was frequently heard during the rating team's meetings.

The standard deviations of the scores and Krippendorff's alpha for the freshman design course were generally similar, or in some cases higher than those for the other courses, suggesting that the reviewers agreed as well for the freshman course or better than for the others. Considering this, either the raters were uniformly biasing their scores downward because of the scrap material effect, or they were generally not biased and the scores represent the true aptitudes of the students. It is unlikely that none of the raters could objectively assess the projects, so were the scrap material effect present, a higher variability among the raters would be expected as some raters were biased and others not. Since this is not the case, we do not expect the material choices to have a considerable effect.

Conclusions

The rubric that was developed and presented can be used for design projects at any level of the curriculum, and can also be used in a wide variety of engineering disciplines. The data indicate steady improvement in design skills starting from the freshman year and continuing to capstone projects, and that team performance in a particular course is relatively constant from semester to semester. The rubric can be used to assess selected ABET Student Outcomes and help identify areas of improvement within the curriculum. The relatively low values of the measure of inter-rater reliability, Krippendorff's alpha, show the difficulty in consistently assessing the various competencies and the need to better define achievement levels within the competencies. To improve the inter-rater reliability scores, we will incorporate a few calibration cases with all of the raters.

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