Tracking Capstone Project Quality in an Engineering Curriculum Embedded with Design

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***Abstract*—This Work in Progress Innovative Practice paper describes efforts to track student design gains in an undergraduate biomedical engineering (BME) curriculum in order to measure the effect of newly integrated design projects on capstone success. Engineering curricula often culminate in team-based capstone experiences in which students face complex design problems. Student capstone teams face significant challenges during design, as solving difficult engineering problems can require a multitude of skills, access to diverse resources, and teaming ability. Assessing the quality of student design work is also non-trivial, as few shared frameworks or assessment tools exist for engineering design.**

Capstone experiences compel students to connect and apply undergraduate curricular learning in a final design experience, and design-rich curricula should better prepare students for success in capstone courses. To this end, we recently embedded team-based engineering design projects in our curriculum at the 200- and 300-levels. Consequently, we have the opportunity to track capstone design projects for students with varying amounts of curricular design experience. We developed a BME Capstone Design Rubric, adapted from several sources, and used it to score design reports submitted by student teams. Thus far, we have used the rubric to assess student design growth at the 200- and 300-levels and to collect baseline data for capstone design reports.

Our preliminary results demonstrate that students produce reports of increasing quality as they complete additional embedded design projects. Due to the growth we see in project reports from the 200- to 400-level and qualitative data that support the benefit of embedded design experiences to capstone success, we expect to be able to measure significant differences between capstone design reports produced by students with varying levels of curricular design experience. This Work in Progress begins to address the research question: Does embedding design projects throughout an undergraduate engineering curriculum affect capstone project quality?

Keywords—capstone design, engineering design assessment, embedded design, biomedical engineering

I. Introduction

A. Engineering Capstone Design and Assessment

Engineering design experiences are often culminating, hallmark events in undergraduate engineering programs. "Capstone design" experiences have taken shape to reinstitute the practical nature of design in engineering curricula, to challenge students to apply knowledge from prior coursework toward design solutions, and/or to prepare students for the design demands of industry [1], [2]. Undergraduate engineering programs have also found ways to challenge first-year student teams with engineering design projects alongside freshman courses that provide essential coding instruction. A chasm can exist between freshman and senior year concerning engineering design [1], as sophomore and junior level courses can often be geared to incorporate theoretical content with hints of application. Some programs recognize this and have begun introducing increased project work prior to the fourth year of undergraduate study [3], [4]. However, student disengagement from engineering design resulting from a curricular gap has the potential to decrease student-reported confidence in technical and communicative skills [5], aspects that can affect capstone performance.

Active learning is one inductive method documented in the literature [6] associated with increased student performance, particularly for small classes [7], and increased motivation and communication skills [8]. As a type of active learning, project-based learning throughout an undergraduate engineering curriculum may provide students a familiarity with software tools, programming languages, and technical equipment to boost student confidence as teams or individuals tackle complex engineering situations during capstone. Whether supported by industry or academia, most capstone design experiences exemplify active learning by their nature and all require design thinking, a recognized complex cognitive process [9], when developing solutions. In addition to building knowledge and technical skills through traditional coursework, a curriculum that requires students to continually practice iteration, modeling, prototyping, and verification and validation testing has the potential to prepare students capable of producing better quality capstone projects.

Outcomes-based program assessment has paralleled the shift in reinvigorating engineering curricula with design [1]. Assessing the quality of student design work can be non-trivial as an engineering design concept inventory does not present itself in the literature as universal. Nonetheless, capturing how students develop and use design thinking has surfaced in the engineering education field [10], [11]. Design ability (beginning vs. informed) [12], reflective practice [13], iterative design language and activity (expert vs. novice) [14], and non-technical constraints (e.g., sustainability contexts [15], professional skills [3]) are topics individually documented. Existing tools to assess design [12], communication [16], and teaming [17] are often disparate or cumbersome to use to their utmost potential in one setting. Thus, fairly assessing and studying varied aspects of capstone design is still an effort worth pursuing.

This work is sponsored by the National Science Foundation (NSF) under Grant 1927150.

This is the author's manuscript of the article published in final edited form as:
Higbee, S., & Miller, S. (2020). Tracking Capstone Project Quality in an Engineering Curriculum Embedded with Design. 2020 IEEE Frontiers in Education Conference (FIE), 1–5. https://doi.org/10.1109/FIE44824.2020.9273929

B. *Efforts to Assess Capstone Project Quality in a Biomedical Engineering Program*

The discipline of biomedical engineering (BME) aims to prepare students to be adept at translating healthcare-related technologies. While our current BME curriculum aims to develop engineering students that can skillfully solve complex problems, it can be difficult to transfer interdisciplinary knowledge to design appropriate engineering solutions when challenged with a complex engineering situation [18]. We envision a BME curriculum that requires students to continually practice iteration, modeling, prototyping, and verification and validation testing in the context of biomedical engineering. Continual practice entails amplifying the challenge each time students encounter design to prepare students capable of producing better quality capstone projects. As such, we intentionally scaffolded discipline-based projects [19] in second- and third-year coursework to provide continual engineering design work connected to course objectives [20], [21]. We envision that after completing smaller design projects, successful capstone teams will take an organized approach to design, integrate engineering analysis, and leverage available resources toward the development of a functional prototype.

Particularly, we are interested in the following research question: *Does embedding design projects throughout an undergraduate engineering curriculum affect capstone design project quality?* To assess capstone design, we have developed and begun implementing a modified rubric, a BME Capstone Design Rubric, to track our student design achievements. We are working to evaluate the suitability of this instrument for evaluating student design success throughout our curriculum and for making year-to-year comparisons in capstone design report quality.

II. Methods and Assessment

A. *Development of the BME Capstone Design Rubric*

As mentioned, design thinking is a recognized complex cognitive process [9]. Assessing the application of design thinking toward engineering capstone situations parallels in complexity. Our program's BME Capstone experience is a two-semester, 400-level course sequence that guides student team application of the U.S. Food and Drug Administration (FDA) Design Controls Guidance for Medical Devices (21 CFR 820.30) [22]. Despite our curriculum including facets of medical innovation and translation, our current capstone assessment includes evaluating team prototypes, oral and written team communication, and teaming. To assess these student deliverables, we have developed a three-part BME Capstone Design Rubric (Design Quality, Communication, Teaming) that integrates three resources: (1) our own internal BME capstone rubric that emphasizes effective trace matrix development, verification, and validation, (2) The Informed Design Teaching and Learning Matrix [12], and (3) the AAC&U VALUE rubrics [16] (Fig. 1). The Rubric categorizes items into Design Strategies shared by Crismond & Adams [12] and allows scoring on a scale of 1-4, with 1 representing Beginner Design Behaviors and 4 representing Informed Design Behaviors. An example section from the rubric is depicted in Fig. 2. The VALUE rubrics, developed from the Liberal Education and America's Promise (LEAP) initiative, add dimensions of sixteen identified Essential Learning Outcomes that serve as a guide to collegiate-level learning. The rubric category of Intellectual and Practical Skills was recommended to be "practiced extensively" throughout a curriculum [16]. Our work includes aspects of the following AAC&U VALUE rubrics: Information Literacy, Creative Thinking, Problem Solving, Quantitative Literacy, Oral Communication, Foundations and Skills for Lifelong Learning, Teamwork, and Integrative Learning.

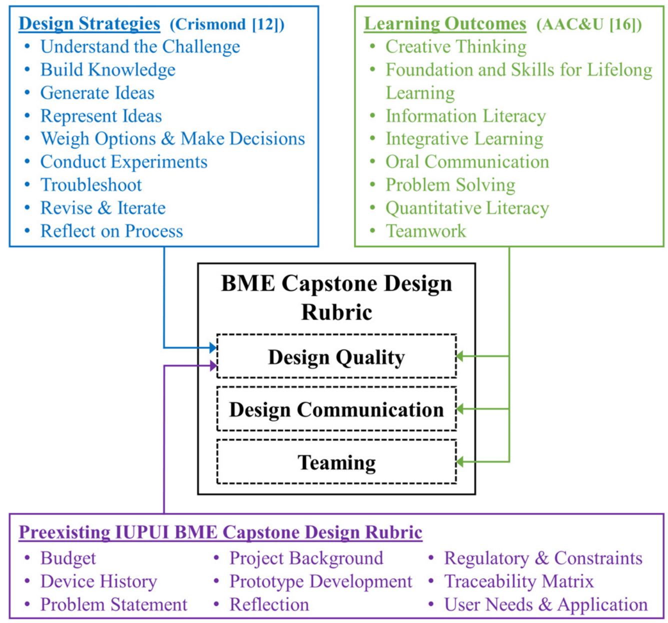

Fig. 1. Adapting multiple resources to develop a comprehensive, three-part BME Capstone Design Rubric.

B. *Assessing Design Quality in Our Curriculum*

Although we developed the rubric with our programmatic end in mind (i.e., capstone experience), we found it useful to also use truncated versions of the BME Capstone Design Rubric to assess design projects embedded earlier in the curriculum. Our efforts to scaffold design projects throughout our curriculum (see below) coincided with the development of the rubric. Hence, this Work in Progress uses the first part of the BME Capstone Design Rubric (Design Quality) to evaluate the following deliverables submitted by student teams in the 2018-19 academic year:

- *200-level*: written design reports – fall (n=11) and spring (n=12) semesters
- *300-level*: written design reports – fall (n=12) and spring (n=9) semesters
- *400-level*: written design reports (n=8) and prototypes (n=8)

Design reports at the 200- and 300-level were scored by both authors, while the final capstone reports (400-level) were scored by just one of the authors.

In an effort to improve student readiness for capstone design, we recently embedded team-based engineering design projects in our curriculum at the 200- and 300-levels [20], [21]. Our BME curriculum includes one required laboratory course per

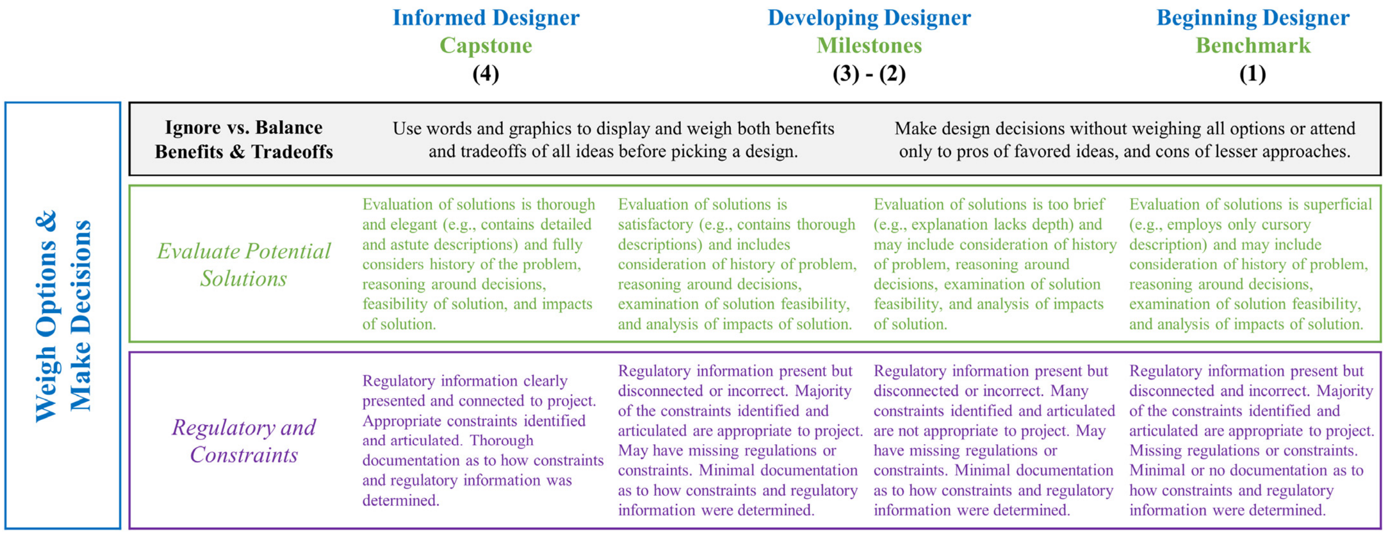

Fig. 2. Example section of the BME Capstone Design Rubric (Weigh Options & Make Decisions), implemented on a four-point scale. The rubric adapts from three sources: Crismond [12] (blue), AAC&U VALUE rubrics [16] (green), and a preexisting capstone rubric internal to IUPUI BME (purple).

semester during the second and third years, so we incorporated new assignments into these courses to achieve vertical integration of design across our curriculum. In these four projects, student teams worked to design fracture fixation plates, electromyogram-controlled motor assemblies, compact spectrophotometers, and drug dosing devices. Each project culminated in the demonstration of a prototype and the delivery of a final team-developed design report. Furthermore, we created assignments that intentionally targeted skill development in areas relevant to design, including computer-aided design, finite element analysis, programming (MATLAB, LabVIEW, and Python), prototyping, and hardware-software integration. As students worked to complete these new design experiences, we performed comprehensive assessment of student design learning, confidence, and achievement [20], [21].

C. *Building and Assessing Student Design Knowledge*

At the onset of each newly embedded design project, we delivered curricular materials that emphasized the role of the engineering design process in medical device development. This common Design Module was aimed at building student design vocabulary, differentiating BME design from other disciplines, and establishing a consistent thread throughout the curriculum. The Design Module was revised for each course to emphasize different parts of the BME design process. Specifically, we delivered a roughly 15-minute introduction to medical device design and organized a relevant and accessible discussion involving an already approved device.

We developed a design quiz, consisting of eight questions and scored out of ten points, and used it throughout our curriculum to assess student design knowledge [21]. Topics covered on the quiz included the design process, specifications, requirements, constraints, and verification and validation. The quiz was given to 200- and 300-level students before completing their first design project, after completing their first design project, and after a second design project. We also delivered the quiz at the beginning and end of the first course of our two-course capstone sequence.

III. Preliminary Results

A. *Design Report Quality*

We scored student design reports at the 200- and 300-levels over the course of one academic year using the BME Capstone Design Rubric (Design Quality). For both populations of students, our preliminary results indicate that student design report quality increased upon completion of a second embedded design project, although the increase was only statistically significant for the 300-level students. Rubric scores were assigned on a scale of 1-4, with 4 representing the highest quality work. The average and standard deviation for the cumulative rubric scoring (all categories averaged together) of team design reports is depicted in Table I.

TABLE I. Student Design Report Quality

	200-level	300-level	
First Project (Fall)	1.68 ± 0.32	2.13 ± 0.40	
Second Project (Spring)	1.86 ± 0.37	2.73 ± 0.29	*

* Statistically significant vs. First Project ($p < 0.05$, t-test)

We also scored final capstone design reports using the BME Capstone Design Rubric (Design Quality). These scores are depicted in Fig. 3 alongside scores from the first design project reports submitted by students at the 200- and 300-level. In general, the scores in each category are higher for students who have advanced further in our curriculum. Unlike Table I, which depicts the cumulative score obtained from all scores on the rubric, Fig. 3 breaks down the scores based on the individual design strategies that organize our rubric (listed down the left side of the figure). Fig. 3 also further describes the 1-4 scoring system, describing scores in terms of the type of design behavior they describe, from “Beginner” (1) to “Informed” (4).

In addition to the assessment of written design reports, we also consider the delivery of a functional prototype to be a key indicator of success for capstone design. Of the eight student teams in the capstone course assessed in this Work in Progress, seven submitted working protypes by the end of the course. We will continue to track this number as a key indicator of capstone design success. The delivery of a functional prototypes is somewhat harder to assess for the 200- and 300-level design projects that we have embedded in the curriculum, but we do plan to add this as a design success indicator in the future.

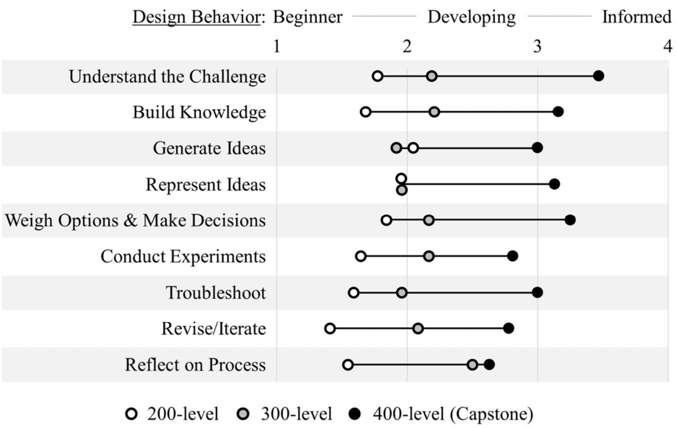

Fig. 3. BME Capstone Design Rubric scores for design reports submitted by student teamss at the 200-level, 300-level, and 400-level (capstone).

B. *Design Knowledge*

Scores from the design quiz indicate that students gain relevant knowledge as they complete design-oriented activities in our curriculum. At the 200-level, students gained biomedical engineering design knowledge after completing one embedded design project, and these gains became significant after completing a second design project. At the 300-level, students gained significant design knowledge after completing one embedded design project and maintained these gains through a second project. At the 400-level, students enrolled in the first course of our two-course capstone design sequence gained significant design knowledge (Table II).

TABLE II. STUDENT BME DESIGN KNOWLEDGE

	200-level	300-level	400-level
Pre- (August)	3.53 ± 1.72	3.92 ± 2.07	4.61 ± 2.19
Post- (December)	4.27 ± 1.85	5.83 ± 1.86 *	7.75 ± 1.38 *
Post-post (April)	4.92 ± 1.28 *	6.25 ± 1.73 *	N/A

* Statistically significant as compared to "Pre" values ($p < 0.05$, t-test)

IV. ONGOING AND FUTURE WORK

This Work in Progress represents the beginning of a longitudinal effort that we will continue for the next several years. We have embedded design projects in our 200- and 300-level lab courses, established a comprehensive assessment regimen for design learning and success, and collected baseline data for design achievement across our curriculum. Our preliminary results exhibit the benefits of our embedded design experiences and show room for improvement in our capstone design course. As we continue to assess student design achievement in capstone design, we expect to be able to measure significant differences between reports produced by students with varying levels of curricular design experience.

The work summarized in this Work in Progress focuses primarily on the application of just one part (Design Quality) of our three-part BME Capstone Design Rubric. Now that we are comfortable using this first part to assess student design reports, we feel able to begin engaging other two parts of the rubric (Communication and Teaming) for further detailed assessment of student design success. First, the Communication rubric will be an excellent tool for our faculty to use to evaluate final posters made by capstone design teams. We have years of these posters archived and can apply the rubric retroactively to gather baseline data. Second, the Teaming rubric will be valuable for instructors and students throughout our curriculum, as all design project assignments in our curriculum are assigned to student teams. While we already incorporate assessment of communication and teaming throughout our curriculum, we see an opportunity here for more robust and longitudinal assessment in these areas.

Finally, the understanding we build in the coming years about design learning and achievement in our curriculum will allow us to improve our capstone design course and overall design curriculum. As we learn of student shortcomings in areas related to design, we can adapt our instructional materials or design projects to more intentionally target areas of weakness. As we learn of weaknesses related to communication, we can leverage existing collaborations with Technical Communication faculty to further engage students with appropriate practice. As we learn of issues with student teaming, we can enact more purposeful team-building exercises in lower-level courses. Furthermore, our continued purposeful and longitudinal assessment of design in our curriculum should allow us become significant contributors to the design education literature, both within the BME field and in engineering, more broadly.

ACKNOWLEDGMENT

This material relies on work supported by a Curriculum Enhancement Grant, funded by the IUPUI Center for Teaching and Learning. This material is also based upon work supported by the National Science Foundation under Award No. 1927150. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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