A Project-Based Approach to Develop Engineering Design Process Skills Among High School Students (Work in Progress)

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Introduction

Implementing engineering curriculum in high school improves student learning and achievement in science, technology and mathematics, increases awareness of the contributions of engineers to society, and promotes student pursuits of STEM careers [1]. In a 2009 report, the Committee on K-12 Engineering Education from the National Academy of Engineering and National Research Council Center for Education emphasized the teaching of the engineering design process (EDP) as a pedagogical strategy to teach science, mathematics and technology in a meaningful context. According to the Accreditation Board for Engineering and Technology (ABET), EDP is defined as “the process of devising a system, component, or process to meet desired needs, specifications, codes, and standards within constraints such as health and safety, cost, ethics, policy, sustainability, constructability, and manufacturability. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally into solutions” [2]. EDP is considered important because it: 1) reinforces the idea that multiple solutions are possible to one problem; 2) utilizes scientific, mathematical and technical concepts from other classes; 3) can be repeated many times while solving; and 4) promotes systems analysis and modeling [1]. Additionally, while working on the design, students engage in engineering habits of the mind such as creativity, collaboration, communication, enjoying challenges and systems thinking.

In practice, educators have successfully implemented EDP in the teaching of science, mathematics, engineering and technical courses in middle and high schools [3-7]. To evaluate student understanding of the EDP, an engineering design rubric can be used as an assessment instrument to monitor the students’ understanding of the design process in both short- and long-term projects [8-10]. According to Reddy *et al.*, a rubric communicates the expectations through assigned grading criteria which are described in terms of poor to excellent quality for a given assignment [8]. In the case of the EDP rubric, each stage of the EDP process becomes the criteria for evaluation.

This study was a collaborative effort between a local high school and graduate fellows in the Experiential Practices in Education Research and Teaching in STEM (ExPERTS) program. ExPERTS is similar to the National Science Foundation’s Graduate STEM K-12 program in that it pairs Ph.D. students with high school teachers to develop STEM curriculum. Graduate students with backgrounds in biomedical engineering and mechanical engineering worked with a high school engineering teacher to optimize a recently created 3-course honors engineering series for high school students in grades 9 to 12. Last year, before fellows joined the classroom, students were assigned main projects which extended throughout the whole semester supplemented with skill-based lessons to introduce new software tools.

In the new format, ExPERTS fellows implemented several short modules spanning 2-3 class periods each. These short hands-on modules, called “Quick-Builds”, supplemented the long-term projects, allowing for more frequent assessment of the student’s understanding of the engineering design process throughout the 3-course engineering sequence. To evaluate main project and Quick-

Build submissions, we developed a rubric with categories spanning the steps in the engineering design process. Accuracy, reliability, and ease of implementation were considered when designing the rubric.

Compared to other high school engineering programs that offer sequential engineering courses, our proposed curriculum is unique in that it offers students an opportunity to learn about different engineering disciplines, teamwork, time management, project management, planning, execution, and evaluation via a project-based learning environment [12-13]. During the semester, students simultaneously work on long term and short-term projects as well as skill development assignments and thus, students practice time management, project management, planning and execution skills, which are required to successfully complete any college engineering curriculum. To expand students' global awareness, modules were motivated by real world problems, including those currently affecting underdeveloped countries, regions after natural disasters or disabled persons. In addition, because public service challenges have been shown to motivate underrepresented groups to persist in STEM [11], these real-world problems may serve to promote diversity in the classroom. We envision these high school students to becoming confident, proactive individuals armed with the engineering mindset and capable of solving modern society's greatest problems.

Methods

Curriculum Overview

This study describes an effort to teach engineering design process skills, expose high school students to the wide range of engineering sub disciplines, introduce students to new software tools, and promote a global service mindset. Two PhD students were paired with a high school teacher and tasked with optimizing and implementing curricula for a 1-year-old, 3-part Honors engineering course sequence. The study was conducted in a high school operating on a 2-semester school year. The teacher has a bachelor's degree in chemical engineering, with brief experience in industry and an extensive background in STEM education (predominantly physics and engineering). The fellows brought biomedical and mechanical engineering experience to the table. On average, fellows spent 2-3 days per month physically in the high school classrooms.

In the first installment of the sequence, the teacher introduced students to the steps of the engineering design process as described in *Engineering Design: A Project Based Introduction* [14] and conducted a series of short lessons to familiarize students with useful engineering tools, such as LabView, Microsoft Excel, and Inventor. The teacher then assigned students to groups of 3 and tasked them with a large-scale engineering design project. Students worked together for several weeks to apply the engineering design process to the large-scale project and ultimately handed in a final design report. In parallel, on days the PhD students came to the classroom, students were assigned shorter-term "Quick-Build" tasks, which were typically completed in 2-3 class periods. The Quick-Builds served as "express versions" of projects and provided instructors with formative assessment opportunities. Throughout the fall semester, students completed 2 projects and 3 Quick-Builds.

To fully master engineering design, students must work through the design process multiple times. Thus, Honors Engineering II will follow a similar format, including projects and Quick-Builds, except that projects will be motivated by multi-faceted problems of increased complexity. By the culmination of the second course, students will have applied the EDP to a minimum of 4 projects and 6 Quick-Builds, allowing them to refine their EDP skills. In Honors Engineering III, students will tackle extremely complex problems, implementing sophisticated techniques and tools such as 3D printing, electrical sensors, and microcontroller-driven control systems. This course will culminate in a capstone project requiring multiple iterations of testing and re-design.

Quick-Build Module Development

Each module was based on an engineering sub-discipline and was divided into 2 periods: 1) brainstorming and 2) building and testing. Fellows consulted with the high school teacher about the design challenge that they wished to introduce to the students. This was followed by extensive research into the topic, identifying underlying scientific principles that the students would need to solve the problem, the materials required to build prototypes, and the method of analysis needed to validate the design. To kick off the brainstorming period, the fellows introduced the challenge to the students and included an overview of background scientific principles required to start researching and brainstorming. The students followed the EDP to identify the problem statement, objectives, constraints, functions, conceptual designs and finally a detailed design. They also listed any materials not already provided by the fellows required to build their prototype.

Fellows gathered the materials identified by the students and prepared necessary testing equipment and stations before the building and testing period. Fellows looked at the full EDP report that students submit after class as well as their behavior to determine whether any adjustments can be made to the prompts or introduction to get the desired outcome. To date, the fellows have developed 3 modules: 1) Think like a Chemical Engineer - Providing Clean Water to Survivors of a Hurricane; 2) Think like a Mechanical Engineer - Designing an Insulating Box to Transfer Medical Supplies with Drones in Rural Areas; and 3) Think like an Electrical Engineer - Designing a Stylus for People with Cerebral Palsy. The fellows are currently developing additional modules to introduce other sub-disciplines in subsequent courses. Examples of final design projects are provided in Figure 1.

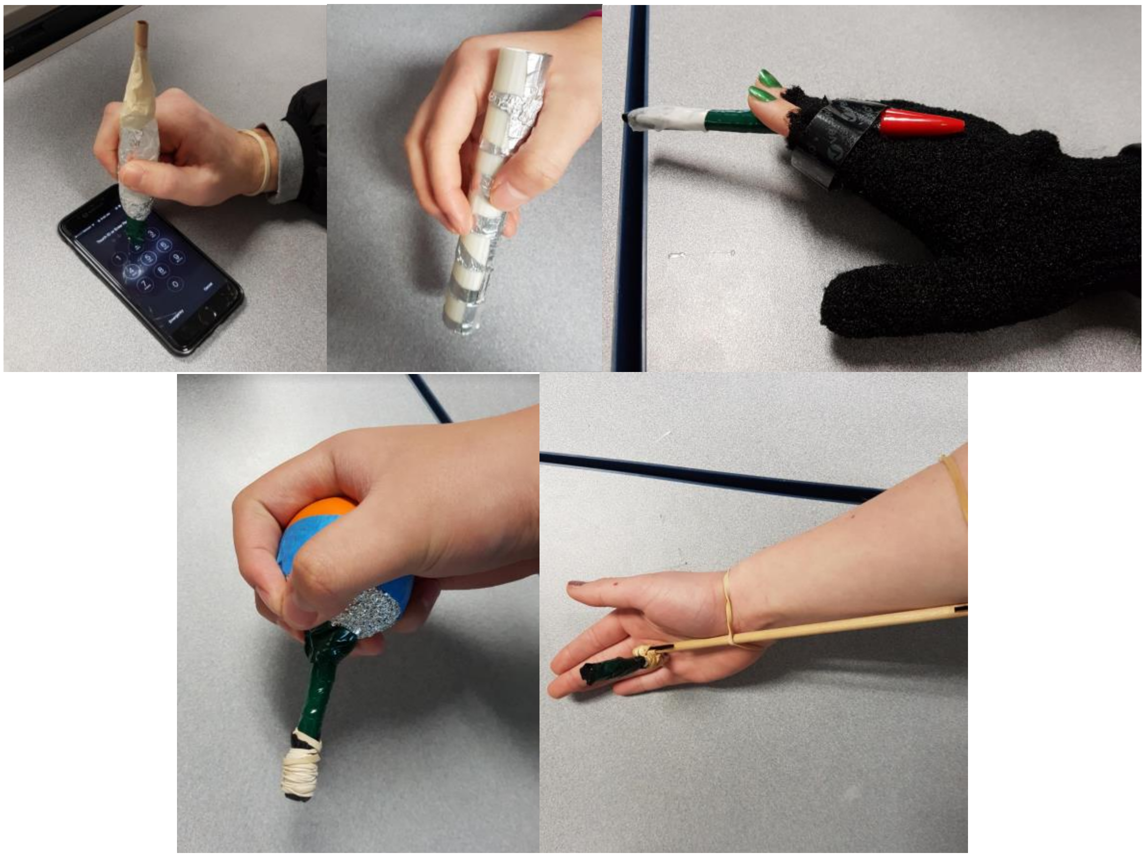

Figure 1. Styluses designed by honors engineering I students for cerebral palsy patients.

Project Rubric Development

Quantitatively assessing student learning in creative, project-based environments represents a major challenge. Design thinking is a complex process, and it can prove to be difficult to successfully evaluate [15].

Because this 3-course sequence is predominantly project-based, a rubric would be useful for evaluating engineering design process skills from student-submitted project reports. To this end, we established criteria that the ideal rubric should meet. It should be easily implemented, allowing the instructor(s) to provide timely feedback to students and be broadly applicable to students with a wide range of EDP experience since it will be used to track EDP skill development.

A search of the relevant literature revealed several rubric-based approaches to evaluating undergraduate and high school students' EDP skills [15-18, 7]. For instance, Project Lead the Way has developed a popular high school engineering curriculum that utilizes a web-based approach to student portfolio submission and evaluation. Evaluation is based on an Engineering Design Process Portfolio Scoring Rubric (EDPPRS) developed by Groves *et al.* [19]. This comprehensive rubric contains a total of 14 sub-categories spread across 5 components. The purpose of the EDPPRS is to provide a standardized method of evaluating high school engineering capstone coursework. Although this provides a useful, standardized means of comparing capstone design projects across high schools, it does not necessarily meet our need for a reliable method of tracking EDP skill development in students initially unfamiliar with the EDP, and it cannot be readily implemented to provide rapid feedback to students.

Moore *et al.* developed a digital design journal-based assessment method whereby high school students were required to maintain design logs documenting each step of the design process. These logs were ultimately evaluated with a rubric [7]. The authors pointed out potential disparities between final design success and EDP skills. For example, students can fail to engage in the EDP, yet produce successful designs, while students following the EDP can occasionally produce unsuccessful designs. By scoring students based on design logs rather than final projects, the authors sought to emphasize the process over the deliverable and eliminate this effect [7].

Davis *et al.* developed a rubric to assess engineering design skills at the undergraduate level [16]. The rubric was split into categories and sub-categories, with a Likert-type scale ranging from 1-7, with descriptors for 1,3,5, and 7. This 7-point scale likely allowed for better resolution of student performance. Importantly, the scale was designed to mirror a modified version of Bloom's Taxonomy, representing not just better performance but evidence of higher levels of thinking at higher point values. The scale was to be implemented throughout a semester, and goals were set for where students should be at the midpoint (Ex: 70% scoring a 3 or better in each category) and at the endpoint (Ex: 70% scoring 5 or higher in each category).

When developing assessment methods in line with Next Generation Science Standards (NGSS), the National Research Council recommends that instructors consider both the skills students are expected to develop as well as an understanding of how that knowledge develops [20]. In accordance with this suggestion, the fellows and teacher continuously developed the EDP rubric throughout the fall semester of 2017, giving significant consideration to how students progressed through the development of EDP skills. Following each implementation of the rubric throughout the fall semester, iterative changes were made to ensure that the rubric spanned all aspects of the design process, provided better separation among submissions, offered more effective feedback, and streamlined the grading process for the instructors. Ultimately, the fellows and teacher created a long-form rubric used to evaluate major projects, as well as a modified, short-form version used to provide rapid grading and feedback on Quick-Build submissions. Rubric samples can be seen in Figure 3.

For our rubric, we drew heavily upon the ideas of Davis *et al*., utilizing a 7-point scale in each of the 15 sections. The sections, illustrated in Figure 2, reflected the various stages of the design process, as well as administrative/project management components of engineering design. In addition to assigning each section a point value, instructors can choose from a number of general comments or input custom comments. This wide range of scores allows instructors to track student progress in each section throughout the 3-course sequence, addressing the criteria of applicability across a wide range of students. By widening the scale and broadening expectations as students progress from course to course, many stages of development can be accounted for [10]. Hence, to reflect increasing expectations, the relationship between assigned grade and rubric score will not be consistent between the first, second, and third courses. For ease of implementation, the entire rubric was converted into a google form, allowing the instructors to efficiently score student submissions and provide meaningful feedback.

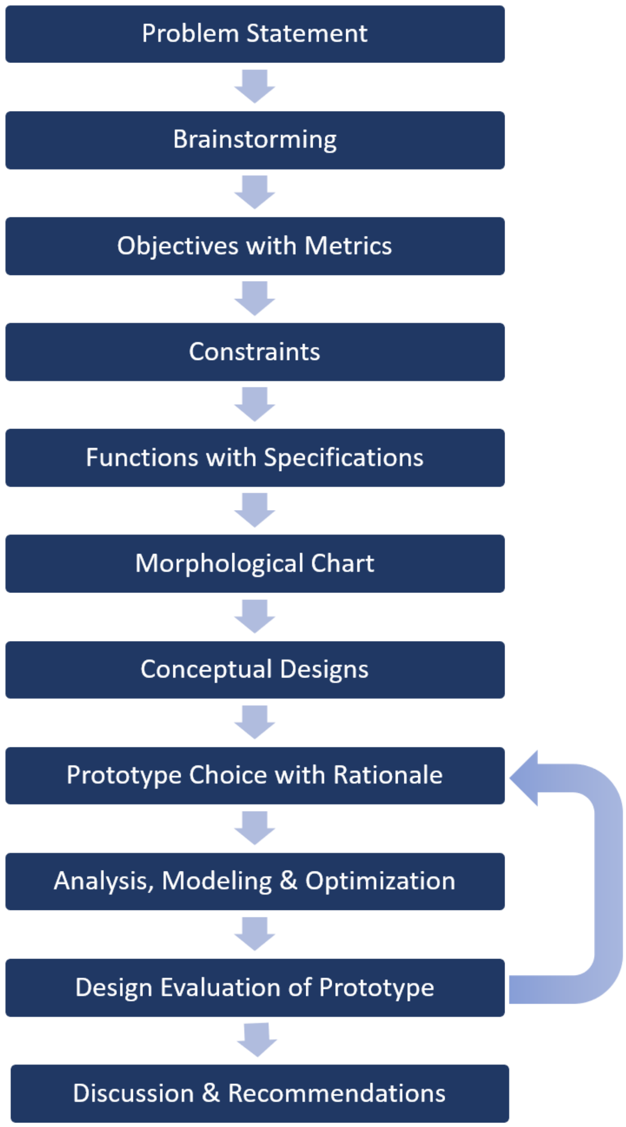

Figure 2. The stages of the engineering design process (EDP).

The Engineering Design Process

Project Evaluation Rubric

NAME: John Q. Engineer | **CLASS:** Honors Engineering I: Introduction | **PROJECT:** Mousetrap Vehicle Design

SUBMITTED: January 1, 2018 | **AVG. RATING:** 7.0 | **GRADE:** 100%

Problem Statement (Design Task)

Mastery 7	6	Intermediate 5	4	3	Novice 2	1
Clear and concise written description of the problem to be solved. The problem statement is open ended, allowing for more than one acceptable solution to the problem.		*A written description of the problem to be solved. The problem statement is open ended, allowing for more than one acceptable solution to the problem. Minimal design bias present in description.*			*A written description of the problem to be solved. Description may lack clarity or may not be concise. Statement may be biased toward a particular design.*	

COMMENTS:
- __ Design task is not clearly written.
- __ Design task includes bias.
- __ Missing problem statement.
- __ Extraneous information clouds clear description of problem
- __
- __

7

Preliminary Research & Brainstorming

Mastery 7	6	Intermediate 5	4	3	Novice 2	1
A great variety of ideas representing important concepts from many different contexts. A wide variety of sources including texts, media, experts or personal experiences. Ideas are combined in unique and clever ways to create new concepts.		*Ideas represent important concepts from several different contexts. Some variety in types of sources. Some processing of concepts to create new ideas.*			*Ideas represent basic concepts relating to the project. Little variety in types of sources. Little or no processing of ideas to create something unique.*	

COMMENTS:
- __ Does not identify important concepts relevant to the project.
- __ Lacks a variety of ideas.
- __ Lacks a variety of sources.
- __ Ideas are not processed or developed into new concepts
- __ Additional detail is needed.
- __ Some research is not relavent to project.

7

Objectives (Attributes of Design) with Metrics

Mastery 7	6	Intermediate 5	4	3	Novice 2	1
Objectives are written as clear, measurable attributes of design. Metrics are clearly defined and used to measure how well objectives are met.		*Objectives are written as measureable attributes of design. Metrics are used to measure how well these objectives are met.*			*Vague or non-measureable objectives are written. Metrics may be lacking or not an appropriate measure.*	

COMMENTS:
- __ Limited listing of objectives provided.
- __ Some objectives not written as attributes of design (adjectives).
- __ Some objectives not written in clear or concise manner.
- __ Some metrics do not adequately measure given objectives.
- __ Some metrics lack specificity.
- __ Missing some or all metrics.

7

Constraints

Mastery 7	6	Intermediate 5	4	3	Novice 2	1
All constraints (stated or implied) are identified and clearly written as specific limits or criteria the design must meet. Constraints are framed as binary choices.		*Most constraints (stated or implied) are identified and written as specific limits or criteria the design must meet.*			*Some important constraints are missing or constraints are not clearly defined.*	

Figure 3. Sections 1-4 of the engineering design rubric.

Discussion

Curriculum and EDP

At this time, we have completed the first pilot semester of Honors Engineering I and II under the new format. From our pilot implementation of the curriculum, we observed some students drawing on previous knowledge and experience, as well as developing proactive, self-learning skills. For example, during one assignment, a group of students ran into the challenge of materializing an idea using the techniques learned previously. Specifically, the students wanted to draw a 3D model of a curved fan blade, but their prior experience with drawing software was insufficient to accomplish this goal. This prompted the team to search for new methods on YouTube, adjust and implement these new methods in their build process. Some students also expressed that they enjoyed the Quick-Builds because of the quicker transition from planning to building and evaluation as compared to long-term projects.

During this trial run, we also identified several key areas to improve upon for the next iteration of Honors Engineering I, as well as Honors Engineering II. First, we changed the classroom approach to Quick-Builds. In the previous semester, students worked on the brainstorming aspect of the first class as a group and came up with the concepts together. We observed that only some students on the team were engaged in the early steps of the engineering design process. Another drawback of this approach was the observed lack of sophistication in preliminary conceptual designs. Frequently, groups developed one thoughtful conceptual design, and 2-3 other simplistic designs. Therefore, in the Spring 2018 implementation of the course, we tasked students to individually complete initial stages of EDP, including preliminary designs. Next, students were put into groups, where they chose one final design to build, test, and evaluate. The task of choosing a final design creates discussion and debate, since students feel ownership of their preliminary designs and come to class prepared to defend their ideas. From our preliminary observations, we saw an increase in the quality of the final designs in the Quick-Builds.

Rubric Design and Validation

A modified version of the project rubric is currently being developed to evaluate Quick-Builds. This modified rubric highlights the same aspects of the design process but is streamlined to allow for rapid, near real-time evaluation of Quick-Builds. Further, more specific descriptors were developed for both project and Quick-Build rubrics to allow for more accurate evaluation. Looking forward, goals can be set for each course to reflect different expectations from novice and advanced students across the multiple courses. For example, during the first course, we observed that students often attempt to rush into the building and testing stages of the EDP, yielding shallow brainstorming sessions, vaguely defined design functions and specifications, and underdeveloped rationales for prototype choice. A similar phenomenon was described by Crismond, who observed that novice and naive engineering subjects made fewer connections to the science that drives the functions of a given design and recommended that instructors implement scaffolding questions to focus the learning of the sciences in early stages of design conceptualization [21]. To address disparate expectations among novice and more advanced engineering students, it may be necessary to weight portions of the rubric related to planning stages of the EDP more heavily than the building and evaluation portions during the first course. During the second course, additional emphasis can be placed on iterative prototype analysis and optimization.

Because we struggled to find existing, validated methods of assessing EDP skills in high school students that could be easily extended to our classrooms, we developed our own rubric. Although our assessment design was heavily influenced by previously published rubrics and recommendations, validation is still necessary to ensure that the rubric is an accurate assessment tool. In our future work, we plan to assess both the validity and reliability of our rubric. According to Moskal *et al.*, an engineering assessment method is considered validated when sufficient evidence is accumulated to definitively prove that assessment outcomes accurately represent student learning [22]. It is important to note that validation is never over, but instead should be viewed as an ongoing process [23]. The authors introduce several types of evidence that can be collected for validation purposes. Among these, we are most interested in *construct-related evidence*, which Moskal *et al.* defines as evidence that an assessment accurately depicts students' underlying individual reasoning and thought processes over the end product, but other lines of evidence will also be considered. Evidence collection can take the form of rubric review by a multi-disciplinary panel of experts, as well as rubric implementation as a project assessment method in other schools' engineering classrooms.

Moskal *et al.* define reliability as a combination of test and rater reliability. Test reliability refers to consistency of a given assessment when administered in different forms or at different times to the same population, as well as internal agreement among sections/questions designed to assess the same material [24]. To assess test reliability, assessments can be designed with redundant questions. By calculating a mathematical descriptor known as Cronbach's coefficient alpha, instructors can get a quantitative measure of internal consistency, but this method may be of limited value when evaluating a rubric for reliability. For rubric-based assessment, rater reliability is a more common source of variability. Rater reliability can be further classified into inter- and intra-rater reliability. Inter-rater reliability refers to consistency across graders, while intra-rater reliability refers to consistency across time from a single grader. Inter-rater reliability can be assessed by well-established statistical methods such as the inter-rater reliability test [25-26]. In an effort to improve intra-rater reliability, the method by which projects are evaluated with the rubric can be modified to reduce grader fatigue, a major contributor to poor grading consistency across time. For example, submissions can be evaluated section-by-section instead of project-by-project, and graders can take frequent breaks to promote a consistent grading experience.

Areas for Additional Research

To determine if exposure to multiple engineering fields and global engineering challenges promoted STEM interest among the general student population as well as underrepresented groups, we plan to implement a series of pre- and post-surveys developed by a consortium of education experts at a STEM Education center at the university dedicated to promoting evidence-based teaching practices. These surveys are currently awaiting institutional approval. Generally speaking, the fellows and teacher did observe increased interest from the students about fields such as mechanical, computer, electrical and biomedical engineering. On multiple occasions, students sought out fellows after class or during free periods to discuss current engineering topics, the university engineering curriculum and 6-month internship/cooperative work experience program, and potential career paths. Fellows also had the opportunity to speak at other classes and become involved in extracurricular clubs, strengthening ties between the university and high school communities.

Finally, this study provided a chance for graduate student fellows considering careers in education to working alongside a knowledgeable and experienced teacher. Through the study, fellows developed and refined lesson preparation, classroom management, and presentation skills in a hands-on setting. Further, the fellows participated in intentional, goal-oriented engineering curriculum development and evaluation. At the same time, the teacher gained access to the intellectual resources a major engineering university can offer. A high school engineering teacher is charged with the task of preparing students to be successful at the university level. Working with university professors, staff and most specifically the graduate student fellows allows the teacher to better understand the expectations universities have for their entering freshmen engineering students. Additionally, the graduate fellows add an excitement as they bring their knowledge of cutting edge research and practice to the classroom. Perhaps most important to the teacher was having the fellows act as a sounding board for curricular development. While the teacher has an engineering background, finding collegial expertise with formal engineering training often came from consultation with former students practicing engineering or parents of students employed in the engineering field.

Conclusions

In this ongoing study, 2 PhD fellows and a high school teacher worked together to optimize curricula for a 3-course, project-based honors engineering sequence. Through course sequence, instructors aimed to familiarize students with the engineering design process, introduce new scientific tools, promote global engagement, and stimulate interest in STEM disciplines and careers. In each course, the teacher implemented a combination of long-term projects designed to give students opportunities to practice the EDP, supplemented with application-specific lessons to provide students with the tools necessary to complete successful designs. The teacher and fellows worked together to develop a rubric to evaluate long-term projects, which is currently being refined, and modified to optimize tracking of EDP skill development across the 3 courses. Fellows also introduced a series of Quick-Build modules designed to promote student engagement, provide additional EDP practice, and yield formative assessment information. A streamlined version of the project rubric is also currently being developed to evaluate Quick-Build projects and provide rapid feedback to students. A short pre- and post-survey will be implemented in the next iteration of the courses to assess student interest in STEM fields and careers. Moving forward, our goal is to continue development, testing, and validation of the rubric and survey, which will be useful for a variety of engineering education-oriented projects. Future studies to verify rubric validity and reliability will be undertaken and reported along with rubric and survey data in subsequent status updates.

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