

Developing and Assessing Authentic Problem-Solving Skills in High School Pre-Engineering Students

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Susheela Shanta earned her bachelor's degree in Civil Engineering from India, a Master of Urban Planning degree from the SUNY at Buffalo, NY and more recently, a doctoral degree in Curriculum and Instruction: I-STEM Ed from Virginia Tech. With ten years of experience in municipal planning in Philadelphia, PA, and Harrisburg, PA, and ten years in community development, planning, financing and redeveloping inner-city neighborhoods, urban main streets, creating housing for seniors and families in low-income communities, Susheela decided to pursue teaching and learning. Since 2009, she has been teaching math and engineering courses and directing the engineering program in the Governor's STEM Academy in Roanoke County, VA. Her doctoral research focused on teaching and learning real-world (authentic) problem-solving and critical thinking skills through engineering design-based learning within an integrative STEM education environment. Susheela continues her interest in researching and practicing ways of teaching and learning to better prepare students for the 21st Century challenges.

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Introduction

Critical thinking and problem solving (CT and PS) skills involved in solving authentic (real-world) problems are desirable for engineering students and practitioners. CT and PS go hand-in-hand, where achieving the end-goal or solving the problem requires decision-making about disciplinary content to be used, discarding irrelevant information, devising a strategy and evaluating progress [1]. Among other reasons for students' failure to persist in college STEM programs, researchers [2] note that students' lack the depth of knowledge, skills, and habits in problem-solving within science and mathematics topics as contributing factors.

These multidisciplinary problem-solving skills are not taught in traditional science and mathematics or in technology education (Tech-ED) classrooms in K-12 grades not assessed in standardized testing in these grades. Without educational objectives that outline CT and PS skills required in the practice of engineering and the associated classroom assessments, instruction in K-12 grades rarely focus on these skills. Assessments in traditional K-12 science and math classrooms focus on the extent of the correctness of the end result, and rarely, if ever, on the reasoning or procedures leading to the result. Furthermore, the content knowledge tested is directly related to what has been recently taught in the classroom. Therefore solvers are not required to demonstrate the metacognitive processes involved in recognizing, recalling, and selecting discipline-specific content knowledge related to the problem. Within Tech-ED classrooms, students are assessed using competencies defined in the Career and Technical Education curriculum framework which typically do not focus on assessing students in solving authentic problems.

In this paper, the design, methods, analysis of data, and results of a research study to evaluate the performance of high school pre-engineering students (completing their fourth and final year in the program) in solving an authentic engineering design-based problem outside the context of a classroom are described. Additionally, the curriculum that supports the horizontally and vertically integrated STEM educational approach will be described in light of the positive results of this research. The specific pre-engineering program design in a mid-Atlantic-region school and the methods of assessment may benefit other educators develop high school pre-engineering programs and develop instructional objectives to support students in developing authentic problem-solving skills. Such programs may help better prepare students to orient themselves for post-secondary engineering education and careers.

Background

The shortfall in the intended outcomes for students' achievement of the implied higher order thinking skills, characterized by one of the five C's of the 21st century skills – critical thinking (CT) and problem solving (PS) is a focus of STEM education reform [1]. Specifically, outside the confines of traditional classroom settings, students are not able to recognize, recall, and utilize the science and math content needed for problem-solving in authentic everyday problems

[3]. One reason for this inability to recognize, recall and utilize the needed science and math content could be that students are not learning and practicing the utilization of multidisciplinary content in the context of designing solutions to authentic problems. The Next Generation Science Standards (NGSS) have a common thread of engineering design from kindergarten to 12th grade explicitly recognizing the need for students learning science in the context of its relevance in everyday life. Furthermore, mathematical practices and modeling are also mentioned as crosscutting skills that align with the practice of science.

The realities of the practice of teaching and learning in science and mathematics in the K-12 grades is that not all students are afforded the opportunity to learn science in the context of real-world applications, i.e. engineering design. This is a combination of the lack of time to include the practice of engineering design within the available instructional time, and/or the lack of teacher knowledge in engineering design instruction and assessment. Electives, such as the technology education coursework provide an opportunity for students to experience engineering design, however, not all Tech-ED teachers are prepared with the science and math content knowledge to do justice to the pedagogical approach needed to integrate the STEM disciplinary content areas and practices [4]. In addition, assessments that are typically used in the classroom environment are aligned with the disciplinary units of instruction (a silo-ed approach) and not conducive to assessing a student's problem solving skills in an authentic or real-world context. In the traditional Tech-ED classroom, design skills are assessed through achievement of competencies specified in select Career and Technical Education (CTE) courses, where disciplinary content in science and math are not the focus of instruction even in the STEM cluster. For example in Virginia, the competencies listed in the CTE website for most of the courses start with workplace readiness skills, identified as: 1) personal qualities, leadership and people skills, 2) professional workplace skills, 3) examining aspects of industries, 4) historical overview of technology or engineering, and, 5) knowing the design process. In some of the engineering courses, managing real-world problems is explained as researching the context of a local problem and interviewing professionals on the various aspects of the problem [5]. While these competencies are only the bare minimum required, it is worth noting that there is a lack of focus on solving authentic or real-world problems. Therefore, as traditionally implemented, the Tech-ED classroom is an opportunity for students to experience project based learning, but not fully utilized as an opportunity to promote the higher order thinking needed in solving authentic problems.

In the traditional secondary educational classroom, the required core subjects of science and math are taught separately, and assessed using standards of learning assessments or other domain specific assessments. Therefore, students with high scores in their science and math assessments, and high levels of proficiency in the competencies measured by the CTE courses, do not develop the interdisciplinary literacy that is necessary for real-world problem solving in situations outside the confines of their classrooms. The lack of integration skills needed for interdisciplinary literacy hinder critical thinking when problem solvers are faced with an authentic (real-world) problem. This lack of integration and problem-solving skills is further evidenced by the poor performance of students in assessments that are not within the confines of the classroom, such as the PISA and the TIMMS.

The practice of an integrative science, technology, engineering and mathematics education (I-STEM ED) pedagogical approach is defined as:

the application of technological/engineering design based pedagogical [T/E DBL] approaches to *intentionally* teach content and practices of science and mathematics education through the content and practices of technology/engineering education. Integrative STEM Education is equally applicable at the natural intersections of learning within the continuum of content areas, educational environments, and academic levels [6].

The absence of such pedagogical practices presents a key problem for promoting student development of higher order thinking skills necessary for critical thinking and problem solving (CT and PS) in the context of the 21st century needs. Engineering in K-12 provides the opportunity to bring together the science and mathematics content and practices within the context of design-based authentic problem-solving. Researchers [7] argue that a sequenced and cohesive K-12 engineering program would be a reasonable option to encourage and prepare students to STEM career pathways and prepare them for a successful transition to postsecondary education if the proper engineering fundamentals are taught throughout the various levels of education. For this to occur in K-12, one of the obstacles to implementation, the lack of evidence to show the benefits, must be addressed.

This paper describes the design of a study that evidences the benefits of an integrative pedagogical approach used in a pre-college high-school engineering program is described along with the results of the study. Graduating students (fourth year in the program) participated in this study. Furthermore, the high school program where this study was conducted is described to show the development of the integrated curriculum with the sequencing of science, mathematics and engineering courses.

Research Design

This study examined student responses to a design-no-make challenge (DNMC) as a means for assessing their higher order thinking skills evidenced by their selection and utilization of science and math content to solve the problem described in the DNMC. The DNMC with prompts was developed using a physics-based authentic problem typical of the types of problems encountered by humanitarian workers from a mid-Atlantic university, engineering students in their work in a less-developed country. In discussions with the faculty-in-charge of the team, and physics educators in secondary education, the design challenge was first developed. Procedures for aligning the DNMC to the established curriculum standards for science and mathematics are described in the following sections. Metacognitive question prompts were developed in order to elicit responses to demonstrate key student abilities (SAs) as identified in this study. The scoring rubric for the DNMC response was adapted from the rubric developed by Docktor & Heller [8] to measure the key student abilities identified as indicators of their ability to solve authentic problems outside the classroom where the related subjects were first learned.

The research study was designed to answer the following research questions (RQ):

1. To what extent are students successful in using engineering, science and mathematics for solving an authentic design-based problem outside the confines of the classroom where the subjects were originally taught?

2. How are the key student abilities in CT and PS correlated to overall student success in solving the problem? Specifically what is the strength of the relationship of the key student abilities identified (SA) with their overall success (OSS) in solving the authentic design-based problem:

When students are tested for their problem solving abilities in the traditional classroom, the focus is on the extent of correctness of the end-result, and rarely, if ever, on the reasoning or procedures leading to the result [8], [9], [10]. Furthermore, the content knowledge tested is directly related to what has been recently taught in the classroom, which does not require the solver's demonstration of metacognitive processes involved in CT that require selecting the relevant discipline specific content knowledge.

Research into the nature and characterization of problem solving over several decades has identified a set of student abilities requisite of success for solving authentic problems outside the confines of a typical classroom [11], [12], [13], [14], [15]. Specifically, these student abilities are: 1) Useful description, both symbolic and descriptive, 2) Recognition and selection of relevant content applicable to the problem, 3) Use of the principles and practices of specific content identified to solve the problem, and 4) adherence to a devised logical strategy for solving the problem.

Three studies from a published literature review [16] had a strong influence on the method employed in the conduct of this study [8], [17], [18]. In these three studies, the common theme was assessment of student problem-solving skills in the discipline of physics or the sub-discipline of mechanics (Statics). The participants in the first study by Docktor and Heller [8], were first year science and engineering students registered for the introductory calculus based mechanics course. The second and third [17], [18] studies were situated within the context of engineering students engaged in the first course in engineering mechanics: Statics. The design of an instrument used to collect data and the relevance of the research to the current study of the three above-mentioned studies are described further.

Development of a PS rubric for this study

The rubric developed by the Docktor and Heller [8] had five main categories that relate to established definitions [11] of problem-solving and critical thinking. Validity for generalizability across different populations and contexts, including those similar to traditional text book problems as well as those that are context-rich was established. The intent of the researchers was to develop an easy to use method to assess the quality of the procedures and reasoning, in addition to the more commonly assessed correctness of end-results. The problem tasks used in the study were characterized as authentic and context-rich. Context-rich problems are short stories where the statement is not explicit about what variable is unknown, the problem may present more information than necessary or some information may be assumed as known to all, and solvers would need to make some reasonable assumptions prior to solving the problem [19]. These types of problems may have one or more of the above mentioned features in common with real-world problems and may also be referred to as authentic problems (ibid). The Docktor and Heller [8] rubric was also intended to make sure that it was applicable to any problem solving

format used by a student, and to a range of problem types and topics typically used by instructors.

The five broad categories addressed by this rubric are organizing problem information into a useful description, selecting and applying appropriate physics principles, selecting and using mathematical procedures appropriately, and the overall communication of an organized reasoning pattern. The rubric uses a likert scale from zero to five for assigning point values and was modified for use in this study.

For purposes of developing a modified rubric for our study, “useful description” was separated into two parts – the descriptive aspect of the category was separate from the graphical representation of the useful description. Several researchers [20], [21], [22] have identified both these skills as essential components of problem identification. For the purposes of this research study, separating the two skills into separate prompts served to ensure that all students responded to both those prompts rather than choosing to use words for a description or a sketch. The modified rubric was then validated and aligned (to the question prompts) with the help of four experts through a process of negotiated agreement. The final rubric is attached in Appendix A.

The Use of Metacognitive Prompts

Conceptual knowledge is not sufficient for solving authentic problems, however, recognizing the relevant content in the context of the problem, and knowing when and how to apply the relevant knowledge are essential. In the research design for this study, the purpose was clearly on the recall, recognition and utilization of specific physics concepts which are critical to being able to solve authentic problems [13]. Metacognitive strategies of identifying useful information and the approach to solving the problem are thinking processes that need to be explicitly demonstrated in order to assess solvers’ PS and CT skills. In the two previously mentioned studies [17], [18] the use of metacognitive prompts were used to elicit deeper thinking and explanations of specific PS skills. The use of sketching (also known as free body diagrams in physics and mechanics) and descriptive language to explain understanding of the problem given, both, are important to successful problem-solving and as indicators of solvers’ ability to select and apply appropriate conceptual knowledge in physics [17]. Reliable evidence of solvers’ problem-solving skills can be found in paper-and-pencil solutions when appropriate metacognitive prompts for the specific PS skills indicators are provided to solvers in order to elicit explanations of their thinking [18]. Hence, questions designed to be metacognitive prompts were developed for this research to cue students to specifically align with both ability indicators in the modified rubric and the research questions in this study.

Problem-Solving Activity

For the problem solving activity in this study, a design-based problem was chosen (see Figure 1). Design-no-make (DNM) was introduced by David Barlex in 1999 through the Young Foresight initiative [23]. At the time it was introduced, it was aimed at helping focus students’ learning, and teachers’ instruction towards the design phase instead of making the designed product. Additional research showed that this approach is valuable in helping students explore a wide range of design criteria, helps develop more understanding of the technological concepts, and

that students enjoyed the experience as well [24]. From an instructional perspective, the distractions of making the prototype were removed from the learning experience, and thus gave students the opportunity to explore various ideas and concepts in greater depth. In this research, this type of a DNM challenge was suitable and instrumental in revealing students' use CT and PS skills.

In this research, the authentic context of the design-based problem used was situated in the physics and mathematics content areas. Both physics and mathematics were components of the curriculum in the program where the sample population was situated (the program is referred to as the Academy in the following sections). Researchers [25], [26] have found that lack of literacy in these two content areas – physics and mathematics, as contributing to the challenges faced by undergraduate students in engineering programs. One of the reasons students drop out or transfer out of engineering programs is that they are inadequately prepared to apply the foundational knowledge in these subjects (ibid). Metacognitive prompts designed to reveal student thinking were included in the student handout to make sure student responses were consistent and addressed the students abilities identified. The entire text of the student handout with the question prompts is attached in Appendix B.

Figure 1. Design-No-Make Challenge Handout

<p>Description of Scenario</p> <p>A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.</p> <p>Challenge</p> <p>Your task in this challenge, is to design a suitably sized (power – measured in horsepower – hp) and priced (dollars) submersible pump to supply water at a rate of 35gal/min. Remember, in America we sell electric motors in horsepower, not watts, and $1.0 \text{ hp} = 746 \text{ W}$. For pricing, use the information provided in the attachment.</p>

Four integrative STEM education experts with background and experience in teaching and curriculum development were part of the pilot study to develop, validate and utilize the assessment rubric (see Appendix A). Scorers (after training) scored the student responses and based on those scores data was collected. The data collected from the scored DNMC question prompts were examined using descriptive statistics, the one-sample *t*-test for testing the significance of the OSS, the covariance between each of the SA with the OSS and the strength of the correlation using an adjusted correlation coefficient. For the *t*-test, the data collected from the group of students graduating from the Academy (pre-engineering program) were compared to the data from students who had the same level of coursework in physics and mathematics (and had the same grade point average in their math and science courses) without the pre-engineering coursework provided in the Academy. These statistical analyses helped obtain a snapshot of

measures for CT and PS skills of students immersed in an integrative STEM pre-engineering program with a small sample of students.

Participants in this study were a cohort of students enrolled in their senior year of the 2017 engineering program at the Academy. Eleven Academy students participated in this study, ten males and one female. Seniors in the Academy would have completed Pre-AP Algebra II, Pre-Calculus, AP Calculus AB, Engineering Explorations I and II, Engineering Methods, Physics and Chemistry during the previous years. Students' senior year coursework includes AP Calculus BC, Engineering Design, Engineering Economy, Engineering Research and Internship. The control group was a cohort of students who were not enrolled in the Academy, but had the same math and science coursework as the students in the sample group, and also the same general range of GPA. The difference between the two groups was the lack of integration achieved through the sequenced pre-engineering coursework and the instructional approach in the Academy.

Results and Discussion

Data analysis showed that students immersed in an integrative STEM education pre-engineering program performed significantly better (as assessed using their overall success score) in designing a solution to the design-no-make-challenge (DNMC) when compared with a the performance of students in a traditional classroom. Correlational analysis of data revealed that the four specific student abilities (out of five identified and used in this research study) were strongly related to students' performance in authentic problem solving.

Overall Performance of Students in the Academy

Research Question 1 (RQ1) was associated with measuring the extent to which students were successful in solving an authentic design-based problem. The overall performance of students was assessed by the overall success score (OSS) achieved (the sum of the individual scores for the five components representing five key student abilities (SAs) previously identified as the essential aspects of problem solving and critical thinking resulted in the OSS). Students from the Academy achieved an average score of 16.45 points (out of 25 possible points) which represents a 65.8% score. The *t*-test results (Table 1) showed statistical significance to the higher mean overall performance score of students in the Academy (higher mean by 4.455; 95% CI, 1.78 to 7.13) when compared with a hypothesized mean which represented a 48% score.

Table 1: *Results from the Two-tailed One Sample t-test for OSS*

Test Value (hypothesized mean) = 12 (Bootstrap = 1000 samples)						
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Overall Success Score	3.708	10	.004*	4.455	1.78	7.13

* $p < .05$

The conclusion drawn from this result is that the students in the Academy performed better than students in the traditional classroom (the hypothesized mean was obtained from the data collected from the students in a traditional classroom not within the Academy). The calculated effect size (Cohen's d) of 0.8 indicated a large effect, which implies that the strength of significance of the t -test is large enough to be practically significant.

Correlations between Overall Performance and Student Abilities

Research Question 2 was aimed at investigating the strength of the relationships between students' overall performance (OSS) and each of the five key student abilities (SAs) in designing a written solution to an authentic problem as posed in the DNMC. For a small sample size it is recommended that the adjusted correlation be calculated and used for interpretations of the strength of correlation between the two variables. The correlational statistic value greater than 0.5 indicates a strong correlation [26]. Table 2 summarizes the correlational strengths between the overall performance (OSS) and the five student abilities (SAs).

Table 2: PPM Correlations between OSS and the five SAs

Student Ability (SA)	PPM Statistic (r)	Significance level	Adjusted correlation statistic (r_{adj})
<i>Useful Description</i>	0.121	0.723	N/A
<i>Sketch</i>	0.635	0.036*	0.581
<i>Specific Application of Physics</i>	0.916	0.000**	0.821
<i>Application of Mathematics</i>	0.953	0.000**	0.898
<i>Logical Progression</i>	0.918	0.000**	0.826

Note: *Significance at $p < .05$; **Significance at $p < .01$

Sketch reflects a solver's ability to represent the information in the problem in a symbolic and graphical manner stating qualitative expectations and quantitative known values described in the problem. Student abilities associated with *Specific Application of Physics* and *Application of Mathematics*, reflect a solver's ability to select relevant physics and mathematical content or principles and applying them to the specific context of the problem. *Logical Progression* reflects a solver's ability to communicate reasoning and laying out a clear and focused strategy in achieving the goal. These four SAs were strongly correlated to their overall performance (OSS) in designing a solution to the DNMC (presented in the adjusted correlation statistic column in Table 2).

Contributions of Specific SAs towards the Variability in Students' Overall Performance

The coefficient of determination is calculated as the square of the correlation coefficient. This statistic represents the percent of the data points that are closest to the line of best fit in the model, and is a measure of how well the regression line represents the data. A higher coefficient is an indicator of a better goodness of fit and can provide a good indication of prediction of the variations of one variable with respect to the other in the regression model [27]. By no means is this an indication of causality, but it best represents a measure of variability in OSS that can be predicted by the variability of those SA's. The calculated coefficient of determination for each of the five correlational analysis is summarized in Table 3.

Table 3: *Pearson's Correlations and Calculated Coefficient of Determination for the SAs*

Student Abilities	PPM Correlation (r)	Coefficient of Determination (r^2)
Useful Description	0.121 ($p > .05$)*	0.015 (1.5%)
Sketch	0.635 ($p < .05$)	0.403 (40.3%)
Specific Application of Physics	0.916 ($p < .01$)	0.839 (83.9%)
Application of Mathematics	0.953 ($p < .01$)	0.908 (90.8%)
Logical Progression	0.918 ($p < .01$)	0.843 (84.3%)

*Correlation is not statistically significant at the .05 level

The most significant contributions of students' abilities attributable to their overall success in designing a solution to the DNMC (from the regression model) come from their ability to select and utilize relevant content and practices in science (84%) and mathematics (91%), and from their ability to logically progress through the process (84%) to design a solution to an authentic T/E design problem. These SA's were found to be strongly represented by the correlational model in this dataset (Table 3). These findings indicate that there is benefit to the type of pre-engineering program that is designed to use an integrative STEM education approach. Specific student abilities associated with the CT and PS skills were indicated as highly correlated to students' success in solving authentic problems in the situated disciplines.

Implications

The results presented in the previous section have direct implications for instruction in K-12 technology and engineering education, student learning and assessment, and engineering program design in secondary schools. One of the primary motivations for this research was the need for STEM literate graduates adequately prepared for the skills needed to tackle the challenges in the 21st Century. US students lag behind in science and mathematics literacy and many studies have linked the lack of preparation of students to use high school science and mathematics knowledge to high rates of attrition in STEM programs at the undergraduate level [28], [29], [24], [10]. In order to develop a robust pipeline of students going into higher education in the STEM fields, it is necessary to develop better practices for teaching and learning in the secondary schools.

The mean overall performance of students in the academy was shown to be statistically significant. The correlational analysis between students' abilities and overall performance revealed that specific skills involving selecting and utilizing science and mathematics content and practices were statistically significantly related to the overall performance in designing a solution to the DNMC provided. The implications from these results are that when designing a solution to an authentic problem, students' abilities to recognize, recall, select and utilize science and mathematics content and practices are significant to their success. This finding may have broader implications for instruction, classroom assessment and student learning. However, further research will be needed to explore those avenues for improving student outcomes.

The rubric developed in this study has the potential to be used as an assessment tool in the technology education classroom, and therefore this study has implications for demonstrating student growth. Specific student abilities could be targeted or the overall success score can be a benchmark for demonstration of student growth using pre- and post-assessments. While teachers in core disciplines use statewide testing for setting their students' performance goals, some Tech-ED teachers use industry credentialing for specific technology for setting up students' performance goals. Teachers in those disciplines or subjects that do not have industry credentialing (such as engineering in high school) can use the modified rubric developed in this study to set up performance goals and indicators.

The following section describes the curriculum and coursework followed in the Academy and the integration of science, math and engineering in the vertically (progression of increasing complexity of engineering coursework) and horizontally integrated (grade-level curricula for engineering, science, math and communication) four year program.

Pre-engineering Program Design

The pre-engineering program at the Academy is designed to be a four year journey into the fields of engineering, architecture, technology and other related fields that is in addition to the high school courses that all students take. Students attend the Academy (a separate physical campus) by starting their classes earlier during the morning hours. Students return to their base schools after their morning at the Academy. During the three-hour timeframe that students are at the Academy, students take courses in the content and practice of engineering fundamentals, various blended fields of engineering, with an instructional focus on the practical design based problem solving approach. These courses are aligned with science and math courses that are grade appropriate. With access to a precision machine shop and 3-D prototyping technology, the students also gain valuable hands-on experiences not found in the traditional classroom.

Engineering and math courses (only) are offered during the first two years of study, and then Chemistry and Physics are added in during the junior year, increasing the number of courses to four during the junior year. Engineering fundamentals, mechanics, electrical theory as well as mechatronics, programming and mechanical/computer aided drafting are included during the first two years. The instructional approach is hands-on but with well-defined projects and parameters. Students are led through the design process with every unit (usually lasting a quarter) where the units are intentionally designed to create deeper connections to and

complement the science and mathematics content that are part of the students' grade-level curriculum. All project experiences are designed to include communication of the experience and results to a wider audience through posters, reports and oral presentations.

During the junior year, students take an engineering methods course, which is comparable to many universities' freshman engineering courses. Advanced Chemistry, Physics and Calculus-1 are also part of the required coursework offered in the Academy. Offering dual-enrollment for the engineering courses at this level encourages students to engage in college-level learning and expectations, and specifically see the rewards in terms of college credits.

During the senior year, in addition to Calculus-2, students take engineering design, engineering economy (which is dual-enrolled), engineering research and internship. Engineering design is a capstone experience where students are required to propose and complete a design project of their interest. Students are encouraged to pick a design problem that is relevant to their interest and benefits the community they live in. This approach is intentionally used to direct students' focus into innovating in a community conscious and reflective manner so that students' intrinsic motivation drives their efforts. Students are expected to engage in the engineering design process using everything they have learned up till this point and their assessments are tied in to the expectations of fidelity to the design process and completion. The instructor is a facilitator in this course and students are encouraged to use all resources available in the program, including the machine shop and other technologies as well as other teachers and professionals. The completed projects are showcased by students at a poster and demonstration session organized by the instructor.

The engineering research course is designed to help students further develop their research and communication skills (interviewing, oral presentations for diverse audiences and writing technical papers). This work leads into the internship course which provides each student with exposure and experience in an engineering or science work environment at a local firm. This experience culminates in a special project report or paper with a topic usually chosen with the mentor, and related to their work during the internship. This paper or report is presented in a formal presentation to a panel of professionals as a final assessment for the course.

Engineering economy is a dual-enrolled course which uses the same curriculum as the college course where the credits are awarded. The instructional materials, assessments and expectations are the same as the college course. This course is strongly linked to the engineering research curriculum where students experience entrepreneurship by proposing to fund an innovation as a startup business. They are required to develop a business plan including financial operating and long term projections of returns that involve an understanding of the concept of time-value of money.

Throughout the four-year curriculum plan emphasis is placed on problem solving skills, critical thinking skills, and both, analytical and open-ended design skills. Authentic problem-solving is intertwined with communication methods (technical reports, design briefs, posters and PowerPoint presentations), including data-driven analysis of the value proposition of their innovations or projects prior to design [27]. Teamwork is also an important element of the

program, with the students learning through practice various aspects of teamwork during design and implementation.

Instructors in the pre-engineering program are highly qualified to teach the courses, with two engineers with graduate degrees (one masters and one doctoral), one science teacher with graduate level training (masters), one mathematician (with a master's degree and certified in Advanced Placement courses), and one shop instructor with extensive qualifications and experience in machining, manufacturing and mechatronics. Instructors routinely plan their lessons with a cross-curricular collaborative approach in designing the units of instruction. All faculty members have a deep understanding of each other's curricula and focus, and therefore are able to utilize an integrative STEM pedagogical approach in their instructional design. In addition, it is also important to note that the program is housed in a building with all classrooms having collaborative spaces and students have open access to all the classrooms and teachers throughout their time in the Academy thus encouraging a culture of integration and collaboration.

Further research needs to be conducted to follow up with developing better classroom-ready instruments for classroom assessments in authentic problem solving challenges. In addition, a larger study that includes follow up of students' performance post-graduation (from high school) to seek an understanding of the impact on their pursuit of STEM education (specially engineering) and careers would be recommended.

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Appendix A – Final Modified Scoring Rubric

	5	4	3	2	1	0
USEFUL DESCRIPTION (Specific to a given problem)	The description provides appropriate details, and is complete.	The description provides appropriate details but contains 1 omission or error.	The description provides appropriate details but contain 2 omissions or errors.	The description provides details but contains 3 omissions or errors.	There is a description contains more than 3 omissions or errors, or is incorrect.	The response does not include a description.
SKETCH (contains dimensioning, legible and correct units of measurement, labels for specific features or known items.)	The sketch provides appropriate details and is complete.	The sketch provides details but contains 1 omission or error.	The sketch provides details but contains 2 omissions or errors.	The sketch provides details but contains 3 omissions or errors.	There is a sketch but contains more than 3 omissions or errors or is incorrect.	The response does not include a sketch.
SPECIFIC APPLICATION OF PHYSICS	The specific application of physics is appropriate and complete.	The specific application of physics 1 omission or error.	The specific application of physics contains 2 omissions or errors.	The specific application of physics contains 3 omissions or errors.	The specific application of physics is inappropriate or has more than 3 omissions or errors, or is incorrect.	The specific application of physics is missing.
APPLICATION OF MATHEMATICS	The mathematical procedures are appropriate for solving this problem and complete.	The mathematical procedures are appropriate for solving this problem with 1 omission or error.	The mathematical procedures are appropriate for solving this problem with a 2 omissions or errors.	The mathematical procedures are appropriate for solving this problem with 3 omissions or errors.	The mathematical procedures are inappropriate for solving this problem or has more than 3 omissions or errors, or is incorrect	The mathematical procedures are entirely missing.
LOGICAL PROGRESSION	The problem solution is clear, focused, logically connected and complete.	The solution is clear and focused with 1 logical inconsistency and complete.	Parts of the solution are unclear, unfocused, and has 2 logical inconsistencies.	Most of the solution parts are unclear, unfocused, and 3 logical inconsistencies.	The problem solution is unclear, unfocused, and inconsistent.	There is no evidence of logical progression.

Appendix B – DNMC Handout

Description of Scenario

A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.

Challenge

Your task in this challenge, is to design a suitably sized (power – measured in horsepower – hp) and priced (dollars) submersible pump to supply water at a rate of 35gal/min. Remember, in America we sell electric motors in horsepower, not watts, and $1.0 \text{ hp} = 746 \text{ W}$. For pricing, use the information provided in the attachment.

Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.

Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?



\$48.30 /each

ECO FLO 1/4 HP
Submersible Utility
Pump

Model SUP55



\$98.12 /each

ECO FLO 1/3 HP
Submersible Utility
Pump

Model SUP56

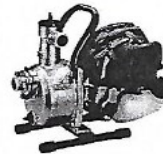


Was ~~\$79.03~~
\$71.13 /each

Save \$7.90 (10%)

Superior Pump 1/2 HP
Submersible
Thermoplastic Utility
Pump

Model 91570



\$439.82 /each

Koshin 1 in. 1 HP
Centrifugal Pump with
Honda Engine

Model SEH-25L