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Board 246: Designing a Curriculum to Broaden Middle School Students' Ideas and Interest in Engineering

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Designing a Curriculum to Broaden Middle School Students' Ideas about and Interest in Engineering

Introduction

Effectively addressing complex societal problems of the 21st century such as climate change and resource scarcity will require an extensive cadre of engineers and other STEM professionals. However, despite the increasing need, there has been declining interest in pursuing STEM-related careers [1]. Given the rapid growth of available engineering jobs and the shortage of talent or motivation to fill these roles [2], it is imperative to develop new approaches for increasing the interest of a broader range of students to fill these roles.

One way to enhance participation in engineering is to expand the participation of historically underrepresented populations (e.g., women, Black, Latinx, and Indigenous groups). Another group that is often neglected is rural students. Although over six million students are enrolled in schools serving rural communities, these students are a relatively unexplored group in relation to engineering participation [3], [4]. Performance in STEM disciplines tends to be lower for rural students than those from urban communities and rural students are less likely to pursue post-secondary study in STEM-related fields [5]. For students enrolled in rural schools across the U.S., barriers to accessing high-quality engineering education include lack of resources, lack of attention from reformers, researchers, and legislation , which in turn lead to lack of awareness of diverse engineering careers. Additionally, rural youth, especially those who are high-achieving, are uniquely attached to their communities and may be discouraged from pursuing engineering careers because of the misconception that they would have to leave their communities in order to do so [6], [7]. These unique challenges discourage otherwise capable students from pursuing high-level courses and careers in engineering. Thus, it is imperative to provide rural students with the opportunity to engage in personally relevant engineering learning experiences.

One reason that students may not express interest in engineering and engineering careers is that many misperceive what types of activities engineering entails. Traditional K–12 approaches to engineering often emphasize designing and constructing prototypes to test and optimize using a trial-and-error approach [8]. Although this approach may appeal to some students, it may alienate others who then view engineering simply as "building things." Indeed, studies have found that students often perceive that engineers primarily engage in designing, constructing, and repairing buildings and machines [9], [10].

Designing engineering experiences that broaden students' ideas about engineering, may increase their interest and ultimately help diversify the students entering the engineering pipeline. Focusing instruction on a different type of problem–an environmental problem that affects their community–can make engineering more meaningful to rural students while broadening their ideas about the types of problems engineers solve. Illustrating the value of STEM in their lives and communities, may increase students' interest [11].

In this study, we examine to what extent an engineering curriculum focused on the socio-ecological problem of managing nutrient pollution in their watershed, can affect students' ideas about and interest in engineering. Using data collected from 145 students in a rural middle school we explore the following research questions:

1. To what extent did students' interest in science and engineering change after completing the curriculum and to what extent did these changes vary by students' gender?
2. To what extent did students' understanding of engineering activities change after completing the curriculum and to what extent did these changes vary by students' gender?

Background

While there has been some progress toward balancing the gender representation in engineering, most fields are still male dominated [12], [13]. Recent scores on science and math aptitude tests show that the ability of boys and girls is essentially equal [14]. Thus, it is choice, not ability that leads women away from STEM career paths [15], [16]. Stereotypes about STEM and who does it can lead students to believe that following such a career path does not fit with personal goals and interests, leading to a choice other than STEM fields [14]. Just being shown a classroom environment that displayed robots, circuits and other technologies led girls to be less interested in enrolling in a STEM-related class as compared to a classroom decorated with objects not stereotypically associated with technology or "geeky" pursuits (e.g., plants) [17]. Thus, creating a learning environment that increases students' sense of belonging can increase their interest in STEM fields [11].

Focusing on a complex environmental problem that can affect rural communities can help address many of these issues. It provides students with an alternative experience that runs counter to stereotypes about engineering being mechanical in nature by putting a focus on helping people and the community. Previous research has found that when girls are exposed to non-stereotypical examples of STEM fields they are more likely to express interest than when exposed to stereotypical examples [11], [18], [19]. Indeed, some studies have found that environmental engineering activities in particular can be particularly effective in changing girls' perceptions of engineering [20], [21]. Thus, focusing on a socio-ecological problem should broaden students' ideas of engineering and the problems engineers solve, and ultimately increase girls' interest in engineering.

The complexity of an environmental problem requires a different approach to designing solutions. While building prototypes of some aspects of solutions may be possible, using models and simulations to understand and design solutions becomes increasingly important for complex systems. K–12 engineering instruction often puts the focus primarily on the designing, building, testing, and optimizing solutions portion of engineering design [8], not providing students with a full understanding of what it means to engage in engineering design. In addition, this portion of the process is often represented as the only iterative part of engineering design, when it can occur at any point, as illustrated in the representation of engineering design in Figure 1. In this representation, any point can lead to any other, depending on the feedback.

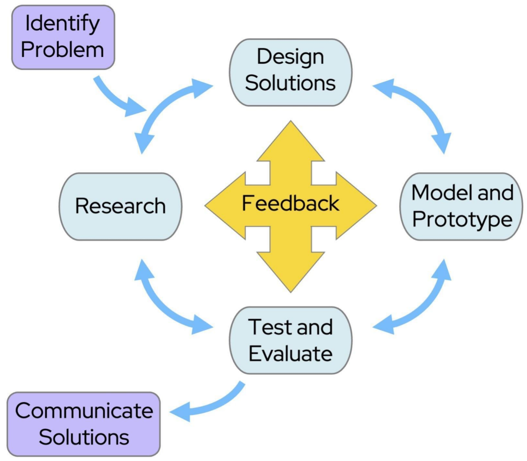

Figure 1. Engineering design from SCoPE, which is a slightly modified version of that represented in the Massachusetts Curriculum Framework for Science and Technology/Engineering [22].

To this end, we developed and piloted *Solving Community Problems with Engineering* (SCoPE), an engineering curriculum that engages middle school students in a three-week capstone project where they focus on developing strategies to manage nutrient pollution in their local watershed. Nutrient pollution is a widespread environmental problem in the U.S.—45% of lakes [23] and about 50% rivers and streams have excess nutrient levels [24]. Fertilizer, waste water, pet and food waste and septic tanks are significant sources of nutrients. Engineers try to address these problems by designing solutions that address the source and mitigate the effects of these nutrients on local watersheds. The curriculum aims to broaden students' ideas of engineering and the types of problems engineers solve by focusing on a common environmental issue–nutrient pollution and illustrate that engineers can work to solve real world problems relevant to communities. In the next sections, we describe the design principles and design and development of the curriculum.

Design Principles

The SCoPE curriculum incorporates several design features to ensure students deepened their understanding of engineering design and the problems engineers may address.

Coherence. Curriculum coherence is critical for building students' abilities to engage in three-dimensional instruction to explain phenomena and solve problems [25]. One way to build coherent curriculum materials is through Project-Based Learning (PBL), which focuses instruction on a problem to solve or question to investigate. PBL is predicated upon a student-centered learning environment and has been shown to increase science and math learning, even among students from historically underrepresented groups [26]. SCoPE is a PBL unit that requires students to apply ideas learned in science class to solve a problem, so it supports coherence within and across units in the curriculum.

Place-Based Instruction. Relating instruction to students' locale, or place-based pedagogy, can make classroom learning more relevant to students [27], [28]. Moreover, by applying school learning to relevant, local issues, students are challenged to ask critical questions, think through alternative solutions, and acquire appropriate knowledge, skills, and training to solve problems in ways that are meaningful to them [29]. National datasets and visualization tools allow students to collect relevant data to define the local nutrient pollution.

Social Interactions & Learning. Social interactions are an important part of the sense-making process for students [30]. It is also important to incorporate a variety of strategies for communicating and making meaning [31]. Throughout SCoPE, students work in teams to define, develop, and optimize solutions to their local nutrient pollution problem.

Design and Development

Design model. We used the Construct-Centered Design (CCD) process to provide a principled approach to guide the design research and development efforts [32]. CCD begins by defining the construct (what we want to measure and/or students to learn by explicitly describing what is required to meet them in a process called unpacking. We also identified potential difficulties and alternative ideas that students may have. Next, we specified (a) claims that describe the knowledge and other attributes to be learned and assessed, and (b) the evidence that describes the behaviors or performances needed to support the claim. Learning experiences and assessment tasks are then designed to help learners develop the knowledge to provide the desired evidence or elicit those behaviors, respectively. The products were subjected to internal and external (content and pedagogical experts) and the curriculum piloted in the classroom.

Through the development process, we worked closely with a middle school STEM teacher. She helped conceptualize the curriculum, ensuring the problem would connect and build upon the middle school science curriculum. She was consulted throughout the drafting process to help ensure the activities would be engaging and meaningful to students.

Curriculum Overview. The SCoPE engineering curriculum engages middle school students in a three-week capstone project focusing on managing nutrient pollution in their local watershed. Students engage with the problem through local news articles and images of algae covered lakes which drives the investigation into the detrimental processes caused by excess nutrients from sources such as fertilizer and wastewater entering bodies of water. Students apply ideas learned previously in science class to help define the problem, which deepens their understanding of the science content and emphasizes the role of science in solving problems with engineering. They research the sources of nutrient pollution and potential strategies for managing it. Simulations play an important role in investigating key variables and optimizing the types of strategies most effective for managing nutrient pollution. All of these activities inform students' final recommendations for improving nutrient levels in their watershed.

Students work in teams of four to develop their recommendations. The SCoPE curriculum focuses on four distinct land covers/uses, each with its own sources of nutrient pollution and strategies for managing it: (1) Farmland; (2) Recreation Area, which includes managed open space such as parks, golf courses, and athletic fields; (3) Rural Community, where where there is space between houses and septic tanks are common; and (4) Town where a significant portion of the land is covered with paved and other impervious surfaces that prevent water from entering the soil. Each member of the team becomes an expert on one type of land use, investigating the sources of nutrients and the most effective strategies for managing them. Teams then work together to optimize their plans for the entire watershed, encompassing all types of land uses, negotiating tradeoffs, as needed, to optimize management strategies for overall effectiveness.

Methods

We piloted the curriculum in classrooms from May–June 2022. The pilot teachers were the teacher who had advised on the curriculum and her co-teacher who taught the same subject and grade within the school. The school where the curriculum was piloted is located in a rural region of the country that is directly affected by nutrient pollution. The school where the curriculum was piloted was 76% White, 9% Hispanic, 7% African American, and 2% Asian and 40% of students were classified as low-income. Student achievement was near the state average for science and math.

For this study, we collected data through a pre- and post-curriculum survey. Consent forms were sent electronically and by paper (on-request) to all the students in both teachers' classes. We received consent forms from 145 students (91% consent rate) out of 160 students. Students who did not return consent forms participated in instruction, but their data was not used within the research. Students in the research sample identified as 51% female, 48% male, and 1% non-binary.

To assess students' attitudes toward science and engineering we included an adapted version of the Middle/High Student Attitudes Toward Science, Technology, Engineering and Math (S-STEM) survey [33]. The scale measures students' attitudes toward their own proficiency in STEM subjects (e.g., "I know I can do well in science"), the value of STEM toward future endeavors (e.g., "Knowing about science will allow me to invent useful things"), and interest in STE|M careers (e.g., "I believe I can be successful in a career in engineering"). The measures had sufficient levels of reliability on the pre ($\alpha = 0.87$) and post surveys ($\alpha = 0.87$) .

Additionally, to measure students' perceptions of engineers and engineering we adapted items from the "What is Engineering?" survey instrument [9]. The scale is designed to measure students' perceptions of what engineering entails. The survey asks about activities that are misperceptions about engineering (e.g., "repairing engines") as well as activities that engineers do frequently but that may not be familiar to students (e.g., "using models"). Students could check whether they thought the activity was something engineering entails or was not something engineering entails. We added a few items to the scale that specifically referred to activities in the curriculum (e.g., "Protect the environment, "Identify problems in the community to solve").

For all research questions, we used independent samples t-test to test for mean differences between girls and boys and paired t-tests to test for mean differences between the pre- and post-survey. To provide context for the magnitude of the mean differences, Cohen's *d* effect sizes were calculated for the S-STEM items. For binary measures, such as students' perceptions of engineering activities, we used the absolute change in percentage to indicate the magnitude of change.

Results

Attitudes Toward Science and Engineering (S-STEM). After completing the curriculum, students significantly increased on the MS/HS S-STEM measure ($d = 0.16$, $p < 0.05$). However, when we disaggregated by gender, we observed meaningful differences between boys and girls in their changes in attitudes. Boys started with higher scores than girls on the S-STEM on the pre-survey ($d = 0.31$, $p < 0.1$). However, girls had significant increases in S-STEM between the pre- and post-survey ($d = 0.29$, $p < 0.01$) while boys did not meaningfully change ($d = -0.03$, $p > 0.1$). Because of these differences in growth, the differences between boys and girls on the post-survey S-STEM became negligible ($d = 0.08$, $p > 0.1$). These findings suggest that the curriculum may have had a disproportionate effect on girls' attitudes toward science and engineering, such that the gender gap that existed between boys and girls was nearly eliminated.

Ideas about Engineer Activities On the whole, students expanded their understanding about the types of activities that an engineer might do in their work after completing the curriculum. Students were 32% more likely to report that engineers can "protect the environment" and 17% more report to think that they can "identify problems in the community to solve. Students were significantly more likely to report than engineers "find out what causes a problem," "generate different ideas," "read about new innovations," "use models to simulate how a system changes," "test ideas," "use science," "design solutions," "solve problems," and "use math." There were no significant changes for "developing new technologies," "repair engines," and "work with machines." The results are summarized in Table 1.

Table 1: Overall Differences in Engineering Activities Ideas

Item	Pre	Post	Abs Diff	sig
Find out what causes a problem	84%	95%	12%	0.002
Design solution	87%	96%	9%	0.002
Develop new technologies	89%	94%	5%	0.109
Generate different ideas	85%	97%	12%	0.000
Identify problems in the community to solve	75%	92%	17%	0.000
Protect the environment	60%	92%	32%	0.000
Read about new inventions	75%	86%	12%	0.005
Repair engines	72%	75%	3%	0.519
Solve problems	87%	96%	9%	0.007
Test ideas	84%	94%	10%	0.004
Use math	88%	94%	6%	0.059
Use models to simulate how a system changes	82%	93%	12%	0.002
Use science	89%	99%	10%	0.001
Work with machines	89%	92%	3%	0.348

There were both similarities and differences between girls and boys in how their understanding of engineering changed after completing the curriculum. Both boys and girls had significant changes in reporting that engineers “protect the environment” “identify problems in the community to solve”, “generate different ideas”, and “find out what causes a problem.” However, girls had larger increases in activities such as “design solution,” “test ideas,” “use models to simulate how a system changes,” and “use science”. See Table 2 for a summary of the results. The differences in shifts between boys and girls suggest that participating in the program may have a larger effect on girls’ conception of engineering than it did for boys.

Discussion
Participating in SCoPE appears to have expanded students’ understanding of engineering design. Students were more likely to include ideas related to working to understand problems and researching potential solutions. In addition, they were more likely to recognize that using simulations to model a system can be part of developing solutions to an engineering problem. Students were more also likely to include protecting the environment to describe the activities of engineers. This suggests that students’ ideas of the types of problems engineers address have been broadened.

Table 2: Overall Differences in Engineering Activities Ideas by Gender

	Girls				Boys			
	Pre	Post	Abs Diff	sig	Pre	Post	Abs Diff	sig
Find out what causes a problem	82%	94%	11%	0.051	85%	97%	12%	0.018
Design solution	82%	95%	13%	0.003	92%	97%	5%	0.260
Develop new technologies	89%	90%	2%	0.709	90%	97%	6%	0.103
Generate different ideas	82%	95%	13%	0.018	89%	98%	10%	0.013
Identify problems in the community to solve	69%	89%	19%	0.002	79%	93%	15%	0.011
Protect the environment	57%	94%	37%	0.000	61%	89%	28%	0.000
Read about new inventions	71%	82%	11%	0.051	79%	89%	10%	0.109
Repair engines	66%	66%	0%	1	80%	82%	2%	0.766
Solve problems	86%	95%	10%	0.057	89%	97%	8%	0.096
Test ideas	77%	92%	15%	0.011	90%	95%	5%	0.260
Use math	86%	92%	6%	0.208	90%	95%	5%	0.260
Use models to simulate how a system changes	77%	92%	15%	0.011	85%	93%	8%	0.096
Use science	87%	100%	13%	0.003	90%	97%	6%	0.159
Work with machines	90%	90%	0%	0.051	89%	93%	5%	0.321

These findings suggest that while both boys and girls were more likely to associate engineering with the core components of the SCoPE curriculum, using engineering to address environmental problems in the community. Girls also had an additional change in being more likely to associate engineering with activities like designing solutions and testing ideas. While professional engineers often associate these types of activities with engineering, students generally are unlikely to associate these with engineering [9], [10]. As a result, the activities may have expanded girls' conceptions of the types of activities they might do as engineers leading to greater overall interest in science and engineering. There did not appear to be any changes in student association with engineering for activities such as "repairing" that students typically associate with engineering but professional engineers do not [9].

Students collected local data about nutrient levels in their watershed, connecting the problem to their local community. Excess nutrients can lead to eutrophication in the contaminated body of water, a process that leads to excess algae growth and mass fish death. In addition to the destruction of the ecosystem, students recognized that nutrient pollution could also have economic ramifications for their community. All of these factors likely made the problem more meaningful to students, leading to the observed increase in interest in engineering as suggested by [11]. The finding that girls' interest in engineering increased after working to solve a local problem that would prevent animal death and help the community is consistent with prior research that indicates girls often prefer engaging in activities that help people and other living things [34].

Conclusion

Although considerable effort has been made in the past few decades towards increasing the number of women and people of color, 83% of employed engineers in the U.S. are male and 68% of engineers are white [2]. While there can be no single solution for improving representation in engineering, the results of this study provide some promising evidence that place-based engineering instructional materials that focus on community or societal problems may be a promising approach for increasing girls' participation in engineering study and careers. To gain more insight into the effect of the SCoPE design principles, the curriculum must be tested in other schools with a more diverse population. In the future, additional instructional materials should be developed for other areas of engineering using the same design principles to investigate which aspects of the curriculum have the greatest effect at changing students' interest in and ideas about engineering. Identifying a set of generalizable design principles that increase girls' interest in engineering can potentially have a positive impact on balancing gender representation across engineering fields.

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