Engaging K-12 Teachers in Engineering Through a Professional Development Program:
Implementation Strategies, Results and Lessons Learned

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***Abstract*— In order for the United States to remain the global leader in engineering and technology, it must produce and retain a higher number of science, technology, engineering, and mathematics (STEM) talent. Over the past few decades, there have been a number of national initiatives that have promoted STEM education with the goal of generating student interest in science and engineering and increasing the number of students entering the STEM pipeline. Research literature confirms that teachers are the single most important factor affecting student achievement and interest in STEM subjects. Several models of teacher professional development have been reported along with the evidence of the degree of their effectiveness in promoting student interest in engineering. These professional development programs are designed to increase the engineering content knowledge of math and science teachers, thereby having a direct impact on student achievement in math and science and helping to promote a positive attitude to engineering.**

This paper presents the design of a teacher professional development program offered in a predominantly Hispanic region in South Texas. The professional development program provides an opportunity for teachers to participate in engineering projects, become more knowledgeable about the engineering profession, and learn new pedagogical tools that they use to develop engineering-based hands-on learning activities for their classrooms. One of the effective approaches adopted by this program is the development of creative engineering connections between the math and science concepts taught by the teacher participants and real-world engineering applications that not only can K-12 students easily understand, but also find tangible and interesting. The paper also provides evidence of the effectiveness of the program strategies that have resulted in about 89% of the developed learning activities being successfully implemented in the teachers' classrooms. The results of the program teacher surveys and discussion of lessons learned by the program management are also presented.

Keywords—K-12 engineering education; teacher professional development

I. Introduction

In order for the United States to remain the global leader in engineering and technology, it must produce and retain a higher number of science, technology, engineering, and mathematics (STEM) talent [1, 2]. However, in the last decade the STEM proportion of all university undergraduate degrees has been decreasing in the United States [2]. In order to meet the projected economic needs for STEM professionals, the number of students graduating with STEM degrees in the United States will need to increase by about 34% annually [2].

Several studies have reported on the positive implications of engineering education in K-12 classroom settings. The reported benefits include: (i) an increased student motivation to learn the mathematics and science concepts, (ii) an increased student learning and achievements in mathematics and science, and (iii) an increased interest in pursuing a career in a STEM field. Initiatives to increase the number of students entering the STEM pipeline include the establishment of STEM high schools [3] and the development of various K-12 engineering outreach programs that focus on promoting science and engineering among K-12 students by engaging them in summer camps and after school programs [4]. When provided with information resources and adequate training, school counselors can potentially play an important role in promoting positive attitudes to engineering and in providing guidance to students who are considering careers in engineering [5, 6].

While these types of initiatives have shown to have merits in achieving student awareness of engineering, the research literature confirms that teachers are the single most important factor affecting student achievement [7]. Several models of teacher professional development have been reported along with the evidence of the degree of their effectiveness in promoting student interest in engineering [6, 8-11]. These professional development programs are designed to increase the engineering content knowledge of math and science teachers, thereby having a direct impact on student achievement in math and science and helping to promote positive students' attitudes to engineering [6, 8-11]. Due to the strong link between engineering, math and science, several initiatives have been taken to introduce engineering content in K-12 math and science curriculum. The motivation behind these initiatives is twofold: (i) make a connection between math and science concepts to real-world applications to engage students and motivate them to learn math and science concepts, and (ii) promote pathways for students to be part of post-secondary STEM degree programs.

There are two main approaches for infusing engineering in K-12 math and science curriculum. In the first approach, engineering is treated as a unique discipline and engineering curriculum is often offered as pre-packaged courses [12, 13]. The second approach calls for employing engineering as a tool for teaching math and science contents - that is engineering is embedded in math and science curriculum [14]. Both approaches have their merits. However, professional development efforts that engage teachers in experiencing engineering design and/or research can potentially help teachers become more confident to teach challenging math and science concepts and know how to relate them to real-world engineering applications [9, 15].

In our efforts to bring engineering into K-12 classrooms, we partnered with several school districts in the Rio Grande Valley, South Texas – where about 90% of the population is Hispanic. The main goal of this partnership was to recruit math and science teachers to participate in a professional development program that engages them in engineering projects and effective pedagogical practices to bring new knowledge of engineering into their classrooms.

This paper presents the design of the teacher professional development program and discusses the challenges faced by the teacher participants in completing the professional development program activities and in implementing the engineering-based learning activities in their classrooms during the academic year. The paper also provides evidence of the effectiveness of the strategies implemented to overcome these challenges, resulting in about 89% of the new hands-on, engineering-based learning activities being successfully implemented in the teachers' classrooms. The paper concludes with some of the findings and the lessons learned from the implementation of this professional development program model that was funded by the National Science Foundation over a three-year period that concluded in 2015.

II. Design of the Professional Development Program

A. Program Objectives and Rationale

The objectives of our teacher professional development program are: (i) provide mentored engineering experience for K-12 math and science teachers for the period of six weeks during the summer, (ii) strengthen teachers' mastery of pedagogical content knowledge and skills related to the planning and development of hands-on, engineering-based activities that are aligned with state standards, and (iii) provide support through a sustained follow-up with the teachers during the academic year to aid them in the implementation of the developed engineering curriculum in their K-12 classrooms. The professional development program provides an opportunity for teachers to become more knowledgeable about the engineering profession and to learn new pedagogical tools that aid them in introducing engineering into their classrooms. One of the effective approaches adopted by this program is the development of creative engineering connections between the math and science subjects taught by the teacher participants and real-world engineering applications that students can easily understand, and find interesting and tangible.

Our professional development program aims at answering the following questions:

- What role does an active participation in research-based engineering projects have on teachers' understanding of engineering and their adoption of new pedagogy that relate math and science concepts to real-world applications?

- How are teacher participants impacted by engineering-inspired, hands-on instruction for increasing their students' knowledge and interest in science, math, and engineering?

B. Teacher Participant Selection

The establishment of our partnerships with the school districts in our local region helped to advertise the professional development program and its objectives to math and science teachers. Interested teachers were asked to complete an application where they listed (i) their education background, (ii) teaching experience and certification, and (iii) top three engineering areas of interest from a list provided. They were also asked to provide a personal statement explaining why they were interested in the program and how they would benefit from it. The program management reviewed all applications and ranked them based on teachers' qualifications, experiences, and demonstrated efforts in introducing hands-on activities and/or innovative teaching strategies in their classrooms. The higher-ranked applicants were contacted and interviewed. A final selection of teacher participants was completed around March of each year. A total of thirty-six teachers (22 male teachers and 14 female teachers) participated in the program over a three year period (twelve participants in Year 1, ten participants in Year 2, and fourteen participants in Year 3). Twenty nine (~80%) of the thirty six teacher participants were Hispanic.

C. Summer Program Activities

The professional development program ran for a period of six weeks during the summer. The main activities were: (i) professional development workshops and seminars, (ii) mentored engineering research experience, and (iii) development of engineering-inspired hands-on learning activities for teaching math and science concepts.

1) Workshops and Seminars: The professional development seminars and workshops helped to provide the necessary tools and knowledge for teachers to work on the mentored research-based engineering projects and to develop engineering-based hands-on learning activities for their K-12 classrooms. The offered workshops and seminars included the following: (i) laboratory safety workshop, (ii) library research workshop, and (iii) the use of the engineering software MATLAB workshop. The offered seminars included: (i) engineering careers seminar, (ii) engineering design and engineering science seminar, and (iii) an introduction to the Lesson study seminar.

a) Laboratory Safety Workshop: Since teachers worked on their research-based engineering projects in the engineering laboratories, a laboratory safety workshop was mandatory. The workshop was tailored for the teachers and was offered by a staff member from the Unviersity Environmental, Health, Safety and Risk Management Department.

b) Library Research Workshop: This workshop was offered by a librarian and focused on what the teachers needed to know to search for articles and resources that aided them in their engineering research projects and the development of the engineering-inspired curriculum based on the subject areas they taught in their K-12 schools.

c) MATLAB Workshop: This hands-on workshop was conducted in one of the engineering computer labs and introduced teachers to the engineering software MATLAB. While not all teacher teams were expected to use MATLAB extensively for their engineering projects, most of the teachers found the software useful for graphing results.

d) Engineering Career Seminar: One of the key objectives of the professional development program was to educate teachers on the employment possibilities and opportunies that an engineering degree could provide. The seminar was offered by a science and engineering career specialist of the University Career Services.

e) Engineering Design Process: This seminar focused on the best practices of planning learning activities following the engineering design cycle that consists of eight-steps [11, 14, 16-19]: (1) Identify the need; (2) Research and formulate the problem/specifications; (3) Develop possible design solutions; (4) Conduct analysis to determine the best solution; (5) Build a prototype; (6) Test and evaluate the prototype; (7) Communicate the solution; and (8) Redesign. Teachers were also provided resources where simplified versions of the engineering design cycle are adopted for K-12 education.

f) Introduction to the Lesson Study Seminar/Workshop: This seminar provided the tools that teachers could use to collaborate on the planning, development, and revision of their hands-on learning activities using the Lesson Study Cycle as a framework for their own professional development [20-22]. The Lesson study is a Japanese form of professional development that centers on collaborative study of live classroom lessons [20, 22]. Being successful at lesson study requires having a collaborative culture where teachers feel comfortable observing one another teaching and sharing classroom observation data with one another [20-24]. There are four key steps to Lesson Study Cycle: (1) Goal Setting and Planning, (2) Research or Study Lesson, (3) Lesson Debriefing, and (4) Consolidation of Learning [21, 23]. The lesson Study approach focuses on developing a better understanding of how students think and learn, and provides a framework for promoting collaboration between teachers. In Years 1 and 2, only a seminar was presented to the teacher participants. In Year 3, we engaged teachers in applying the first two steps of the Lesson Study, where the learning hands-on activity of one of the teacher participants was used as an example.

2) Engineering Research Experience: The recruited teachers were grouped into teams of three to four teachers to collaborate on a research-based engineering project mentored by an engineering faculty. The purpose of this activity was to have teachers experience engineering first hand. The teams were formed based on several considerations that included: (i) teacher's interest in the engineering topic, (ii) K-12 math or science subject and grade level taught by the teacher, and (iii) teacher's education and professional development background. Four engineering projects were offered in each of the first two years of the program and five engineering projects were offered in the third year of the program. At the end of the summer program, teacher teams prepared a technical report and a poster to document their work on their projects.

3) Engineering-Based Learning Activities: An important component of the summer program was to engage teachers in exploring and designing engineering-inspired hands-on activity lessons for their math and science classrooms. The process of developing these learning activities is presented in Section III.

III. Connecting Mathematics, Science, and Engineering

A. Engineering-Inspired Hands-On Lessons

Before the teachers started the summer program, neither the project management team nor the teachers had determined which of the teachers' existing lesson plans should be redesigned and used with their students during the following academic year. On the first day of the summer program, teachers, however, were asked to identify some important concepts that their students either found difficult to understand or showed no interest in learning. The idea was to develop an engineering-based hands-on activity that links math and/or science concepts to a real-world application. Weekly curriculum development sessions were held to guide the teachers in the development of their learning activities. The development of hands-on lesson plans was an iterative process. The first step of the process was to formulate an engineering connection to the math and science concepts. During the early lesson development sessions, teachers discussed their engineering research experiences and shared ideas for lessons with other program participants and the project management team. Throughout the lesson development sessions, inputs from teachers, engineering and education faculty were instrumental in formulating the engineering connections and shaping up the engineering-inspired hands-on lesson plans. Supplies and materials were acquired for teachers to experiment with the various design components of their new hands-on lessons during the summer program.

B. Making An Engineering Connection

To help in the design of the hands-on activities, teachers were guided to formulate concrete engineering connections to the science and math concepts taught in their lessons. More specifically, teachers had to identify some real-world engineering applications that demonstrate how engineers apply the science and math concepts to design new systems and solve engineering problems. As the summer progressed, teachers improved the formulation of the engineering connections to their lessons.

The idea of presenting the engineering-inspired learning activities as a challenge for K-12 students was adopted in almost all the hands-on learning activities developed through this program. The activities were designed with the idea of having students work in teams and engaging them in playing the role of engineers to solve the activity challenge. Lesson assessments (pre-activity assessment, activity embedded assessments, and post-activity assessments) were developed for each learning activity.

IV. Results and Lessons Learned

A. Implementation of Lessons in the Classroom

Following the summer program, equipment, materials and supplies were acquired by the program to help teachers implement their learning activities in their classrooms. For most of the learning activities, the cost of expendable materials per student team is kept below 20 US dollars to ensure that the activities could be easily adopted by other teachers.

Visits to the teachers' classrooms were coordinated with the program management to observe the implementation of the activities. Because of late changes in their teaching assignments, a number of teachers were not able to implement their learning activities during the following academic year, but were given the opportunities to implement the lesson one year later when they taught the math/science subject based on which their engineering-based activity was developed. By maintaining a continued contact and support to teachers after they completed the summer program, 89% of the developed learning activities were successfully implemented in the teachers' classroom, thereby achieving an important objective of our program. One teacher participant reported that her engineering-inspired learning activity was adopted and taught by another teacher from the same school, thereby impacting additional students.

B. Survey Results

Teacher participants completed a post-program survey that was administered at the end of the six-week summer fellowship of each program year. The post-program survey items were grouped into content domains. These domains consisted of items grouped together based upon common content/content validity. For example, these content domains may be reflecting emphasis on impact and value-added learning from the activities that teacher participants engaged in during the professional development program. For content domains with items that had a four-point (or five-point) Likert scale response formats, the grand mean and standard deviation for a given content domain were derived by aggregating/summing across items within that given domain. Then each respective item mean with a content domain was obtained and then compared with the grand mean for that given content domain. If a mean for an individual item was one standard deviation or greater than the grand mean for that content domain it was defined as a strength within that domain and if a mean for an individual item was one standard deviation or more below the grand mean for that content domain it was defined as a weakness within that content domain. If an individual item mean was within plus or minus one standard deviation of the grand mean for that domain it was defined as neither a strength or weakness within that content domain.

Table I shows the results of the post-program survey that was adopted from the assessment tools developed and made publicly available by the Research Experiences for Teachers Network. The survey content domain consists of eleven items that measure 'the extent of which participants felt they experienced various types of learning as a result of their participation in the program' using a four-point Likert scale: not at all (1), small extent (2), moderate extent (3), great extent (4). For this content domain, the grand means, $\bar{\boldsymbol{X}}$, and standard deviations, $\boldsymbol{S}$, are: $\bar{\boldsymbol{X}} =$ 3.48, 3.70, and 3.55, and $\boldsymbol{S} =$ 0.73, 0.40, and 0.46 for Years 1, 2, and 3, respectively. The survey content domain items that can be considered as strengths are: Item 1: "I gained a greater understanding of the applications of science, mathematics, or technology in everyday life", Item 4: "I learned about innovative ways to use standard materials and equipment in my field", and Item 5: "I increased my knowledge of current issues in scientific and mathematical research". It is worth noting that in Year 3 of the program, Item 7: "I better understood how collaborative inquiry can be done successfully" is rated higher than in previous two years. This could be attributed to the exercise that involved the application of the first steps of the Lesson Study that only Cohort 3 got the opportunity to experience.

Table II shows the results of content domain consisting of eight items that measure the impact of the program on the teachers personally using a five-point Likert scale ((1) Strongly Disagree to (5) Strongly Agree). For this content domain, the grand means, $\bar{\boldsymbol{X}}$, and standard deviations, $\boldsymbol{S}$, are:

$\bar{X}$ = 4.83, 4.62, and 4.92, and S = 0.37, 0.59, and 0.15 for Years 1, 2, and 3, respectively. The survey content domain items that can be considered as strengths are: Item 3: "It increased my interest in research and the ways that science, mathematics, or technology can be applied" (Years 1 and 3), and Item 8: "It increased my commitment to learning and seeking new ideas on my own" (Years 2 and 3).

The survey results reported in Tables I and II show that the various strategies implemented within the professional development activities helped achieve the program objectives and enabled the teacher participants to learn the application of math and science to real-world engineering problems, and helped to increase the teachers' confidence in developing engineering-based curriculum for their K-12 classrooms.

C. Lessons Learned by the Program Management

Even after a careful planning during the design stage of this type of professional development model, there were a number of challenges encountered during the initial program implementation. In this section, we share the main lessons learned that helped improve our best practices for managing the program.

- Teachers are required to complete a number of hours of professional development education and training during their careers in order to maintain their licenses. While there are different forms of professional development activities delivered by school districts, our professional development program has unique objectives and requirements that most teachers are often not familiar with. In addition to the printed materials describing our program objectives and requirements, we found that it was very important to clarify and re-iterate those objectives and requirements to teachers during the interview process. To ensure the success of the training, it was important that teachers expressed their time commitment to the program during both the summer and the academic year before a final selection of teacher participants was made.
- An important component of the program was for teachers to experience engineering by working on a research-based engineering project under the mentorship of engineering faculty. Because of the various program activities planned during the summer, it was important to provide a detailed summer schedule that allocated the number of hours that teachers were expected to work on their research-based engineering projects. An orientation session for faculty mentors was conducted every Spring semester to further clarify the program requirements and to re-emphasize that teachers were expected to work on the engineering projects only for a portion of the summer program. This helped the faculty mentors define the scopes of projects and set reasonable expectations for teachers.
- Research has shown that positive working conditions in schools are instrumental for recruiting and retaining teachers [25]. This should also be applicable to professional development programs designed for teachers. The results of post program surveys and the written comments of Cohort 1 were used to identify and introduce improvements to our supportive training environment in subsequent years of the program.

TABLE I. POST PROGRAM TEACHER PARTICIPANT SUVERY RESULTS: GAINED LEARNING EXPERIENCES

Content Domain Question: To what extent, if any, do you feel that you experienced each of the following types of learning as a result of your participation in the program?	***$\bar{X}$ Y1/Y2/Y3 (N=12/10/14)***
I gained a greater understanding of the applications of science, mathematics, or technology in everyday life	3.75/3.7/3.84
I acquired greater understanding of fundamental concepts in science or mathematics	3.5/3.7/3.53
I became familiar with new materials and equipment that I can use in my teaching	3.75/3.7/3.69
I learned about innovative ways to use standard materials and equipment in my field	3.75/3.9/3.46
I increased my knowledge of current issues in scientific or mathematical research	3.83/3.8/3.84
I gained a greater appreciation of the difficulties some students encounter when learning science or mathematics	3.25/3.7/3.46
I better understood how collaborative inquiry can be done successfully	3.67/3.7/3.84
I became more proficient at using the Internet for communicating with colleagues and accessing information that will be helpful in my teaching	3.17/3.5/3.38
I learned about magazines and professional journals that will be relevant to me as a teacher	3.33/3.7/3.38
I expanded my knowledge of how to use computers in my teaching	2.75/3.6/3.15
I increased my knowledge of careers that utilize science, mathematics, or technology	3.50/3.7/3.46

TABLE II. POST PROGRAM TEACHER PARTICIPANT SUVERY RESULTS: IMPACT OF THE PROGRAM ON TEACHERS PROFESSIONALLY

Content Domain Question: To what extent do you agree or disagree with each of the following statements concerning the impact of the program on you personally?	***$\bar{X}$ Y1/Y2/Y3 (N=12/10/14)***
It increased my confidence in myself as a teacher	4.67/4.3/4.84
It elevated my enthusiasm for teaching	4.83/4.4/4.92
It increased my interest in research and the ways that science, mathematics, or technology can be applied	5.00/4.8/5.00
It stimulated me to think about ways I can improve my teaching	4.92/4.6/4.92
I believe I will be a more effective teacher	4.83/4.6/4.84
It increased my interest and ability in networking with teachers and other professionals	4.75/4.6/4.92
It increased my motivation to seek out other experiential professional development activities	4.83/4.8/4.92
It increased my commitment to learning and seeking new ideas on my own	4.83/4.9/5.00

V. Conclusion

This professional development program provided an opportunity for teachers to become more knowledgeable about engineering and to gain new skills to develop and teach math and science lesson activities with embedded engineering content. Each of the three recruited teacher cohorts spent six weeks during the summer to experience engineering research, participated in education workshops and seminars, and developed engineering-inspired math and/or science learning activities for their classrooms. Teachers worked in teams on various engineering research projects. The teacher participants found the engineering research projects to be interesting and engaging. They learned concrete examples of what engineers do and appreciated the applications of math and science to engineering. In addition to engaging the teachers in the engineering research projects, this project provided the necessary pedagogical tools to guide the teachers in the development of hands-on learning activities for their math and science classrooms.

A total of 36 engineering-inspired hands-on learning activities were developed. To serve as a motivation for students' learning, each hands-on activity incorporated an engineering connection that shows how engineers apply math and science concepts to design new systems and/or to solve engineering problems. The visits to the teachers' classrooms provided an opportunity for the project personnel to observe the implementation of the engineering educational activities and to provide feedback to teachers. These classroom observations were also used as a learning experience for the project personnel to improve the effectiveness of the professional development program in the following cycle. The follow-up strategy of this project has been effective. In fact, a total of 32 out of the 36 new lesson plans, developed during the summer periods, were fully implemented in the teachers' classrooms during the academic years. The teacher participants disseminated their professional development summer experiences and their engineering-inspired lesson activities to other teachers during a STEM Education Workshop that was organized annually as part of this project's dissemination efforts.

Acknowledgment

The contents of this paper were developed upon work supported by a grant from the National Science Foundation (Grant CNS-1132609). However, these contents do not necessarily represent the policies and views of the National Science Foundation. Endorsement by the federal government should not be assumed.

The authors would like to thank: (1) Drs. Y. Chu, H. Foltz, S. Kumar, J. Li, K. Lozano, and J. Son, who served as faculty mentors, (2) the teachers who participated in our professional development program, (3) the school administrators who supported the teacher participants in their implementations of the developed engineering-inspired educational activities in their classrooms, (4) the library staff: Mr. C. Nelson, Mr. A. Portner, and Ms. D. Tyink for conducting their workshops on library resources, (5) Mr. R. Ramirez from the University career services for providing a seminar on engineering careers, and (6) Ms. M. Salazar from the University Environmental Health, Safety and Risk Management Department for offering the laboratory safety training for teachers.

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