Int. J. Engng Ed. Vol. 23, No. 1, pp. 3–8, 2007
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Integrating Engineering in Middle and High School Classrooms*

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This paper introduces a model that has been successful for introducing engineering concepts and activities into middle and high school courses. Science, mathematics, and technology teachers participating in the Pre-College Engineering for Teachers (PCET) professional development project attended a two-week summer institute focused on engineering concepts and the engineering design process. As the final project for the Institute, teachers each modified a unit or lesson that they had previously taught to include engineering concepts. The extremely high rate of implementation of these modified lesson or units in the classroom by the teachers the following school year, the integration of engineering design into additional lessons, and the continued inclusion of these units and engineering in subsequent years demonstrate that this approach to including engineering in middle and high school classrooms is successful.

Keywords: professional development; engineering; middle school; high school; science integration; teacher knowledge

INTRODUCTION

INTRODUCING THE 'NEW' DISCIPLINE OF ENGINEERING to students can prove challenging for many middle and high school science, mathematics, and technology teachers. One of the principal obstacles can be the teachers' lack of knowledge about what engineering is and how they might teach it. Traditionally, engineering has not been part of the K-12 curriculum. Thus it is not surprising that most science teachers, like the United State's population in general, lack a firm understanding of engineering practices, uses, and concepts [1]. Few teachers learned about this discipline while they were in school. Therefore, for a teacher to feel comfortable integrating it into their class will generally require that they engage in teacher professional development that focuses on engineering concepts (subject matter knowledge) and pedagogical strategies to teach this discipline (pedagogical content knowledge).

There is a wide array of professional development models for educators. Some programs focus on developing teachers' in-depth understanding of specific concepts so they can more accurately convey these to their students. Other workshops focus on helping teachers to hone their pedagogical skills focusing, for example, on how to set up and manage effective group work or how to attend to the needs of English language learners.

In general, there are two models for teaching K-12 students about engineering. Engineering may exist as a stand-alone course in which the discipline of engineering is the primary organizer for student learning. Initiatives such as Project Lead the Way, the Infinity Project, Engineering the Future and others have adopted this approach. The second model is one in which engineering and technology concepts and skills are integrated into other subjects such as science, mathematics, or technology. In this model, engineering concepts are one tool for teaching science and mathematics; these concepts and skills are needed to create optimal solutions. We have adopted the integration model. While this model affords an opportunity for many more teachers to introduce their students to engineering (and includes the potential for students to be exposed to engineering in multiple classes and contexts), it also presents some challenges for professional development. With this model, teachers might span middle school (6–8) or high school (grades 9–12) and could be teaching a large variety of math, science, and technology courses and content. The traditional strategy of anchoring teachers' professional development learning to particular activities that they will experience and then carry back to implement in their classes is not feasible.

Thus, we have chosen to focus on content as it relates to one of the central features of engineering—

* Accepted 18 October 2006.

the engineering design process. We have selected the engineering design process as the overarching theme for our program because it is a core characteristic of the engineering process (and, as such, is emphasized in State and National technology/engineering standards), provides a unifying feature across the various grade levels, enables teachers to engage their students in 'real' engineering without requiring detailed knowledge of engineering and physics concepts, and promotes the integration of engineering with other school subjects [2, 3]. Our prior experiences in teaching the design process have illustrated that teachers quickly understand it—the engineering design process in engineering is similar to the inquiry process in science—and that it often appeals to students who have not been successful in traditional science courses.

A focus on the engineering design process also supports treating teachers as professionals with expertise. Instead of introducing our participants to activities that we expect them to replicate faithfully in their classrooms, we expose them to a new discipline and process. Then we ask them to apply what they have learned by synthesizing their new knowledge of engineering with the science, math, or technology concepts that they need to teach during the year. Finally, we expect them to develop a lesson that teaches engineering as well as science or math concepts.

THE PCET PROGRAM AND RESEARCH QUESTIONS

The Pre-College Engineering for Teachers (PCET) project is a professional development program designed to help science, mathematics, and technology teachers understand and teach engineering concepts and skills. Funded by the National Science Foundation, PCET is a collaborative program between Tufts University, Worcester Polytechnic Institute, University of Massachusetts Lowell, University of Massachusetts Amherst, and the Museum of Science in Boston. In the initial year, 2003, 22 mentor high school teachers (admitted in teams of 2–4 teachers from a school or district) participated in a two-week Tufts Engineering Mentor Institute (TEMI) on the Tufts campus. TEMI was focused around the engineering design process, in particular we engaged teachers in two engineering design challenges: designing and building a water filter and designing devices that help handicapped people. The challenges were chosen because they clearly conveyed how engineers interact with society, were attractive to girls and underrepresented minorities, and together had links with biology, chemistry, physics, mathematics, and technology. Teachers learned what the engineering design process is, heard lectures by engineering faculty and industry engineers, conducted background research, and designed and created engineering design projects. During the professional development program, each teacher was required to modify a lesson that s/he already taught to include concepts related to engineering and the engineering design process. Teachers submitted these engineering project lesson plans at the end of the summer program. Each project was different depending upon the teachers, his/her students, the courses s/he taught, and the resources of the school.

During the 2003–4 school year, the mentor teachers implemented their modified lessons. Sample engineering design projects included:

- using students' understanding of mass, gravity, and forces to design and construct a mobile (Physics);
- using mathematics to design an evacuation plan for a building (Math);
- designing and constructing a stormwater treatment device (Technology).

Each mentor teacher was associated with one of the four university partners: WPI, UMass Lowell, UMass Amherst, or Tufts University. The teachers had the option of requesting the support of a local engineering graduate student fellow who could help to collect resources, provide an extra set of hands in the classroom, or offer insights about the field of engineering.

One goal of the PCET Program is to develop teachers who can be leaders in engineering education. One way to develop teacher leadership is to involve teachers in developing professional development [4, 5]. In early spring 2004, each of the four local teams of TEMI teachers, graduate students, and faculty members met to plan a two-week Satellite program that they would then run on the local campus for approximately 24 more high school and middle school teachers that summer. Since their classroom experiences and projects all varied, teachers and faculty drew upon these varied experiences to create unique Satellite programs that incorporated the teachers' interests and classroom experiences. In July 2004, the mentor teachers led these programs. Similarly to TEMI, the Satellite programs introduced a new cohort of teachers (hereafter called satellite teachers) to the engineering design process and engaged them in two or three design challenges. During the 2004 program, each of the 86 participating satellite teachers also modified a lesson or unit s/he already taught to include engineering concepts. The satellite teachers then implemented their lessons in their classrooms during the 2004–2005 school year (Table 1).

Thus, by the conclusion of the PCET cycle 108 teachers (22 mentor and 86 satellite teachers) had designed lessons tailored to their classrooms, students, and needs that integrated engineering with 'regular' classroom content. This paper explores the effectiveness of our model. Specifically, we explore the following questions: What do teachers learn during the PCET workshop? Does introducing teachers to a process and then asking them to apply it result in any changes in their

Table 1. Pre-College Engineering for Teachers Program schedule

Summer 2003	Academic Year 2003–4	Summer 2004	Academic Year 2004–5
Tufts Engineering Mentor Institute (TEMI) at Tufts	TEMI teachers implement design projects TEMI teachers, graduate students, faculty plan PCET Satellite program	PCET Satellite Workshops at Tufts, UMass Lowell, UMass Amherst, and WPI	Satellite teachers implement design project

teaching? To answer these questions, we have been conducting research and evaluation of the TEMI and PCET programs.

ENGINEERING IN THE CLASSROOM: RESULTS OF PCET

Methods

The following instruments were used to collect data from the mentor and satellite high school teacher participants.

- Teacher background survey: This instrument collected basic demographic data from teachers, as well as information about their education and prior teaching experience.
- Teacher presurvey: This survey collected information about teachers' knowledge of and comfort with teaching engineering and technology.
- Teacher project plan: A detailed proposal outlining what the teacher planned to do in his/her classroom during the coming year. Details included what engineering/technology content s/he would cover; which science, mathematics, or technology content the engineering would integrate with, and details about the probable activities.
- Teacher postsurvey: This instrument collected information about how teachers felt their knowledge of and comfort with teaching engineering and technology had changed, information about their classroom implementation and, for mentor teachers, data about their experiences planning and running a professional development program.
- Teacher interviews: Teacher interviews were conducted with a random sample of 10 participants from the mentor and satellite program.

Teachers had the options of completing the surveys online or in paper form. Data were collected in a spreadsheet and statistics run using SPSS.

Teacher population

The teacher population included 67 high school and 41 middle school science, mathematics, and technology teachers from across Massachusetts. A one-way ANOVA test of the mentor (all high school) vs. satellite (high school and middle school) data evinced that these two populations and their responses are similar enough to be combined for analysis.

The participating teachers taught in a range of types of schools: 18.5% taught in urban districts, 54.6% taught in suburban districts, and 26.9% taught in rural districts. Forty-four percent of the participants were female and 56% percent were male. The number of years of teaching experience ranged from half a year to thirty years. The mean number of years was 6.8 years and the median was 3.5 to 4 years. As Table 2 illustrates, almost half of the teachers taught science, 28% taught math, and 16% taught technology. About 6% of teachers taught multiple subjects that included math, science, and/or technology.

Over half of the participating teachers had earned their initial (bachelors) degree in science, mathematics, or engineering (Table 3). These numbers increase slightly when advanced degrees are considered. Interestingly, 53.7% of participants reported that they had held another career previous to teaching.

Findings

Educators teach best when they understand a concept and feel comfortable teaching it. Thus, one baseline measure of the workshop model was whether teachers felt that it affected their knowledge of and comfort with engineering. On the postsurvey, teachers were asked to assess their knowledge of and comfort with a number of topics on a 10 point (10 being the high point) scale before and after the workshop they attended. Table 4 reports the changes in teachers' knowledge and comfort.

Table 2. TEMI/PCET subject taught

Subject	Number	%
Science	52	48 6
Math	30	28.0
Technology	18	16.8
Multiple	7	6.5

Table 3. Teachers' degree fields

Subject	Initial	%	Any	%
Science	25	24 5	29	28.2
Math	15	14.7	17	16.7
Engineering	16	15.7	17	16.7
Education	24	23.5	52	51.0
Other (English, business, etc.)	28	25.9		

Table 4. Teachers' assessments of their knowledge and comfort before and after the workshops

Topic	N	Mean before	Mean after	Sig. (2 tailed)
Knowledge of:				
The Massachusetts State Science and Technology/Engineering Standards	99	4.3	7.2	0.000
Integrating engineering into science, math, or technology classrooms	96	4.6	7.9	0.000
Determining the relevant design features in an engineering project	96	3.8	7.7	0.000
Engineering concepts	79	4.4	7.8	0.000
The engineering design process	96	4.1	8.7	0.000
The types of considerations that must be taken into account when evaluating an engineering solution.	96	4.0	7.7	0.000
Comfort with:				
Designing engineering project for the courses they taught	97	3.8	7.7	0.000
Implementing engineering projects in the classroom	97	3.9	7.8	0.000
Answering students' engineering-related questions	96	4.2	7.4	0.000
Assessing students' engineering projects	97	4.1	7.5	0.000
Talking about engineering concepts	97	4.5	7.7	0.000
Interacting with engineering faculty and graduate students	79	4.5	7.9	0.000

Teachers reported gains on all measures of both self-assessed knowledge and comfort after the workshop. On average, teachers' rankings of their knowledge increased 3.6 points and their comfort 3.5 points. Paired t-tests showed significant increases ($p < 0.001$) for all measures of self-rated knowledge and comfort with aspects of engineering design instruction.

To investigate teachers' knowledge and comfort gain further, we ran one-way ANOVA tests that analyzed changes in teachers' knowledge of and comfort with respect to the subject that they were teaching (science, math, technology, or multiple). As Table 5 reports, the analysis surfaced that significant differences exist between the fields of teaching. The one exception was knowledge about standards. In general, the technology teachers reported much less change in their knowledge and comfort with teaching about engineering. This is not surprising—many of these teachers have done design projects as part of their courses for years, and with the adoption of the new Massachusetts State Technology/Engineering standards in 2001 [6], many of these teachers began to adapt their courses to include more of an emphasis on engineering before they participated in this program.

When asked whether the workshop provided them with enough understanding of the engineering design process to use it with their students, 95.0% agreed with the statement and 63.4% of the teachers strongly agreed that this was the case. Again, an ANOVA test indicated that differences in responses by subject matter taught was significant (0.048). In this case, mathematics teachers generally agreed with this statement much less than science teachers, which could partly be explained by the workshops' design challenges which primarily focused on challenges related to science, with mathematics being used more as a tool than the focal point.

Knowledge is an important initial step to implementation; we also studied whether teachers implemented their planned projects and their insights about how well our professional development model worked. Survey and follow-up interviews indicate that almost every teacher who was teaching the year following the mentor or satellite PCET course implemented an engineering design project.

Over 91% of the high school teachers reported

Table 5. Change in teachers' knowledge and comfort by subject matter

Topic	Science change	Math change	Multiple change	Tech change	Sig.
Knowledge of:					
The Massachusetts State Science and Technology/Engineering Standards	2.7	3.6	2.7	1.7	0.138
Integrating engineering into science, math, or technology classrooms	4.0	3.6	3.7	1.9	0.017
Determining the relevant design features in an engineering project	4.6	4.0	3.6	1.5	0.000
Engineering concepts	4.0	3.7	2.3	1.2	0.002
The engineering design process	5.3	5.0	4.3	1.6	0.000
The types of considerations that must be taken into account when evaluating an engineering solution.	4.2	3.9	3.1	2.1	0.022
Comfort with:					
Designing engineering project for the courses they taught	4.5	3.7	2.7	2.5	0.020
Implementing engineering projects in the classroom	4.2	4.0	3.7	2.4	0.045
Answering students' engineering-related questions	3.6	3.3	3.7	1.7	0.025
Assessing students' engineering projects	4.1	3.3	2.9	2.1	0.017
Talking about engineering concepts	3.8	3.3	3.6	1.6	0.019
Interacting with engineering faculty and graduate students	3.8	3.4	3.3	1.6	0.048

that they preferred the flexibility of creating their own engineering design project to having a set project to implement. However, 79% of them did indicate that the design project took longer than they initially expected.

When asked to compare their students' learning during the engineering design project to a regular classroom activity, the vast majority of teachers ranked the learning during the engineering design project higher than the routine activities. Teachers felt that their students were more engaged with the engineering design project than with regular classroom activities—41.0% of teachers strongly agreed that this was the case, 29.0% moderately agreed, and 18.0% slightly agreed. During her interview, one teacher commented:

> The timing worked out, [the engineering design project] was a nice end of the year thing, and the students were engaged. One of those days I was out of school and the substitute didn't show up, but when a teacher walked into the room, everyone was working on their project! They liked doing it, it was a valuable experience.
>
> Chemistry Teacher, 10th grade

Almost seventy percent (69.0%) of teachers also felt that students devoted more out of class time working on their engineering project than they normally spent on science, math, or technology homework. On teacher commented:

> [The students] realize that they have to use resources, their dad, use their partner, a lot have gone to Grossman's [a hardware store] and talked about it with someone, I thought that was good, they found the information they needed.
>
> Physical Science Teacher, 9th grade

Finally, 95% of teachers felt that students learned the science, mathematics, or technology concepts they were trying to teach through the design project. 94% believed that their students actually gained a better understanding of the application of science, mathematics, or technology to the real world through the design project. One 9th and 10th grade math teacher commented 'It really brings in an answer to "why are we learning this" that comes to the surface over and over'. A physics teacher decided to start out the year by having students design catapults. Even though his students did not do well on the project, his students connected physics concepts back to their project throughout the year.

> As we got more and more physics done, the students kept saying 'if I had known this when [we did the project]' . . . They kept pushing me, they wanted to go back and do it better. The project interested them but they found it frustrating for when we did it. The fact that they went back, and they wanted to reexamine the project . . . said to me that it had a lot of potential. When we had our call back session at that time I was saying I wouldn't do it again, I would do it again, [I would] do it as more of an exit project for juniors and seniors.
>
> Honors Physics Teacher, 12th grade

Although the first year of implementation of a new project is often the most difficult, 100% of the teachers indicated that their experience with the engineering design project inspired them to continue to use engineering design in their classrooms in future years. Many of the teachers articulated that they planned to expand the number and scope of the engineering projects that they did with their students in future years. For example, teachers wrote about their future plans:

> I plan to do 2–3 engineering projects per year in the future. The engineering design process and the scientific method share many of the same goals (testing/retesting).
>
> Science Teacher, Grades 6–8

> I am doing more/smaller engineering-related projects such as making a sextant and finding the height of objects by measuring angles of elevation and depression; areas of sectors and segments using radian measures; building a tower made of paper and tape and having to negotiate unannounced obstacles.
>
> Math Teacher, Grades 9–12

> Yes. We will do the same project but try to do it better and use more technology than this year. The kids have so much fun and learned a great deal. Besides, I'll like to add the water purification activity.
>
> Science Teacher, Grades 6–8

> Design and construct a hand-held game; design, construct, and test a liquid-filled mass damper; test building materials for strength; build a wind generator system; design and construct animated holiday displays.
>
> Technology Teacher, Grades 9–12

These examples suggest that knowing what the engineering design process is and having the experience of modifying a lesson to include engineering can lead to additional emphasis on engineering and the engineering design process in subsequent years.

DISCUSSION

The model of professional development that grounded the Pre-College Engineering for Teachers project was one that focused on helping teachers to understand one of the core aspects of engineering, the engineering design process, by directly engaging teachers in the process. We assumed that, as professionals, the teachers could apply their new skills and knowledge to their classroom and teaching. Asking teachers to modify a science, math, or technology lesson that they already taught to include engineering was partly a response to how we might help teachers to introduce engineering concepts to their students while being sensitive to their already packed curricula and the problem of introducing 'yet more' materials. It also stemmed from the challenge of finding ways to make engineering relevant to teachers who teach three subjects at six grade levels.

While we had strong philosophical ideas about how we might structure professional development to help the infusion of engineering, whether or not teachers felt that our somewhat unconventional methods prepared them to teach this new discipline, and resulted in classroom implementation was unknown.

The findings of our study indicate that, indeed, teachers felt they learned much about engineering concepts and became more comfortable with teaching engineering as a result of their professional development experience. Additionally, having had the experience of modifying an activity, lesson, or unit to include engineering, the majority of the teachers responded that they were planning to engage in such an exercise again either to improve or expand the same lesson or to work to infuse engineering concepts into other science, mathematics, and engineering lessons that they teach.

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