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Elementary Teachers' Engineering Design Activities from a State Without Engineering Standards

Abstract

Engineering education can be a wonderful mechanism for students to apply mathematics and science in authentic real world settings; however, less than half of U.S. states have engineering requirements in their mathematics and science standards. The many positives of engineering education can be used to help teachers see the benefits of integrating engineering. This article explores engineering activities written by elementary teachers both before and after a year-long professional development focused on STEM education. The teachers did not have any required engineering state standards, but increased their knowledge about engineering education, and saw the benefit of this approach. The activities were evaluated based on a framework for quality K-12 engineering education. The teachers improved in their inclusion of the engineering design process, and in their understanding of design constraints. The teachers' activities could still be improved though with respect to incorporating redesign and the explicit integration of mathematics and science.

Keywords: Elementary teachers; Engineering design; Professional development

Elementary Teachers' Engineering Design Activities from a State Without Engineering Standards

Engineering has the potential to be a driving force for the integration of STEM subjects. Engineers use applications of mathematics and science to design new technologies. This is done through the use of the engineering design process. However, not all states explicitly include engineering in their K-12 science standards. There are 8 states that include engineering in their science standards (Carr, Bennett, & Strobel, 2012). An additional 16 states have adopted the Next Generation Science Standards (NGSS), which include engineering design standards (National Research Council, 2013). While there is movement for more states to incorporate engineering in their standards, in the absence of engineering standards, what incentivizes teachers to teach engineering? There are many benefits to engineering integration. Incorporating engineering in K-12 schools improves achievement in mathematics and science, and increases technological literacy (Katehi, Pearson, & Feder, 2009; Wendell & Kolodner, 2014; Wendell & Rogers, 2013).

STEM knowledge is becoming more important because more jobs rely on technological advances that are driven by engineering, which relies on mathematics and science knowledge (United States Bureau of Labor Statistics, 2017). Incorporating engineering principals and activities into science instruction is one way to prepare students with this knowledge.

Engineering education motivates student learning in mathematics and science (Brophy, Klein, Portsmore, & Rogers, 2008; Wendell & Rogers, 2013). This can be done through hands-on learning and open-ended problems that develop effective teamwork skills (Carlson & Sullivan, 2004). Engineering integration can also lead students to be interested in STEM careers (Capobianco, Yu, & French, 2015; Carlson & Sullivan, 2004; Yoon, Dyehouse, Lucietoo, Diefes-Dux, & Capobianco, 2014). At the elementary level, teachers can save time as well by teaching multiple subjects through the engineering design process. Further, connecting subjects makes learning more connected and relevant (Furner & Kumar, 2007).

Elementary teachers need support if they are to be prepared to bring engineering into their classroom. Research has shown that elementary teachers are unprepared to teach engineering (Dalvi & Wendell, 2016; Hammack & Ively, 2017; Settlage et al., 2009). Thus, high quality professional development that is attentive to elementary teachers' limited knowledge of engineering practices and minimal experience with planning for engineering design, is needed (Capobianco & Rupp, 2014). Brophy et al. (2008) echoes this in that "while the introduction of engineering education into P-12 classrooms presents a number of opportunities for STEM learning, it also raises issues regarding teacher knowledge and professional development, and institutional challenges such as curricular standards and high-stakes assessments" (p. 369). Therefore, professional development for engineering education for elementary teachers is necessary, but further research is needed to elucidate the specific types of experiences and professional support that elementary teachers need to successfully implement engineering (Hammack & Ivey, 2017).

The purpose of this study was to determine the change in elementary teachers' engineering design activities after participating in a professional development experience focused on mathematics, science, and integrated STEM education. At the time of the study, the state in which the participants taught did not have required engineering state standards. Regardless, most of the teachers still implemented engineering in their classroom during the year of the professional development due to the perceived benefits of this approach. Since the majority of states do not have required engineering education standards, this study adds to the literature on the potential impact of engineering design professional development in states without engineering standards. The research question that guided this study was:

Based on a framework for quality K-12 engineering education, how well structured are elementary teachers' engineering design activities before and after participating in a year-long STEM education professional development experience?

Theoretical Framework: Engineering Design

In this study, even though the NGSS (Next Generation Science Standards) had not been adopted by the state where the professional development program occurred, the standards still received an important emphasis during the program. The NGSS (2013), which are based on the *Framework for K-12 Science Education* (National Research Council, 2012), indicate that elementary science education should be built around three dimensions: (1) science and engineering practices, (2) crosscutting concepts, and (3) disciplinary core ideas. To achieve this vision for elementary science education, teachers must be equipped with the knowledge and skills necessary to integrate engineering concepts and practices within their teaching, and they must have appropriate classroom curricular materials to introduce engineering concepts and practices to their students.

The NGSS highlights the importance of including engineering in elementary school classrooms. The NGSS adopted the NRC's broad definition of engineering as "any engagement in a systematic practice of design to achieve solutions to particular human problems"(NRC, 2012, p.11). Engineering is the practical application of scientific and mathematical knowledge to solve everyday problems. It is often described as design under constraints. Engineering should not be a separate course, but engineering concepts should be integrated within mathematics and science courses so that it is not an additional subject for teachers to teach, but a powerful way to engage and motivate students to apply and develop their mathematics and science knowledge (Brophy et al., 2008).

As in the case of science where there exists no single scientific method, engineers employ multiple approaches, and no single engineering design cycle exists. The NGSS introduces a three-step engineering design process (Define, Develop Solutions, and Optimize). A popular engineering design process that provides a little more detail is that from the Engineering is Elementary Curriculum, which has a five-step design process of Ask, Imagine, Plan, Create, and Improve (Cunningham & Hester, 2007). In the professional development in this study both of these engineering design processes were discussed with the teachers. The teachers also reflected on how they went through this process after participating in engineering design challenges and discussed how they could best have their students go through the engineering design process.

Framework for Quality K-12 Engineering Education

The framework for Quality K-12 Engineering Education (Table 1) was used to guide the engineering activities and discussions of the professional development. Quality means the distinctive attributes that are integrated in engineering design. The framework is a "high level statement of principles to inform groups interested in K-12 engineering education; general guidance for improving existing curriculum, teacher professional development, and assessment" (NRC, 2010, p.38). It is designed to represent the engineering concepts a student should understand if they have participated in engineering throughout their K-12 schooling. It can be used to evaluate curricula to see if they address the important components of a quality K-12 engineering education. The framework has 12 key indicators. The key indicators that appear at the top of the list are thought to be defining characteristics of engineering. Where, key indicators that appear later, although essential for engineering, are concepts that are required for success in multiple disciplines. While distinctions are made between the key indicators, in reality we recognize that there is some overlap between them. The development of the framework has been described in detail previously and was based on a careful document content analysis of engineering integration in STEM education standards in the U.S. states, an extensive literature review on engineering education, and in consultation with engineering and engineering education experts (Moore et al., 2014). The framework was used in this study as the coding scheme for the teachers' written descriptions of their work. We describe each key indicator briefly.

Complete Process of Design (POD)

Design processes are at the center of engineering practice. Solving engineering problems is an iterative process involving preparing, planning, and evaluating the solution at each stage including the redesign and improvement of current designs. At the K-12 level, students should learn the core elements of engineering design processes and have the opportunity to apply those processes completely in realistic situations. Although design processes may be described in many forms, certain characteristics are fundamental. This indicator represents all of the three POD sub-indicators (POD-PB, POD-PI, POD-TE) below.

Problem and background (POD-PB)

An engineering design process begins with the formulation or identification

Table 1. Framework for Quality K-12 Engineering Education

Key Indicators
Processes of Design (POD)
Problem and Background (POD-PB)
Plan and Implement (POD-PI)
Test and Evaluate (POD-TE)
Apply Science, Engineering, and Mathematics (SEM)
Engineering Thinking (EThink)
Conceptions of Engineers and Engineering (CEE)
Engineering Tools (ETool)
Issues, Solutions, and Impacts (ISI)
Ethics
Teamwork (Team)
Communication Related to Engineering (Comm-Engr)

(Moore et al., 2014).

of an engineering problem. When confronted with open-ended problems, students should be able to formulate a plan of approach and should be able to identify the need for engineering solutions. This stage also includes researching the problem, participating in learning activities to gain necessary background knowledge, and identifying constraints.

Plan and implement (POD-PI)

At this stage, students develop a plan for a design solution. This includes developing multiple solution possibilities and evaluating the pros and cons of competing solutions. This stage likely concludes with the creation of a prototype, model, or other product.

Test and Evaluate (POD-TE)

Once a prototype or model is created it must be tested. Students may collect data through experiments and/or be provided with data to analyze graphically, numerically, or in tabular form. The data should be used to evaluate the prototype or solution, to identify strengths and weakness of the solution, and to use this feedback in redesign. Since design is iterative, students should be encouraged to consider all aspects of a design process multiple times in order to improve the solution or product until it meets the design criteria.

Apply Science, Engineering, and Mathematics Knowledge (SEM)

Engineering education at the K-12 level should emphasize the interdisciplinary nature of engineering. Students can apply developmentally appropriate mathematics or science in the context of solving engineering problems. This could occur where students study mathematics or science concepts through engineering design problems. Or this could happen where students are asked to apply what they have already learned in mathematics, science, or engineering courses. Technology was intentionally placed under engineering tools, techniques and processes (ETool) below.

Engineering Thinking (EThink)

Engineering requires students to be independent, metacognitive thinkers who understand that prior experience and learning from failure can ultimately lead to better solutions. Students can come to learn that they can seek out and troubleshoot solutions to problems and develop new knowledge on their own. Students must also learn to manage uncertainty, risk, safety factors, and product reliability. There are additional ways of thinking that are important to engineers that include systems thinking, creativity, optimism, perseverance, and innovation. Collaboration (Team), communication (Comm-Engr), and ethics (Ethics), are distinct key indicators so not included here.

Conceptions of Engineers and Engineering (CEE)

This key indicator relates to an understanding of the discipline of engineering and the job of engineers. This includes how engineers' work is driven by the needs of a client, the idea of design under constraints, and that no design is perfect. Students should learn about engineering as a profession, including an understanding of various engineering disciplines and the pathways to become one of those types of engineers. Students should also gain knowledge about the engineering profession as a whole, for example: diversity, job prospects, and expectations.

Engineering Tools, Techniques, and Processes (ETools)

Engineers use a variety of techniques, skills, processes, and tools in their work. Techniques are defined as step-by-step procedures for specific tasks (examples: DNA isolation and safety protocols). Skills are the ability of a person to perform a task (examples: using Excel, creating flowcharts, drawing schematics). Tools are objects used to make the work of engineering easier (examples: hammers, rulers, calipers, calculators, CAD software, Excel software). Processes are defined as a series of actions or steps taken to achieve a particular end (examples: manufacturing, production, universal systems model). Engineering processes were not coded as *ETools* processes, because they are specific types of foundational processes, which are already covered in the POD section.

Issues, Solutions, and Impacts (ISI)

The problems that we face in today's society are increasingly multi-faceted. In order to solve these problems, students need to be able to understand the impact of their solutions in a global, economic, environmental, and societal context. Additionally, it is important to prepare students to be able to incorporate a knowledge of current events and contemporary issues locally and globally (such as urban/rural shift, transportation, and water supply issues), which will help to bring about an awareness of realistic problems that exist in today's every changing global economy.

Ethics

A well-rounded K-12 engineering education should expose students to the ethical considerations inherent in the practice of engineering. Engineers have the responsibility to use natural resources and their client's resources effectively and efficiently. They also should consider the safety of products for individual and public health. Governmental regulations and professional standards are often put into place to address these issues, and engineers have the responsibility to know and follow these standards when designing products. Engineers should conduct themselves with integrity when dealing with their client and as part of the engineering community. The products and solutions they design should work consistently and as described to the client. In creating these products, engineers must respect intellectual property rights.

Teamwork (Team)

A valuable aspect of K-12 engineering education is development of teamwork skills. This may include assuming a variety of roles as a productive member of a team. This may also include aspects of cooperative learning that focus on collaborative work as students build effective teamwork and interpersonal skills necessary for teamwork. Some of these skills include, developing good listening skills, the ability to accept diverse viewpoints, learning to compromise, and including all members of the team in the process.

Communication Related to Engineering (Comm-Engr)

K-12 engineering education should allow students to communicate in ways similar to those of practicing engineers. Engineers use technical writing to explain the design and process they have gone through in their work. The audience for this technical writing is someone with background knowledge in the area being addressed. In addition, engineers need to be able to communicate their technical ideas in common language for those without an engineering background. Using these two types of communication, engineers create presentations, write client reports, and perform explicit demonstrations. Engineers need to convey information using multiple modes, including verbal communication, symbolic representations, pictorial representations, and manipulatives. For example, reports may contain drawings, plans, and schematics, in addition to written language. All communications should be situated in a real-world context, as there must be a specific need for an engineering design.

Literature Review

Professional Development

The research on professional development for implementing engineering at the elementary level is growing, but still limited (e.g. Capobianco et al., 2011; Capobianco & Rupp, 2014; Guzey et al., 2014; Webb, 2015). Professional development experiences have been successful in helping elementary teachers to participate in engineering, but there have been mixed results in teacher implementation of engineering design in their classrooms.

In a week long engineering summer academy for forty elementary teachers, the teachers demonstrated significant positive changes in their own understanding of engineering at Bloom's Taxonomy Cognitive levels of analyze and evaluation. The teachers participated in engineering design projects and then created photo journals of their work with written reflections about their experience (Duncan, Diefes-Dux, & Gentry, 2011). Similar to this study, our professional development incorporated Model-Eliciting Activities (MEAs). MEAs are client-driven, open-ended, real world engineering design activities in which participants work in teams to apply and develop their STEM knowledge (Lesh & Doerr, 2003).

Another engineering professional development experience for elementary teachers focused on the teachers' content and pedagogical content knowledge; as well as perceptions of self-efficacy to teach engineering. The results showed that the teachers experienced statistically significant gains in content knowledge, pedagogical content knowledge, and self-efficacy to teach engineering (Webb, 2015). The professional development experience had the teachers participate in the Engineering is Elementary curriculum and also emphasized the NGSS disciplinary core ideas, cross cutting concepts, and science and engineering practices. Our professional development also incorporated these components. Another study conducted on a three day professional development program for elementary teachers which also focused on knowledge of engineering and teacher self-efficacy found significant increases in teacher confidence, efficacy, and perceptions of engineering in participating teachers (Nadelson, Callahan, Pyke, Hay, Dance, & Pfiester, 2013).

Some studies have investigated elementary teacher implementation of engineering design after a professional development program through examination of lesson plan content. In one study, teachers who participated in a yearlong engineering design professional development program produced posters, lesson plans, and student artifacts. Examination of these products yielded results that indicated that the majority of the teachers who participated in the professional development program were able to effectively implement engineering design lessons. The study results suggested that the teachers' success in implementing engineering lessons was closely related to the structure of the professional development program (Guzey, Tank, Wang, Roehrig, & Moore, 2014). Some of the Guzey et al. study professional development program structure was also utilized in the current study. We can have confidence that these similar components were implemented in the same way, as the first author in this study was a professional development facilitator during the Guzey et al. study. Although many of the programming components were the same or similar, the professional development program in the Guzey et al. study did not include the same focus on the NGSS standards as in the current study. Some professional development materials, such as the "Engineering is Elementary" curriculum and the "Model-Eliciting Activities" were used in both studies.

Another engineering design professional development program impact study followed 23 fifth and sixth grade teachers who planned and implemented engineering-design instruction after participating in a two-week summer institute. Data was gathered from lesson plans and classroom observations. The teachers demonstrated strength in planning for standards, and incorporating engineering practices. However, the lessons did not include integration of science concepts. The teachers also did not spend much time on testing designs, communicating results, and redesign (Capobianco & Rupp, 2014). As the prior study demonstrated, quality curricular materials for engineering design that incorporate mathematics and science content are needed at the elementary level. Curricula should require an explicit focus on students going through the full engineering design process and have students apply mathematics and/or science knowledge.

A partnership between university faculty members and elementary teachers can be a productive method for designing and testing curriculum. Lehman, Kim, & Harris (2014) described a study in which university personnel designed a curriculum, and elementary teachers implemented the curriculum and provided constructive feedback to revise the curriculum. The teachers found that the provided curricular materials were an important element in the success of their work. Another university and teacher partnership involved a year-long professional development experience in which 48 teachers designed 20 engineering design-based STEM curricular units (Guzey, Moore, & Harwell, 2016). This curriculum was not available at the time of the professional development program carried out as part of this study, but the participating teachers were provided curricular resources, including MEAs, the "Engineering is Elementary" curriculum, and several websites containing vetted engineering design activities.

In total, there is a need for further research on how to properly prepare elementary teachers to effectively implement engineering education. Studies show that even after quality professional development experiences, important components of engineering education are often missing during implementation. The development and use of well-designed engineering education curricula that include an explicit focus on the steps of the engineering design process can aid teachers in the successful use the engineering design process in their classrooms. In this study, teachers utilized and discussed well-designed curricular materials during a professional development experience guided by a well-developed Framework for Quality K-12 Engineering Education (Moore et al., 2014), which is inline with how engineering education is represented in the NGSS. The teachers also implemented engineering education in their own classrooms, and reflected upon this experience.

Method

Setting

This study took place in a large urban school district in a Southwestern state of the United States. Thirty-three 3rd to 5th grade teachers comprised the sample. Of the 33 teachers, 29 were female and 4 were male. Thirty-one of the teachers were Caucasian, one teacher was African American, and one teacher was Asian. The year-long professional development program that the teachers participated in focused on teaching science, mathematics, and STEM integration, using engineering design. Since integration should not be forced, and should only be incorporated using natural connections with other content, not all aspects of the professional development program included STEM integration. The Common Core Math Standards (Common Core State Standards Initiative [CCSSM], 2010) would be assessed in the following year at the school, and thus some time was dedicated solely to mathematics. The leaders of the professional development program involved the first author, one of the writers of the NGSS, and a district mathematics specialist, who had previously been an elementary school teacher.

The professional development involved four full summer days with seven two hour professional learning community meetings during the school year; as well as two three hour follow-up meetings. Of the total professional development time, two of the summer days focused on STEM integration through the engineering design process; as well as two of the professional learning community meetings. Table 2 contains the focus of the STEM integration professional development activities. There were two essential questions for the focus of the professional development that tied together the mathematics, science, and integrated STEM education foci. (1) What instructional strategies are most useful to engage students in using evidence to construct explanations and solutions? (2) What is the nature of instruction that leads to students valuing and using STEM in enjoyable, useful, and memorable ways? The first question tied into organizing the eight science and engineering practices from the National Research Council (2012) into strategies that allow students to gather, reason, and communicate with an emphasis on writing and representations. The second question connects with the Framework for Quality K-12 Engineering Education presented above. After each of the engineering design activities, the teachers reflected on the science and engineering practices, crosscutting concepts, and disciplinary core ideas that were involved in the activities.

Discussions were also conducted based on the key indicators of the Framework for Quality K-12 engineering education. Since the teachers were new to engineering, the focus was placed on the engineering design process, and what mathematics and science concepts and processes were incorporated in the activities; which are included in the first four key indicators of the Framework for Quality K-12 engineering education. For example, the teachers completed the Robot Art MEA in which they have to develop directions and a method to program a robot to draw any picture. In MEAs the problem and background main idea key indicator is accomplished through a pre-reading and discussion of the problem statement provided to

Table 2. STEM integration through engineering design professional development activities

Summer sessions	• Presentation on the National Research Council Framework for K-12 Science Education (2012) and Next Generation Science Standards (NGSS Lead States, 2013) • Design a paper airplane with criteria for horizontal distance flown based on the height the plane was dropped • STEM Integration framework (Stohlmann et al., 2013) • Framework for Quality Engineering Education (Moore, et al., 2014) • Commonalities and differences in science and engineering • Engineering is Elementary (EiE): A slick solution: cleaning an oil spill • Lesh Translation Model (Lesh & Doerr, 2003). • Integrated STEM Model-Eliciting Activities (Stohlmann et al., 2013).
Professional Learning Communities	• National Research Council Report (2011): Successful K-12 STEM Education • STEM integration lesson ideas discussion • STEM integration lesson and student work sharing
Follow-up meeting	Sharing integrated STEM lessons

teachers. The teachers saw the need for the solution, could use the Internet to research more information, and were able to discuss the constraints of the problem. The teachers next brainstormed ideas and developed multiple solutions through trying to give directions to one teacher in the group who pretended to be the robot. Through this process they were able to create a model and express, test, and revise through trying different pictures. The mathematical knowledge and skills involved in this activity included various mathematical vocabulary, geometry concepts, and measurement skills. The teachers also learned the importance of creativity, innovation, and learning from failure. All MEAs have a client that the participants work for, and thus it is important for participants to learn that designs have constraints.

The separate science activities focused on developing models, using models to make sense of phenomena, science core ideas, gathering information, reasoning, science communication, investigating variation in growth patterns of quaking aspen trees at different elevations, and investigating the forces of attraction and repulsion between objects with a static charge. The professional learning community meetings focused on discussions from the book, *Ready, Set, Science!: Putting Research to Work in K-8 Science Classrooms* (Michaels, Shouse, & Schweingruber, 2007). The focus of three meetings was on making thinking visible through talk and argument, models and representations, and investigations. The follow-up science meeting focused on models and representations as well. The separate mathematics activities focused on the Common Core State Standards for Mathematics, the Standards for Mathematical Practice, the 5 strands of mathematical proficiency from the book, *Adding it up: Helping Children Learn Mathematics* (Kilpatrick, & Swafford, 2002), and definitions of addition, subtraction, multiplication, and division. The mathematics professional learning community meetings were based on the five strands of mathematical proficiency, discussing the article snapshots of student misunderstanding (Burns, 2010), and student work on a rational number interview. The mathematics follow-up meeting focused on story problems for division and fractions.

Data Collection and Analysis

At the beginning and conclusion of the professional development the teachers provided written responses to a prompt.

Describe a problem that can be used in a classroom to engage students in the engineering design process.
a. Describe the problem
b. Describe the constraints
c. Describe the instruction to scaffold student learning of the engineering design

Due to the fact that a few of the teachers did not implement a STEM integration lesson in their classroom, the teachers were allowed to write about a classroom-implemented activity, or one that they have not implemented. While we do not know if every teacher implemented the activities that they described, from discussions during the professional development and professional learning community documents, it appears that most of the teachers did implement the discussed activities in their classroom. The teachers' written work was analyzed using the key indicators of the The Framework for Quality K-12 Engineering Education (Table 1) as a coding scheme. Since each key indicator encompassed multiple ideas, each key indicator was detailed with several main ideas that were used in the coding process.

Two of the researchers coded the teachers' written responses. The coders were both doctoral students in mathematics education. One of the students had worked with the first author on several projects on integrated STEM education and did her dissertation work on engineering-design based MEAs with elementary students. The other student was familiarized with engineering education through literature provided by the first author. The two doctoral students coded and discussed three of the elementary teachers' responses with the first author before completing the coding individually, and then meeting to compare codes. The Cohen's K coefficient of inter-rater agreement was 0.97, and thus was within an acceptable range (Fleiss, 1981; Landis & Koch, 1977). Once coding differences were identified, the raters came to agreement on the discrepancies so that full agreement was reached.

Results

We first provide a summary of each key indicator that includes the main ideas of each key indicator, the number of teachers that included each main idea on the pre and post responses, and examples of responses that fit the main ideas. There were 33 teachers that completed the description of their activity on the pre-test and 30 teachers on the post-test. On the pre-test 11 of the teachers did not have the knowledge to answer the questions and left the page blank.

Problem and Background (POD-PB)

There are six main ideas for this key indicator. Table 3 has a summary of the codes and frequencies for each main idea from the pre and post written descriptions of the activities. Some of the engineering problems on the pre-test included designing a bridge or tower with criteria of height or weight to be held. On the post-test, some of the engineering problems included designing a chair or boat to hold a specified amount of weight, designing a kite to fly the height of the school, and designing a system to prevent flooding. On the post-test, most of the teachers included a requirement for a design plan. Nine teachers on the pre-test provided more background information for their engineering problem to show the need for the solution. Some of the needs included a water shortage in the city, designing a bridge so vehicles can cross, and designing a bridge to span a river to connect the people on both sides. On the post-test, some of the needs included flooding prevention, increasing the number of customers at a mini golf course, and for a pioneer family moving west to be able to cross a river with their belongings.

On the pre-test five teachers described learning activities to be used before students began the design phase. These included investigating the strengths and weaknesses of different bridge designs through examples and non-fiction texts, learning about the laws of motion, and learning about chemical reactions. Learning activities on the post-tests included knowledge about mining, erosion, flight, and buoyancy. On the pre-tests most of the constraints mentioned were materials. Other constraints included design specifications including maximum measurements, minimum weight to be supported, and the time needed for a structure to stand. On the post-tests materials again were the most often stated constraints, but money and time were also frequent constraints. Other constraints included maximum measurements, using the least amount of materials, and requirements for mini golf holes.

Plan and Implement (POD-PI)

All three main ideas for this key indicator had an increase of at least forty-four percent (Table 3). On the post-test all but four of the teachers emphasized the importance of trying to develop multiple solutions before selecting one as the initial design. On the post-test all but three of teachers mentioned that students would brainstorm or plan their designs. On the pre-test fourteen teachers described that students would design a physical model including a bridge, rocket, roller coaster, and a device to measure power output of wind. On the post-test teachers also described physical models including towers, bridges, boats, chairs, and a water slide. In addition to physical models, processes were also described. Two teachers described an activity where students would come up with a process for cleaning a simulated oil spill. One teacher described how students would develop a process for a simulated mining of materials. Another activity would require students to have a process for throwing their paper airplanes the farthest distance.

Test and Evaluate (POD-TE)

All three main ideas for this key indicator showed an increase of at least nine teachers (Table 3). On the pre-test seven teachers described a bridge or structure design to be tested with data collection and analysis for how much weight it could hold. Other ideas included the height from a rocket launch, a structure to withstand an earthquake, a tower to withstand wind, and testing a roller coaster design. Four teachers also described the need to give students a chance to redesign. On the post-test the most frequent way to test a design and collect and analyze data, was again to see how much weight a bridge, structure, chair, or boat could hold with ten activities. Some of the other ideas included the amount of oil cleaned from an oil spill, farthest distance of a plane, distance from target of a projectile, difficulty of a mini golf course, highest tower, and fastest water slide.

Table 3. Processes of Design summary

Problem and Background Main Idea	Pre	Post
Identification of an engineering problem	18 (54.5%)	27 (90%)
Formulate a plan of approach	15 (45.5%)	27 (90%)
Identify the need for engineering solutions	9 (27.3%)	12 (40%)
Research the problem	1 (3%)	3 (10%)
Participate in learning activities to gain necessary background knowledge	5 (15%)	11 (36.7%)
Identify constraints	18 (54.5%)	28 (93.3%)
Plan and Implement Main Idea		
Brainstorming/Plan	15 (45.5%)	27 (90%)
Developing multiple solutions	14 (42.4%)	26 (86.7%)
Creation of a model or prototype	14 (42.4%)	27 (90%)
Test and Evaluate Main Idea		
Test the model	11 (33.3%)	26 (86.7%)
Collect and analyze data	11 (33.3%)	26 (86.7%)
Evaluate and redesign	4 (12.1%)	13 (43.3%)

Apply Science, Engineering, and Mathematics (SEM)

There are three main ideas for this key indicator (Table 4). Types of mathematics knowledge included in the pre-test responses involved measurement and general problem solving skills. The types of science knowledge mentioned included concepts related to circuits, force, laws of motion, chemical reactions, and wind. On the pre-test, the engineering knowledge applied related to techniques to build a stronger bridge or tower. The mathematics knowledge described on the post-test was slope and three-dimensional figures. On the post-test**,** science concepts included simple machines, laws of motion, acceleration, friction, buoyancy, erosion, drag, thrust, tension, and force. One teacher on the post-test described engineering knowledge in the context of the strength of bridge designs.

Engineering Thinking (EThink)

This key indicator showed a large increase in the main idea of learning from failure and prior experience, while examples of five of the *EThink* main ideas were not found in the data (Table 4). On the pre-tests, four teachers described the importance of students learning from tests of designs to guide improvement in their designs. Two teachers also stated the importance of safety in designs. On the post-tests thirteen teachers mentioned students having the opportunity to redesign after learning from their initial designs. Five teachers also mentioned that students could use their prior experience about boats, paper airplanes, motion, and literature about kites to aid in their designs. Two teachers mentioned safety in designs. The idea of uncertainty was involved in two designs that involved the environment to stop flooding and erosion.

Conceptions of Engineers and Engineering (CEE)

This key indicator showed a ten percent increase in one main idea and an approximately fifty percent increase in another main idea (Table 4). On the

Table 4. Four of the key indicators summary

Apply Science, Engineering, and Mathematics Main Idea	Pre	Post
Apply mathematics knowledge	3 (9.1%)	2 (6.7%)
Apply science knowledge	7 (21.2%)	11 (36.7%)
Apply engineering knowledge	2 (6.1%)	1 (3%)
Engineering Thinking Main Idea		
Learn from failure/prior experience	4 (12.1%)	18 (60%)
Manage uncertainty, risk, safety, and product reliability	2 (6.1%)	4 (13.3%)
Systems thinking	0	0
Creativity	0	0
Optimism	0	0
Perseverance	0	0
Innovation	0	0
Conceptions of Engineers and Engineering Main Idea		
Work driven by the needs of a client	3 (10%)	6 (20%)
Designs have constraints	18 (54.5%)	28 (93.3%)
No design is perfect	1 (3%)	1 (3.3%)
Learn about engineering profession (jobs and disciplines)	0	0
Engineering Tools Main Idea		
Engineering techniques	0	0
Engineering skills	0	0
Engineering tools	0	2 (6.7%)
Engineering processes	1 (3%)	0

pre-tests clients included two schools and a class of students. On the post-tests clients included many different scenarios, involving a mini golf course, a condominium manager, a water park, a class of students, a city, and the President of the United States. On the pre and post test one teacher wrote about the need for students to redesign their design, so that they understand they can always continue to make changes for improvement.

Engineering Tools (ETool)

This key indicator had the fewest amount of representative examples found within the teacher responses (Table 4). On the pre-test a teacher stated that the construction process of a bridge would be discussed with students. On the post-test one teacher stated that students would use stream tables to model flooding and another teacher mentioned that technology would be available for students to use in their designs.

Issues, Solutions, and Impacts (ISI)

This key indicator had two main ideas, which connected with a couple of teachers' written work (Table 5). On the pre-test the impact of design solutions in a social and environmental context were noted with a design for a device to conserve water for a school's bathroom sinks and for a building design to withstand earthquakes. Knowledge of current events was shown with the identification of a local water shortage problem as part of the problem description. On the post-test the impact of solutions in an environmental context was met through design requirements for a water barrier to control flooding and for a natural design to prevent erosion on a mountain. These contexts also tied into current events near the schools of the teachers.

Ethics

Only a couple of teachers' written work fit the ethics key indicator (Table 5). On the pre-test a teacher described the need to decrease water flow in sinks to conserve water. On the post-test a teacher noted the need for a design of a new water slide to be safe. Another teacher described the need for a water barrier system to help prevent damage to roads. The same teacher also had constraints for students to specifically use a limited amount of materials in their design to try to conserve resources.

Teamwork (Team)

There was a slight increase from the pre to post-test for the teamwork key indicator (Table 5). On the pre-test two teachers stated that students would be working in teams, with one of these teachers stating that her students would be used to this. On the post-test, it was mentioned that students would work in groups by five teachers, with one teacher explicitly mentioning cooperative learning.

Communication Related to Engineering (Comm-Engr)

Only a few responses were coded for this key indicator (Table 5). On the pre-tests two teachers described students having to write a final report of their design. One teacher on the pre and post-test also mentioned multiple representations through a design sketch, prototype, and written description. On the post-test four teachers described that students would create a final report, with two teachers mentioning students would give a presentation of their findings.

Change in number of key indicators

We calculated the number of key indicators that each teacher was coded for their pre and post-tests to determine the improvement or decline in their activities. Just the teachers that completed the pre and post-tests were included. Kersten (2013) described that for an activity to be of adequate quality it needed to include the first five key indicators central to engineering (PB, PI, TE, SEM, and EThink). Because of this, we separate the change in number of key indicators for these five first before displaying the change for all eleven key indicators. The majority of teachers increased at least one key indicator (Table 6). Of the seven teachers that showed no improvement, three of the teachers were coded as including all main ideas except for EThink on the pre-test, and one of the teachers was coded as including all five key indicators on the pre-test.

Table 7 displays the change in all eleven key indicators and shows that most

Table 5. The last 4 key indicators summary

Issues, Solutions, and Impacts Main Idea	Pre	Post
Impact of solutions in global, economic, environmental, or social context	2 (6.1%)	2 (6.7%)
Knowledge of current events	1 (3%)	2 (6.7%)
Ethics Main Idea		
Use natural resources and client resources effectively	1 (3%)	1 (3.3%)
Consumer safety	0	2 (6.7%)
Government standards and professional regulations	0	0
Engineers should conduct themselves with integrity	0	0
Teamwork Main Idea		
Develop the ability for students to participate as contributing team members	2 (6.1%)	5 (16.7%)
Communication related to engineering Main Idea		
Write client reports, presentations, or demonstrations	2 (6.1%)	6 (20%)
Embody information through multiple representations	1 (3%)	1 (3%)

of the teachers (21 teachers or 70%) improved. Over half of the teachers improved in at least 2 key indicators.

Discussion

This study was conducted to determine the change in quality of engineering activities developed by 3rd to 5th grade teachers after participating in a year-long STEM education professional development. The state where the study was conducted did not have required engineering education state standards at the time of the study, but the teachers still showed development of their engineering education knowledge.

On the post-tests, all but four of the teachers included all three key indicators for engineering design as defined by The Framework for Quality Engineering Education. The Framework for Quality Engineering Education (Moore et al., 2014) has identified engineering design as the focus of engineering in K-12 education. Similarly, engineering design is central in the Next Generation Science Standards (NRC, 2013) and the Framework for K-12 Science Education (NRC, 2012). Incorporating the engineering design process in activities is an integral part for K-12 engineering education; but is not sufficient for students to develop their engineering expertise.

While the teachers' activities that were developed after the professional development program improved in a number of areas, there were identified areas that could be strengthened further. For instance, less than half of the teachers wrote about redesign. Stohlmann, Roehrig, & Moore, (2014) noted that the most common part of the engineering design process skipped by teachers is the redesign step. While time constraints may play a part in this, it is important that students understand and experience the iterative nature of the engineering design process. Also, students can see how they can learn from failure and improve their designs through redesign. Students also gain a better understanding of the real work of engineers when recognizing that redesigns are often necessary.

Another area of improvement was the explicit integration of mathematics and science in the engineering activities. One of the key parts of the Framework for Quality K-12 Engineering Education is the integration of math and science content through engineering design activities (Moore et al., 2014). While on the post-test over a third of teachers wrote about the integration of science, only two teachers wrote about the integration of mathematics in the post-test. Engineering education should not be viewed as additional content for teachers to teach, but integrated as a pedagogy for learning and applying mathematics and science content in authentic scenarios. Integration of subjects should be implemented using natural connections between subjects, so that it is not forced. It is challenging to teach all science or mathematics concepts through engineering, but areas commonly covered using an engineering design process are force, motion, measurement, and data analysis (Guzey, Tank, Wang, Roehrig, & Moore, 2014).

The understanding that engineers work for a client, and also general knowledge of the engineering profession, were other areas of improvement reflected in the post-test responses. Including a client in an engineering design activity scenario helps to situate the activity in a realistic context, and highlights the need for the engineering solution. Chubin, May, & Babco (2005) note that an effective precollege program must promote awareness of the engineering profession. The Engineering is Elementary (EiE) curriculum includes components which allow students to effectively learn about a field of engineering and the work that engineers do (Cunningham, 2009). Two of the participating teachers wrote about the oil spill EiE unit: A slick solution: cleaning an oil spill (which was demonstrated in the professional development program), in their post-test responses. The material kits for these units can be expensive, so it is important for teachers to be provided with fiscal support for their implementation of STEM education. The need for materials kits for activities was one of the four main parts of a s.t.e.m. (support, teaching, efficacy, and materials) model of considerations for teaching integrated STEM education proposed by Stohlmann, Moore, & Roehrig (2012). For teachers working

Table 6. Change in first five key indicators

Change in key indicators	–1	0	+1	+2	+3	+4	+5
Number of teachers	4 (13.3%)	7 (23.3%)	3 (10%)	7 (23.3%)	1 (3.3%)	6 (20%)	2 (6.7%)

Table 7. Change in key indicators

Change in key indicators	–2	–1	0	+1	+2	+3	+5	+6	+8	+9
Number of teachers	1 (3.3%)	2 (6.7%)	6 (20%)	3 (3.3%)	7 (23.3%)	2 (6.7%)	3 (3.3%)	4 (13.3%)	1 (3.3%)	1 (3.3%)

in states without engineering standards, fiscal resources for material kits may be more difficult to acquire, and thus this particular barrier to implementation may be more of a critical concern.

The teachers in this study were provided with several resources in order to identify engineering design activities that they could implement. In addition to the EiE units that were available to teachers, websites for Model-Eliciting Activities were provided (https://unlvcoe.org/meas and http://www.cpalms.org/cpalms/mea.aspx). Several other websites were also recommended: (a) teachengineering.org, (b) http://teachers.egfi-k12.org, (c) http://www-g.eng.cam.ac.uk/mmg/teaching/peterstidwill/interact/interact.htm, (d) http://www.engr.ncsu.edu/theengineeringplace/educators/k8plans.php, and (e) http://pbskids.org/designsquad/. Moore & Smith (2014) note that "curricula that integrate STEM are rare for K-12 spaces, and of those that do, even fewer are research-based and have meaningful mathematics and science. Funding to back new and research-based STEM integration curricular innovations is needed and should be targeted" (p.7). If research-based STEM integration curricular can be developed then this will help lessen the issue of teachers attempting to identify their own engineering design activities. Work in this area has been increasing (e.g. Guzey et al., 2016; Lehman et al., 2014).

While there are few research-based curricula that have meaningful mathematics and science content, overall mathematics content tends to be lacking more often (NAP, 2014; Tran & Nathan, 2010). A focus on the mathematics in integrated STEM education is a necessary next step. Since most states have adopted the Common Core State Standards for Mathematics (CCSSM, 2010), STEM integration curriculum that is connected to these standards would lead to greater buy-in for teachers and districts and increased time devoted to professional development. STEM integration connected to the Common Core Math Standards was modeled and discussed in the professional development program implemented as part of this study through Model-Eliciting Activities (MEAs). Model-Eliciting Activities (MEAs) are supported by a strong research base (e.g. Lesh & Doerr, 2003), and have been shown to be effective with elementary students (e.g. English, 2009).

As the number of states that incorporate engineering education in K-12 schooling increases there is a great need for high quality professional development. The American Society for Engineering Education (ASEE) has published documents to assist with this need. *Standards for Professional Development for K-12 Teachers of Engineering* (ASEE, 2014) describes five standards for effective professional development for teachers of engineering. These standards were developed based on the research on effective professional development both in general, and in science and mathematics. A related document, *Matrix for Professional Development for K-12 Teachers of Engineering (ASEE, 2014)*, details how a professional development program could demonstrate a level of emphasis on the parts of each standard.

Many teachers are not knowledgeable or comfortable using engineering design as a vehicle to teach content (NAE, 2010). In this study, a third of the teachers left the pre-test blank because they did not have the knowledge to answer the prompts. The teachers showed growth in the quality of their produced engineering activities by the end of the year. This study shows that it is possible to still have teachers grow in their appreciation and development of engineering knowledge in the absence of state-mandated engineering standards. This process, however, will likely take longer than one year for many teachers. For instance, in-service teachers will likely need multiple concurrent years of professional development to effectively implement STEM integration through engineering.

There are many benefits of engineering education, and children in the elementary grades have a strong natural connection with engineering. Young children are inherently active with strong impulses to investigate, to share with others what they have found out, to construct things, and to create. In other words, a child is a natural engineer (Genalo, Bruning, & Adams, 2000).

It is vital that support for professional development occurs so that teachers do not simply decide to not teach science or engineering because they are not comfortable with the content. Given the importance of STEM and engineering instruction, engineering standards should be required in elementary curriculum, but until this happens this study serves to show that elementary teachers without engineering state standards can still be motivated to implement engineering.

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