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**Is Adding the E Enough?: Investigating the Impact of K-12 Engineering Standards on the
Implementation of STEM Integration**

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Introduction

National policy documents related to STEM and STEM education have been abundant in the past four years. Each of these reports is based on the premise that continued progress and prosperity within the U.S. depends on the development of the future generation of STEM professionals, in fact, that our ability to compete in the global economy is at risk. For example, in the executive report to President Barack Obama, *Prepare and Inspire: K-12 education in Science, Technology, Engineering, and Math (STEM) Education for America's Future*, the President's Council of Advisors on Science and Technology stated that the education system in the U.S. must prepare students to have a strong foundation in science, technology, engineering and mathematics (STEM) (President's Council of Advisors on Science and Technology, 2010). Similarly, the congressionally commissioned report, *Rising Above the Gathering Storm* (National Academy of Sciences [NAS], National Academy of Engineering, and Institute of Medicine of the National Academies, 2006), called for a comprehensive, coordinated federal effort to ensure more students pursue STEM fields. The report recommends a comprehensive investment in quality STEM education programs that will increase the quality and knowledge of the teaching force in the STEM fields.

The problems that we face in our ever-changing, increasingly global society are multidisciplinary, and many require the integration of multiple STEM concepts to solve them. In addition to the national competitiveness arguments cited above, the multi-disciplinary nature and complexity of real-world problems is a driving force behind national calls for changes in STEM education (NAS et al., 2006; National Center on Education and the Economy [NCEE], 2007). The rapid evolution of technology in the 21st century is also changing the needs for the workforce in general and more specifically in STEM fields; in turn, this changes the expectations for students entering this ever-changing workforce and the teachers who prepare them to do so. Professional societies, such as the American Society for Engineering Education (ASEE) and

National Academy of Engineering (NAE), call for new educational approaches that focus on the hands-on, interdisciplinary, and socially relevant aspects of STEM, specifically highlighting engineering as a discipline that can meet these goals (Brophy, Klein, Portsmore, & Rogers, 2008). This is not only to develop the next generation of STEM workers but also to develop technological, or STEM, literacy for all. As a precursor to these varied national policy documents, Hurd (1998) clearly indicates that current ways of teaching and learning "need to be reinvented to harmonize with changes in the practice of science/technology, an information age, and the quality of life," (p. 411) because science today is becoming more "holistic in nature" (p. 409) and "transdisciplinary" (p. 409). Hurd emphasizes teaching science around issues of the world (healthcare, the environment, etc.) that will naturally integrate traditional subject areas.

Although policymakers and educators are aware of the importance of STEM education, there is no common understanding or agreement on the nature of STEM education as an integrated or multidisciplinary endeavor. One of the biggest educational challenges for K-12 STEM education is that few general guidelines or models exist for teachers to follow regarding how to teach using STEM integration approaches in their classroom. For example, one of the recommendations from the national *Rising Above the Gathering Storm* report (NAS et al., 2006) calls for the development and evaluation of world-class STEM curriculum, citing Project Lead the Way (a K-12 engineering curriculum) as an example. Yet recent research has indicated that Project Lead the Way curricula do not integrate mathematics and science in a manner that leads to gains in mathematical and scientific knowledge (Tran & Nathan, 2010) or address state-level mathematics and science standards (Stohlmann, Moore, McClelland, & Roehrig, in press). Research on STEM integration in K-12 classrooms has not kept pace with these sweeping policy changes in STEM education. This study addresses the need for research to explore the translation of broad, national-level policy statements regarding STEM education and integration to state level policies and implementation in K-12 classrooms and is guided by the following research question:

What models of STEM integration do secondary science, mathematics, and technology teachers implement in response to new STEM state standards?

Background Literature

The goal of curriculum integration derives from an awareness that, in the real world, problems are not separated into isolated disciplines (Beane, 1995; Czerniak, Weber, Sandmann, & Ahern, 1999; Jacobs, 1989). Integration is not a new idea in education; Hirst (1974) pointed out that an artificial separation of subject areas restricts learning, as students are alienated from the real world experience. Many researchers and educators agree that curriculum integration can provide more meaningful learning experiences for students by connecting disciplinary knowledge with personal and real world experiences (Beane, 1991; 1995; Burrows, Ginn, Love, & Williams, 1989; Capraro & Slough, 2008; Childress, 1996; Jacobs, 1989; Sweller, 1989).

Conversations about STEM integration have been grounded in these broader discussions about STEM integration, and an integration of STEM subjects offers students one of the best opportunities to experience learning in a real world situation, rather than learning piece by piece (Tsupros, Kohler, & Hallianen, 2009). Unfortunately, “as STEM education is currently structured and implemented, it does not reflect the natural interconnectedness of the four STEM components in the real world of research and technology development” (NAE, Katehi, Pearson, & Feder, 2009, p.150), which has consequences for student interest and performance in science and mathematics, and the development of technological and scientific literacy. Additionally, there are no agreed on articulations for the goals, curriculum arrangements, and classroom practices for STEM integration (Venville, Wallace, Rennie, & Malone, 1999).

In spite of this lack of consensus related to the details of STEM integration, both national and state policymakers are pushing a STEM agenda. At the national level, the draft of the *Next Generation of Science Education Standards* articulates and discusses the role for engineering and technology in science education (National Research Council [NRC], 2010). This document moves the conversation from the

rhetoric and broad recommendations of *Rising Above the Gathering Storm* (NAS et al., 2006) into an articulation of standards for teaching. With the growing pressure of improving student performance in science and mathematics to secure federal education dollars, states have embraced STEM and advanced new standards in science and mathematics ahead of these national documents. Twelve states (Colorado, Illinois, Indiana, Massachusetts, Minnesota, Nebraska, New York, Oregon, Tennessee, Texas, Vermont, and Washington) have formally included engineering concepts as part of their state science academic standards (Strobel, Carr, Martinez-Lopez, & Bravo, 2011) with several other states in the process of changing their standards to incorporate engineering. There is an increased emphasis at the national and state level on considering connections between science, technology, engineering, and mathematics, yet agreement and research on effective models of STEM integration is lacking.

A recent report from the National Academy of Engineering (2009), *Engineering in K-12 Education: Understanding the Status and Improving the Prospects*, reviewed the current status of K-12 engineering education. The report's findings explicitly identify K-12 engineering as "a catalyst for integrated STEM education" stating that "there is considerable potential value, related to student motivation and achievement, in increasing the presence of technology and, especially, engineering in STEM education in the United States in ways that address the current lack of integration in STEM teaching and learning" (p. 150). Engineering provides a vehicle to provide a real-world context for learning science and mathematics as "in the real world, engineering is not performed in isolation—it inevitably involves science, technology, and mathematics. The question is why these subjects should be isolated in schools" (NAE, 2009, pp. 164-5). Researchers and professional associations provide further compelling rationales for inclusion of engineering in K-12 curriculum, either as a course in its own right or woven into existing mathematics and science courses. Some of these rationales for the inclusion of engineering in K-12 coursework include (Koszalka, Wu, & Davidson, 2007; Hirsch, Carpinelli, Kimmel, Rockland, & Bloom, 2007; Brophy et al., 2008):

- Engineering provides a **real-world context** for learning mathematics and science;
- Engineering design tasks provide a context for developing **problem-solving skills**; and
- Engineering design tasks are complex and as such promote the development of **communication skills and team work**.

Integration of engineering into the K-12 curriculum makes sense given the interdisciplinary nature of the problems of the 21st century and the need to provide more authentic, real-world meaning to engage students in STEM. In order to prepare students to address the problems of our increasingly technological society, it is necessary to provide students with opportunities to understand the problems through rich, engaging, and powerful experiences that integrate the disciplines of STEM.

Recommendations for the scope of the knowledge and skills to be included in K-12 engineering standards call for a focus on (i) engineering design, (ii) the incorporation of important and developmentally appropriate mathematics, science, and technology knowledge and skills, and (iii) engineering habits of mind (NAE, 2009). Engineering practice, at its core, is a way of thinking in order to solve problems for a purpose. This is characterized by the engineering design process, which is the "distinguishing mark of the engineering profession" (Dym, 1999). Dym, Agogino, Eris, Frey, and Leifer (2005) define engineering design as "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" (p. 104). Indeed, engineering design is a prominent feature of existing state science standards that incorporate engineering. For example, Minnesota's state standards incorporate engineering design, engineering habits of mind and an articulation of the intersection of the STEM disciplines in the Nature of Science and Engineering strand (see Table 1).

[Table 1 approximately here]

As is the case with other states, the articulation of the integration of specific science and mathematics concepts with engineering design principles is less explicit. The introduction to the Minnesota

standards states, “It is important to note that the content and skills in The Nature of Science and Engineering are not intended to be taught as a stand-alone unit or an isolated course, but embedded and used in the teaching, learning and assessment of the content in the other strands” (Minnesota Department of Education [MDE], 2009). However, schools and teachers are left to determine a structure through which this integration could or should occur without guidance from policymakers or research into STEM integration models.

Professional development opportunities related to K-12 engineering are not common, and when they do occur, they are usually designed for technology teachers and directly associated with specific engineering curriculum projects. In addition, these existing curricula are not designed with a STEM integration model in mind (NAE, 2009). As the existing state STEM frameworks call for the integration of engineering under the umbrella of the science standards, science teachers are suddenly confronted with the challenge of implementing STEM integration into their classrooms. Without systematic professional development for science teachers thrust into a system that requires them to integrate engineering in a STEM integration context, the possibilities and promise of national and state policy will not be fulfilled. To address the need for STEM professional development for science teachers, research that looks into the effective models of STEM integration in K-12 science classrooms needs to be done without delay in order to provide timely information for teachers and educators. The National Academy of Engineering (2009) report recognizes that integrated STEM education will require changes in teachers’ practice and possibly the structure of the school setting itself. The report calls for research in STEM integration to both develop and test STEM curricula and approaches to teacher professional development.

The Study

This study is qualitative in nature. An interpretive multi-case study design was employed to conduct an in-depth investigation of secondary science and mathematics teachers’ implementation of STEM integration in their classrooms (Merriam, 1998). The interpretive approach was used because it provides

holistic descriptions and explanations for the particular phenomenon, in this case STEM integration. Case study particularly suits this study, since it aims to understand teachers' interpretation and implementation of a new construct in their classrooms. Each case is embedded within a bounded system (Creswell, 2007) that includes schools and teachers who participated in a STEM integration professional development during the 2009/2010 school year.

Context

In response to the need for professional development to implement new standards in both mathematics (introduced in Fall 2008) and science/engineering (introduced in Fall 2009), the Minnesota Department of Education funded 11 regional teacher centers, Mathematics and Science Teachers Academies (MSTA), to provide professional development and technical assistance through institutional partnerships of higher education, regional service cooperatives, high-needs school districts, and other optional partners. Each funded MSTAs was expected to design and implement professional development modules to improve teacher content knowledge and pedagogical content knowledge to more effectively implement the Minnesota Mathematics and Science Academic Standards. In this study we describe only the work of the Region 11 MSTAs, which serves the metropolitan area and surrounding suburbs of Minneapolis and St. Paul.

Each MSTAs was initially funded through state allocated dollars and during this first year, MSTAs were required to provide professional development to assist middle school mathematics teachers to meet the new requirement of mastery of the algebra of lines by the end of 8th grade and to develop modules to address either the new engineering standards or further mathematics professional development at elementary or high school level. Due to state budget cuts, Mathematics and Science Partnership (MSP) money was used to provide continued funding to the each region's MSTAs for a four-year total funding commitment. Each year has a different grade-level and subject matter focus of the professional

development modules as shown in Table 2. Region 11 choices are made in collaboration with schools within the area and reflect the stated needs of the local schools and teachers.

[Table 2 approximately here]

Theoretical Framework for STEM Professional Development

Our work has focused on STEM integration as the merging of the disciplines of science, technology, engineering, and mathematics for the purpose of: (1) deepening student understanding of each discipline by contextualizing concepts, (2) broadening student understanding of STEM disciplines through exposure to socially and culturally relevant STEM contexts, and (3) increasing interest in STEM disciplines to broaden the pipeline of students entering the STEM fields (Wang, Moore, Roehrig, & Park, in press). We operate from two models of STEM integration to develop professional development activities: *content integration* and *context integration*. These different approaches allow teachers flexibility in how they integrate STEM in their classrooms (Moore, 2008b).

Content integration focuses on the merging of the content fields into a single curricular activity or unit in order to highlight "big ideas" from multiple content areas. For example, in the STEM professional development, we included a series of activities on wind turbines and heat transfer to illustrate the power and possibilities of teaching within a fully integrated STEM context. The wind turbine design lessons utilize robust hands-on wind turbine kits that allow teachers and students to explore the variables that impact electricity generation. Teachers had direct experiences with engineering design by considering variables that impact the blade design and efficiency (the number, the shape, the pitch, the weight, and length of the blades) and developed an understanding of the physics behind their various blade designs. A full understanding of an optimal wind turbine design also involves developing and applying physics concepts related to electricity generation and the mathematical concepts behind the gear system. A unit using a content integration model allows a teacher to teach content from each discipline and highlight how these disciplines are all needed to solve a problem in this area.

Context integration primarily focuses on the content of one discipline and uses contexts from others to make the content more relevant. For example, a mathematics teacher might choose a unit focused on a company that must look at the reliability of tires for vehicles in order to increase the safety of driving a vehicle. The content would be around ideas of statistics, particularly leading up to ideas of Chi-square testing, but the context would allow for iterations and designing of solutions for the company in order to introduce engineering as a field to the students. This tire reliability is an example of a broader set of engineering/mathematical problems called Model-Eliciting Activities (for other examples see Moore (2008a), Moore & Hjalmarson (2010)).

Model-Eliciting Activities (MEAs) are complex problem-centered, team-oriented activities that are situated in realistic, meaningful contexts that require students to design approaches to solving a task. Solutions to MEAs are generalizable mathematical models that reveal the thought processes of the students. The models created include procedures for doing things and more importantly, metaphors for seeing or interpreting things. The activities are such that student teams of three to four *express* their mathematical model, *test* it using sample data, and *revise* their procedure to meet the parameter of the problem. This developmental iterative process (an *express-test-revise* cycle) is a form of engineering design. The nature of an MEA is such that iteration occurs due to purposeful constructs built in the problem that allow students to self-assess whether or not their solutions meet the needs of the clients. Lesh and Doerr (2003) suggest that MEAs can be used to lead students to significant forms of learning and suggest in particular that these activities can help students invent, extend, refine or revise STEM constructs.

Overview of 2009-2010 teacher professional development on STEM integration.

The Middle and High School STEM Integration module was developed using the Principles and Standards for School Mathematics (National Council of Teachers of Mathematics, 2000), the National Science Education Standards (NRC, 1996), ABET Engineering Accrediting Criteria (ABET, 2008), and the new Minnesota Academic Standards for Science and Mathematics (MDE, 2009). This module provided

instructional strategies to assist secondary school teachers in implementing STEM contexts into their mathematics and science classrooms and increase their understanding of the connections between the areas of STEM. As a new mandate for teachers, engineering represented a new challenge for teachers in their instruction. Thus, engineering was used as the driver for the majority of models of STEM integration used in the PD modules. The schedule for the modules included 5 training days throughout the 2009-2010 school year as outlined in Table 3.

There were four Professional Learning Community (PLC) meetings between each training day. The purpose of the PLC meetings was for teachers to meet together in school level teams and reflect on what they learned during the training sessions and to plan for the implementation of STEM integration activities into their classrooms. These hour-long meetings are highly structured and closely tied to the training days of the module.

[Table 3 approximately here]

Participants

The participants in the Region 11 STEM professional development program were 74 secondary science (33), mathematics (33), and technology education (8) teachers from 10 schools, including 4 middle schools and 6 high schools. Of the 33 science teachers, licensures broke down as followed: 8 physical science or physics, 5 chemistry, 14 life science, 1 earth science, and 5 middle school general science. Schools were expected to participate as STEM teams, sending at least one teacher from each different grade level/subject in science and mathematics. The size of school teams varied from a small charter school sending a two teacher team consisting of the single science and the single mathematics teacher employed at the school to a larger public middle school sending a thirteen person team that also included all of their science and mathematics teachers.

Data Collection

Each school was required as part of their PLC work to implement at least one STEM integration lesson/unit during the school year. Schools and teachers determined the approach for planning and implementing their STEM lessons. All schools and teachers shared their STEM integration experiences as a poster on the last day of the STEM training. Artifacts from PLC meetings, including lesson plans, student artifacts, and lesson reflections, were collected throughout the year and are the primary data used in this study. In addition, five of the ten schools were selected for classroom observations to provide deeper insight into decisions about the implementation of STEM lessons. Two class observations were conducted in five of the participating schools (29 teachers) during the implementation of their STEM lessons. Detailed field notes were taken throughout the classroom observations to document the specifics of the implementation strategies during the STEM integration lessons.

Data Analysis

As we began our data analysis, it became clear that the unit of analysis for the cases differed depending on the approach to STEM integration determined by each of the 10 school teams. For example, three schools chose a team planning approach with groups of teachers implementing the same STEM integration lesson. In these cases, a single lesson plan represented the intentions of a group of teachers with the unit of analysis being a grade-level school-based team, for example a team of 9th grade physical science teachers. Whereas, in five schools each teacher planned an individual approach to STEM integration, and while these approaches were shared and reflected on a group in their PLC, each lesson represented the intentions of an individual teacher with the unit of analysis being an individual teacher. Thus, the unit of analysis used was the STEM integration lesson plans, which represented a grade-level school-based team or an individual teacher depending on the chosen approach used by each school.

Forty-one STEM lesson plans were reviewed and summaries of STEM integration activities were developed. The focus of the analysis was the strategies used by teams or individuals to integrate engineering into their science or mathematics classrooms. The following preliminary codes were developed

by the first author: (i) integrated engineering design – product focus, (ii) integrated engineering design – process focus, (iii) engineering design with no integration, and (iv) absence of engineering. These codes were discussed and agreed on by the co-authors with a distinction in coding being added for product-focused engineering design being used as the context for the unit or the culminating activity of the unit (a mechanism to apply science content to a novel situation). Following the coding of the lesson plans, classroom observations were analyzed and integrated into the STEM activity summaries to provide richer details about the nature of the STEM integration. Classroom observations provided a triangulation point for the lesson plans provided by teachers as well as a depth of data not available from a lesson plan. The observation data was critical in analyzing the extent of the integration that occurred in classrooms and provided information about if and how teachers talked about science and mathematics during an engineering design lesson.

Results

Forty-one separate STEM integration lessons/units were reported by teachers during the STEM Integration professional development. A list of these lesson/unit topics is shown in Table 4. A preliminary analysis of these units revealed four structural approaches to planning for STEM integration: (i) co-teaching (multiple teachers in the same classroom, e.g. “Chair”-ity project in Table 4), (ii) team teaching (multiple teachers instructing within a unit but within the walls of their individual classroom, e.g. Aluminum boats and packaging engineering, Table 4), (iii) team planning with individual implementation (a group of teachers plan together so that each student has the same experience regardless of teacher, e.g. 9th grade physical science (submarine design, punt pass, and keeping in the heat), Algebra II (vertical motion), and 8th grade Engineering (Rube Goldberg), Table 4), and (iv) individual planning and implementation (34 examples, in Table 4). Detailed descriptions of these approaches are provided through illustrative cases in the following section. By using illustrative cases, we also share the varied approaches within the larger individual implementation group.

[Table 4 approximately here]

Illustrative Cases

Co-teaching

One middle school had a unique situation where two of the teachers had been charged with developing a new elective engineering course for 7th and 8th grade students. Because of the school's focus on STEM as a means for engaging students and maintaining student enrollments in the district, a science and mathematics teacher were co-developing and co-teaching the engineering class. The engineering challenge for their STEM integration unit was to build an adult-sized cardboard chair that could hold 150-200 pounds (product-focused engineering design lesson). The final products were auctioned and the proceeds sent to a local charity, thus the unit title/descriptor "Chair-ity". This unit was a two-month unit where student teams actively engaged in the engineering design process building and testing prototype chairs before constructing the full-size final product.

These two teachers believed that an effective STEM integration unit, while driven by an engineering challenge, also needed to directly address specific content in science and mathematics. As the science teacher commented, students should be able to "pull mathematics or science concepts in to help them solve the problem." During an observation on the second day of the unit, science content was emphasized through the importance of understanding human body structure and anatomy for designing a chair. This was integrated with mathematics concepts as students measured each others arms and legs and looked at ratios/proportions of femur to tibia etc. Mathematics was embedded in other aspects of the project, for example students had to maintain a budget and keep track of their expenditures. In another example, the mathematics teacher introduced concepts of scaling and proportional reasoning as students moved from their prototype chairs to the full-scale chairs.

Teaming

Two middle grade-level teams chose a team-teaching approach to their STEM integration unit. In both cases the team included a science and mathematics teacher. The Aluminum Boats is an example of the integration of science and mathematics (absence of engineering). The lesson started in science class, students were asked to investigate whether a gold crown was counterfeit or real. Students worked in groups to collect mass and volume data for a set of “gold samples” including the “gold crown”. In a traditional science class students would employ the density formula ($\text{density} = \text{mass}/\text{volume}$) to calculate the density of the unknown, in this case the “gold crown”, and compare this value to the density of a known sample or a density value from a reference manual or textbook. The mathematics teacher used the context and data from science class as a reason to use graphical analysis and slope as an alternative to the standard algebraic substitution methods. In reflecting on student learning, the mathematics teacher commented on the power of having students write about the mathematical approaches they used to solve the problem and particularly that “students used unexpected although appropriate approaches to solving the problem”. The teacher expected students to calculate the slope of their graph and use this value for density to compare to the density found in science class, however some groups used the graph to predict the volume of the crown and compared this value to the volume measured in science class.

The second teaming example used the context of packaging engineering. The context of the engineering challenge was presented by the mathematics teacher: a church in Europe broke their stained glass window and will buy their replacement stained glass from the U.S. He told students that they would be designing packages in science class to ship these stained glass windows to Europe, but they needed to learn how to measure the different polygonal shapes before engaging in designing their packaging process. After introducing the context of the problem and sharing some images of stained glass windows, the mathematics teacher went over how to calculate area of different polygons and had students complete a worksheet. With the mathematical skills in hand, students participated in the design challenge over the next week in science class and returned to their regular mathematics lessons.

Individual (co-planning and individual planning)

The final two approaches to STEM integration are merged here since, regardless of the extent of the integration (in all 9th grade physical science classes vs. only one of the 9th grade physical science classes), at the classroom level a single teacher is responsible for STEM integration. We note that in four school cases, where all teachers from that grade level or subject area team attended the MSTA training, teachers worked as a team to plan a common unit to be taught in each of their classrooms. The first case involved a team of 8th grade technology teachers. The second case was a 9th grade physical science team who shared several STEM integration projects throughout the year. The final two cases were teams of mathematics teachers, one geometry team and one second-year algebra team.

Individual classroom cases (both co-planned or individually planned) fell into specific sub-categories that drew more heavily on certain STEM content areas depending on the primary subject area of the teacher: Science/Engineering (primarily product-focused with some process-focused lessons), Science/Mathematics (absence of engineering), Engineering/Mathematics (primarily process-focused with some product-focused lessons), and Engineering only.

Science/Engineering

One common model of STEM integration for science teachers was to include an engineering design project as the culminating activity to a science unit. A team of 9th grade physical science teachers developed a submarine engineering design activity as the culminating event for a unit on chemical reactions. Students were charged with designing a submersible that would sink, float to the top and then sink again in a large aquarium. Students were provided with a variety of materials, and the final submarines were manufactured from common materials, such as film canisters, soda cans, plastic cups, etc. Students used their knowledge of chemical reactions to create changes in density within their submersible thus allowing it to sink and float. These teachers were able to clearly articulate both engineering design and science content standards in their unit.

A second common model was to use an engineering design challenge as the context at the beginning of a unit. For example, one of the middle school science teachers designed a six-day unit around the challenge of designing the best candy bag (a bag that would hold the most candy without breaking). Her goal was to integrate the engineering design cycle into her science teaching. The students designed and built their candy bag within some constraints, such as type of materials and the cost of materials. On the first day of instruction, the teacher introduced the history of paper bags and showed different bag design to students to allow them to investigate the features of a bag. The teacher limited bag design to a bag with handles at this point. Next, students explored the provided materials and drew a prototype design. After building their candy bags, students tested their design by determining the weight the bag could hold before it “failed”. One specific measurement that students were asked to make was the bag dimensions, so they could calculate the volume of their bag. Using their test data, students redesigned their bags and presented their final design to the class on the last day of the unit.

Finally, although much less common, some science teachers chose to integrate engineering into their classrooms using engineering process and engineering thinking as opposed to having students engage in an engineering design cycle that culminated in an actual physical product. For example, a high school life science teacher developed a lesson on genetically modified organisms. The learning goal for this activity was for students to apply their knowledge of genetics (gamete, genotype, phenotype, chromosomes, etc.) to make up their own imaginary organisms. In this activity, the engineering concept was genetic engineering. The teacher provided background information about genetic engineering and careers and gave the students the challenge of creating a genetically-modified organism (GMO) that could benefit society or nature. First, students needed to decide the specific ways in which their GMO would benefit society or nature to determine the necessary characteristics of the GMO. Second, students sketched a draft for their GMO including the scientific name for their GMO and an explanation of genes they would need to splice from other organisms. At the end of this activity, students presented their GMO to

the class. This lesson effectively integrated scientific concepts into an engineering design cycle to develop the GMO as well as specific content related to genetic engineering.

A chemistry teacher worked with project staff to develop an MEA to use as an addition to her unit on “mystery powder”. In previous years the teacher had taught mystery powders using known powders and an unknown; students were then assessed on their ability to identify the unknown. This modified version of the lesson incorporated aspects of engineering thinking and design by asking student to develop a process for efficiently identifying any unknown white powder thus making the product of the activity an engineering process rather than just an answer for a specific situation.

Science/Mathematics

Four units/lessons integrated science and mathematics in the absence of an engineering context. One of these lessons was the Aluminum Boats example described previously as an example of a teaming approach. Two lessons involved parabolic motion of projectiles, one with a punt kick and the second tossing a basketball, and used video capture to plot the motion of the object using graphical analysis to determine the velocity and acceleration of the object at different time points during the action. While similar in mathematical concepts to the “vertical motion” project described in the team planning section, there was no attempt to integrate engineering design. The final example of science and mathematics integration was from a middle school life science teacher. This lesson involved an MEA that used aerial photographs of pelican colonies. Students applied concepts of area and percent to estimate the pelican population and relate this back to the ecosystem in which the pelicans lived.

Engineering /Mathematics

The most common model of STEM integration for mathematics teachers was the implementation of MEAs in their classroom. A wide variety of MEAs applicable to multiple mathematics concepts were available to teachers, and seven mathematics teachers chose an MEA that fit their content as a mechanism for integrating engineering. Teachers commented that MEAs provided a direct connection to the

mathematics standards that they were expected to cover at their particular grade level without having engineering “take over the class”. With the exception of the two lessons described below mathematics teachers used engineering or science as a context for learning a specific mathematical concept minimizing time spent on engineering and maximizing class time on mathematics.

Four mathematics teachers integrated an engineering design component to their STEM unit that involved students both designing and building a product. For example, a team of algebra II teachers implemented a unit based on an engineering design context, specifically students were asked to design a free-standing slingshot that will consistently fire an object close to the ceiling but not hit it. Students worked with a variety of different sling shot materials (different grades of rubber bands) in order to determine how far to pull back each rubber band to optimize the height of the projectile. Students were required to keep a budget and data tables that included height and time data. Using the data, students calculated initial velocity and graphed and explored parabolic motion curves. The teachers’ intent was to use engineering design to provide a hands-on experience for students and a real-world connection to the mathematics of parabolic motion.

In another example, the tenth grade geometry team implemented a unit on kite design. Teams of students designed and built a functional kite. The project involved research on the history and structure of kites culminating in a scale drawing of the design and explanations for their choices, such as shape and materials. A requirement of the students’ final poster was a coordinate proof of the two special quadrilaterals that were included in their design. Students were also graded on the flying ability of their final product and the relation of the full-size kite to the scale drawing.

Engineering only

All eight technology teachers reported on their standard technology curriculum. For example, one school had adopted the Project Lead the Way Gateway to Technology as a STEM course for their 8th grade students. This case has been reported in detail in a previous study (Stohlmann et al., in press) that

includes a detailed analysis of the limited integration of science and mathematics concepts in the engineering design challenges included in the PLTW curriculum. Similarly, other technology presented projects that required the use of computer-assisted drawing (CAD) programs to develop the designs for items such as pull-toys. Students were assessed on their use of CAD and the quality of their final manufactured product.

Conclusions

Minnesota represents a useful case for exploring the impact of policy decisions related to STEM integration. STEM education is valued in the state and the decision to integrate engineering into the state science standards was based on the national reports advocating engineering (e.g. NAS et al., 2006). The placement of engineering in the science academic standards as opposed to separate engineering standards and clear statements within the standards frameworks is an unmistakable policy statement that STEM integration is the desired outcome. In this paper, we explored the models of STEM integration implemented by secondary science, mathematics, and technology teachers in response to new STEM state standards. Approaches ranged on a continuum from lessons that attempted to integrate all of the STEM disciplines (12 lessons) to lessons that only addressed engineering/technology standards (5 lessons), with most lessons representing an integration of two disciplines (science and mathematics (4 lessons), science and engineering (6 lessons), or mathematics and engineering (14 lessons)). All STEM integration lessons were planned by a science teacher, although the highest quality of STEM integration was found in the lesson co-planned and implemented by a science and mathematics teacher. All engineering-only lessons were implemented in engineering classrooms taught by technology teachers. Lessons integrating two of the STEM disciplines varied in approach with the majority of science teachers implementing product-focused engineering design lesson and the majority of mathematics teachers implementing process-focused engineering design lessons. In the following section, we describe STEM models implemented in science, mathematics, and engineering classrooms including policy implications for these different approaches.

STEM Integration Models in Engineering Classrooms

These new directions in K-12 engineering have forced schools to rethink not only how their science courses meet the new standards but also the role of technology and mathematics teachers with respect to engineering. Some schools have responded by adding stand-alone engineering coursework, particularly at the middle school level. Schools view an engineering course not only as a mechanism to address the new engineering standards but also as a vehicle for improving students' test scores, particularly in mathematics. This approach is problematic based on the analysis of STEM units presented by technology teachers in this study. First, most schools were offering engineering as an elective meaning that all students were not receiving instruction on the new engineering standards unless engineering was also integrated into science classes. Second, a review of the STEM lessons presented by technology teachers revealed only engineering content with no explicit attention paid to mathematics or science concepts. In a previous study (Stohlmann et al., in press), we reported on the limited integration of science and mathematics concepts in the engineering design challenges included in the PLTW Gateway to Technology curriculum used by one middle school in the MSTTA training. We note here that this absence of mathematics and science concepts was found in all lessons implemented by technology teachers in this study. In spite of five days of instruction on how to integrate STEM, technology teachers persisted in traditional implementations of technology/engineering teachers.

One school chose a unique approach to an engineering course – the co-teaching model. While titling their new 8th grade course as an engineering elective, the school was determined that the course would be more than “just engineering” and provide needed reinforcement of science and mathematics concepts for their students prior to required 8th grade state testing. 96% of 8th graders in the school took this elective course. The inclusion of both a science and mathematics teacher in the classroom provided a more authentic treatment of science and mathematics concepts and allowed for “just in time” teaching throughout the various engineering design challenges. The teachers also deliberately chose engineering

challenges that would naturally include science and mathematics concepts rather than trying to force science and mathematics artificially into an engineering lesson. While requiring the most unique and expensive challenges to the school – scheduling two teachers into a single classroom, the highest quality STEM integration was observed in this classroom.

STEM Models in Science Classrooms

There were striking differences between the attitude toward and implementation of STEM integration by science content strand. The preponderance of sample lessons were in the physical science with only three life science lessons (evolutionary tree MEA, genetically-modified organisms, and pelican populations) even though fourteen life science teachers attended the MSTA training. Throughout the year an on-going discussion with teachers and school administrators related to the question – where in the science curriculum should engineering be included? The intention of the Minnesota standards is that teachers at *all* grade levels and subjects should integrate engineering to some degree into their science courses. In fact, the state mandated focus for professional development during the 2011/12 academic year is STEM integration in the life sciences. However, the Minnesota standards alternate between the practice of science and practice of engineering standards for grades 3-8 with no standards related to the practice of engineering occurring specifically in 7th grade life science. This policy document unintentionally reaffirmed the teachers' natural inclination to include engineering only in physical science units. Similarly, at the high school level where biology is traditionally taught at the 10th grade level there was a push within schools to integrate engineering only in 9th grade physical science as it was viewed as a more natural fit with the content and the biology curriculum was already overwhelmed with a plethora of content standards. While there are many examples of engineering within the life sciences (e.g. genetic engineering, prosthetics, artificial heart valves, neuro-engineering), many of these engineering fields are beyond the scope of K-12 life science classrooms in terms of the level of content and access to equipment. It was also difficult for teachers to move past a view of engineering design as requiring the construction of a physical product even

though the training also emphasized processes as a possible culmination to an engineering design cycle. The only two life science lessons that did integrate engineering focused on engineering processes. Process focused approaches to STEM integration appear to be more applicable in life science contexts, especially at the secondary level.

The many physical science-based STEM lessons had varied levels of success with respect to STEM integration. With few exceptions, science-based lessons include mathematics only as a tool – i.e., charts, graphs and algebraic manipulation of data. At issue here is implicit use of mathematics in a STEM integration vs. explicit teaching of mathematics in a STEM integration – science teachers are skilled end-users of mathematics but rarely have the expertise in the teaching of mathematics. In all examples, science teachers were unable to articulate the role of mathematics in their lesson beyond the use of charts and graphs to document their process and data. The strongest examples of mathematics in any STEM integration lesson were from the co-taught middle school class and the aluminum boat example of team-teaching bringing the expertise of a mathematics and science teacher to bear.

Physical science teachers used two different approaches to STEM content integration in their classrooms with differing degrees of success. The first approach involved the addition of an engineering design activity as the culminating event to a unit where students were expected to apply their science knowledge to a design project. This approach produced a seamless integration of engineering and science content and was a successful learning experience for students. The second approach was to start a unit with an engineering design challenge. This approach was modeled in the training using wind turbines introducing physics and mathematics concepts to explain the various levels of success of different design approaches. As noted in our critique of technology approaches to STEM integration it is possible to build a successful design through a tinkering approach without explicit discussion of science and mathematics concepts. Unfortunately, science teachers struggled with this approach to STEM content integration and

missed opportunities to explicitly teach science content connected to the engineering design challenge and the lessons more resembled a traditional technology approach than a STEM content integration approach.

STEM Models in Mathematics Classrooms

With the exception of the team-teaching cases, mathematics teachers added engineering concepts to their instruction but not science. In the two team teaching situations, the role of the mathematics teachers was limited to the teaching of mathematics. In one case (package engineering), a single mathematics lesson was included so that students had the mathematics skills necessary to be applied to the science/engineering portion of the unit. The second team-teaching case (aluminum boats) had more parallels to the individual teachers' inclusion of engineering into their mathematics lessons. Each of these lessons used engineering (science in the case of aluminum boats) as the context for learning the mathematics. The mathematics teachers valued the engineering process/thinking approaches from MEAs that afforded them a real-world context in which to learn the mathematics, a reason to do iterative, complex problem solving, and a conceptual approach to learning the mathematics. While seeing the value in the engineering product design lessons, time constraints were a perceived barrier in adding the engineering design process into coursework. None of the mathematics-based STEM lessons included any science instruction, teachers reported both time and content knowledge as issues in this regard.

The results of this study demonstrate the possibilities of policies that use state standards documents as a mechanism to integrate engineering into science standards. Unlike the recommendations of the National Academy of Engineering (2009), our cases do not lend evidence to using technology and engineering teachers to implement STEM integration lessons or the need to certify engineering teachers. Science and mathematics teachers, if provided with appropriate professional development, have the capacity to integrate engineering and content in meaningful ways for their students. The goal of integration of engineering is more readily obtained than full STEM integration however. Various constraints impeded the inclusion of mathematics into science/engineering lessons – time within the curriculum, expertise of the

science teacher – that were only mediated when a mathematics teacher partnered with the science teacher. Our cases suggest that full STEM integration may require new school organizational structures that facilitate the teaming of science and mathematics teachers.

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Table 1

Sub-strands and standards within the Minnesota Nature of Science and Engineering Strand

Sub-Strand	Standards
<i>The Practice of Science</i>	Understandings about science Scientific inquiry and investigation
<i>The Practice of Engineering</i>	Understandings about engineering Engineering design
<i>Interactions Among Science, Technology, Engineering, Mathematics and Society</i>	Systems Careers and contributions in science and engineering Mutual influence of science, engineering and society The role of mathematics and technology in science and engineering

Table 2
State policy requirements for professional development focus

Academic Year	State Professional Development Requirements	Region 11 Professional Development Focus
2008/2009	Algebra (6-8)	Algebra (6-8)
2009/2010	Further training in a mathematics related area	Pre-algebraic thinking (3-5) STEM Integration (6-12)
2010/2011	Nature of Science and Engineering (3-6) Further training in a mathematics related area	Nature of Science and Engineering (3-6) Algebra (6-8)
2011/2012	Nature of Science and Engineering in the Life Sciences (7-12) Further training in a mathematics related area	Nature of Science and Engineering in the Life Sciences (7-12) Algebra (6-8)

Table 3

Outline of the five training days for 6-12 STEM Integration Module

Time	Content Focus	Participant Activities
Day 1 October	Introduction to engineering and engineering design	Overview of the nature of engineering and introduction of the engineering design process. Teachers participated in a concept mapping about “what is engineering?” and a content integration STEM activity to develop their understanding of the engineering design cycle and the integration of science and mathematics content through wind turbine blade design.
Day 2 December	Engineering Redesign and STEM Integration	Teachers continued working on teaching STEM through an engineering design context. Specifically, they investigated wind turbines’ gear systems and generators and worked through a redesign activity with constraints based on their blade designs from Day 1.
Day 3 January	Problem Solving and Modeling	Teachers experienced a variety of Model-Eliciting Activities (Lesh & Doerr, 2003) across the STEM disciplines: Paper airplanes (Richardson, Moore, Sales, & Mackritis, 2011), nanotechnology (Moore, 2008a; Moore & Hjalmarson, 2010), evolution.
Day 4 March	Integration through Technology Tools	Teachers learned a variety of ways to use technology in their classrooms as a means to integrating STEM. Kinematics and relationship of time, distance, velocity, and acceleration was modelled using Vernier motion detectors. Vernier® video capture technology to explore parabolic motion of projectiles, heart rate investigations using Vernier technology, and Tinkerplots® (a statistical software package)
Day 5 May	Representation, Translation, and Celebration	Teachers learned models of student understanding (representational fluency, Lesh translation model (Cramer, 2003)) through participation in a heat transfer based Engineering Teaching Kit (Schnittka, Bell, & Richards, 2010); National Speaker presented on explicit vs. implicit inclusion of mathematics in engineering classrooms; Teachers participated in a culminating poster session to share their STEM Integration lessons with the community.

Table 4
Topics of STEM Lessons and Units

Science Classrooms	Mathematics Classrooms	Technology or Engineering Classrooms
Co-teaching (middle school)		
		Chair-ity Project
Team-teaching (middle school)		
	Aluminum boats	
	Packaging Engineering	
Team Planning/ Individual Classroom		
<i>High School</i>		
Submarine Design	Vertical motion (catapults and mathematical modeling)	
Keeping in the Heat (designing a thermos flask)	Kite Design	
Punt Pass (force and motion)		
<i>Middle School</i>		
		Rube Goldberg design (PLTW)
Individual Planning/ Individual Classroom		
<i>High School</i>		
MEAs: Mystery powders Dimensional analysis	MEAs: Historic hotels Paper airplane	Pull-toy design (CAD design)
Evolutionary Tree MEA	Linear programming	Egg bungee (PLTW)
Speaker design	Video Analysis of parabolic motion	
Airplane wing design		
Pumpkin catapults		
Atomic Force Microscopy		

Genetically modified organisms

Middle School

Popsicle Stick Bridges

Kool-aid ratios

Rocket Design

Slime Engineering

Models and inventions

Shelter Design

Candy Bag design

Popsicle Bridges

Ice Device (designing an insulated ice cooler)

MEAs:
Paper airplane
Track and field
Big Lawn

Solar oven design

Pelican Population Investigation
