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PECASE: Implementing K-12 Engineering Standards through STEM Integration - An Executive Summary of the Products and Research

Prof. Tamara J Moore, Purdue University, West Lafayette (College of Engineering)

Tamara J. Moore, Ph.D., is an Associate Professor in the School of Engineering Education and Director of STEM Integration in the INSPIRE Institute at Purdue University. Dr. Moore's research is centered on the integration of STEM concepts in K-12 and postsecondary classrooms in order to help students make connections among the STEM disciplines and achieve deep understanding. Her work focuses on defining STEM integration and investigating its power for student learning. Tamara Moore received an NSF Early CAREER award in 2010 and a Presidential Early Career Award for Scientists and Engineers (PECASE) in 2012.

Kristina Maruyama Tank, Iowa State University

Kristina M. Tank is an Assistant Professor of Science Education in the School of Education at Iowa State University. She currently teaches undergraduate courses in science education for elementary education majors. As a former elementary teacher, her research and teaching interests are centered around improving elementary students' science and engineering learning and increasing teachers' use of effective STEM instruction in the elementary grades. With the increased emphasis on improved teaching and learning of STEM disciplines in K-12 classrooms, Tank examines how to better support and prepare pre-service and in-service teachers to meet the challenge of integrating STEM disciplines in a manner that supports teaching and learning across multiple disciplines. More recently, her research has focused on using literacy to support scientific inquiry, engineering design, and STEM integration.

Mr. Aran W Glancy, University of Minnesota, Twin Cities

Aran Glancy is a Ph.D candidate in STEM education with an emphasis in Mathematics Education at the University of Minnesota. He has experience teaching both high school physics and mathematics, and his research focuses on supporting mathematics learning, specifically in the domains of data analysis and measurement, through STEM integration and engineering. He is also interested in mathematical modeling.

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Elizabeth Gajdzik is the Assistant Director of the INSPIRE Research Institute for Pre-College Engineering in the School of Engineering Education at Purdue University. She received both her B.S. in Interdisciplinary Studies with a specialization in mathematics education and M.S.Ed. in Curriculum and Instruction with an emphasis in mathematics education from Baylor University. Prior to her work at INSPIRE, Elizabeth was a district curriculum math specialist in San Antonio, TX and a middle school mathematics teacher at a Title 1 school in Waco, TX.

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Introduction

K-12 Engineering Education has risen to the forefront as engineering continues to gain state-level and national attention (Moore, Tank, Glancy, & Kersten, 2015; NGSS lead states, 2013; National Research Council [NRC], 2009; 2012). However, engineering at this level does not have the same extensive literature base that is seen at the post-secondary level or within other disciplines at the K-12 level, like mathematics or science. Therefore, it is necessary for researchers to continue to explore engineering content, practices and pedagogy at this level to gain a better understanding of what engineering could and should look like and how to support the integration of engineering into K-12 settings.

Project Overview

The project, *PECASE: Implementing K-12 Engineering Standards through STEM Integration*, was the Early Faculty Career Award for Tamara J. Moore [NSF # 1442416]. The goal of this project was to better understand engineering integration in K-12 schools through a STEM Integration research paradigm (Moore, Glancy, et al., 2014). Dr. Moore and her research team were concerned primarily with how K-12 standards, curriculum, teachers, and schools are implementing engineering in STEM integration learning environments. To accomplish this goal, there were two main threads of research related to integrating engineering into the K-12 setting:

- 1) A Framework for Quality K-12 Engineering Education: The Framework for Quality K-12 Engineering Education was created to meet the growing need for a clear definition of quality K-12 engineering education. It was the result of research focused on understanding and identifying the ways in which teachers and schools were implementing engineering and engineering design in their classrooms. The framework was designed to be used as a tool for evaluating the degree to which academic standards, curricula, and teaching practices address the important components of a quality K-12 engineering education. The research from this thread included a design study on the development of the framework and an assessment of the engineering contained in the Next Generation Science Standards (NGSS) and state-level academic standards for all 50 states. Additionally, this framework could be used to inform the development and structure of future K-12 engineering education initiatives and related standards.
- 2) PictureSTEM: The PictureSTEM curricula (<http://www.pictureSTEM.org>) include an instructional unit at each grade level, K-2, which employs engineering and literary contexts to integrate science, technology, mathematics, and computational thinking content instruction in meaningful and significant ways. These transformative new models for STEM+C (science, technology, engineering, mathematics, and computational thinking) learning use picture books and an engineering design challenge to provide students with authentic, contextual activities that engage learners in specific science, mathematics, and computational thinking content while integrating across traditional disciplinary boundaries. These units have been classroom tested and research has been published and is ongoing regarding student learning and teacher implementation of these STEM integration curricular units in the classroom.

Major Products and Research

This executive summary of the grant, *PECASE: Implementing K-12 Engineering Standards through STEM Integration*, comes at the conclusion of the project. With the limited research base within K-12 engineering that existed at the start of this project, this project worked to develop a definition of K-12 engineering and explore the practice of engineering in K-12 STEM classrooms. The definition was then used to assess curricula, policy documents, teacher practice, and student learning. Through this work, the definition was then used to help with the framing and development of STEM integration curricula for K-5 classrooms which utilize engineering design and picture books to teach young students about mathematics, science, engineering, technology, computational thinking, and reading in an integrated manner. Major products and research findings related to the two main threads of this project will be presented in more detail in the following sections.

A Framework for Quality K-12 Engineering Education. Related to the first thread of research, we developed a Framework for Quality K-12 Engineering Education that could be used to describe what constitutes a quality K-12 engineering education. The development of this framework resulted in 12 key indicators that were determined based on an extensive review of the literature, established criteria for undergraduate and professional organizations, content analysis of content standards in science, mathematics, and technology, and in consultation with experts in the fields of engineering and engineering education. Work on this framework was finalized in the summer of 2012 and a truncated version is presented in Figure 1 below. To learn more about this framework and the development process, a journal article related to this work, *A Framework for Quality K-12 Engineering Education: Research and Development*, was published in 2014 in the *Journal of Pre-college Engineering Education Research*.

Key Indicator		Description
Complete Processes 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. Students should understand design by participating in each of the sub-indicators (POD-PB, POD-PI, POD-TE) below.
Sub-indicators of	Problem & Background (POD – PB)	Identification or formulation of engineering problems and research and learning activities necessary to gain background knowledge.
	Plan and Implement (POD – PI)	Brainstorming, developing multiple solutions, judging the relative importance of constraints and the creation of a prototype, model or other product.
	Test and Evaluate (POD – TE)	Generating testable hypotheses and designing experiments to gather data that should be used to evaluate the prototype or solution, and to use this feedback in redesign.
Apply Science, Engineering, Mathematics Knowledge (SEM)		The practice of engineering requires the application of science, mathematics, and engineering knowledge and engineering education at the K-12 level should emphasize this interdisciplinary nature.
Engineering Thinking (EThink)		Students should be independent and reflective thinkers capable of seeking out new knowledge and learning from failure when problems arise.
Conceptions of Engineers and Engineering (CEE)		K-12 students not only need to participate in an engineering process, but understand what an engineer does.
Engineering Tools, Techniques, and Processes (ETool)		Students studying engineering need to become familiar and proficient in the processes, techniques, skills, and tools engineers use in their work.
Issues, Solutions, and Impacts (ISI)		To solve complex and multidisciplinary problems, students need to be able to understand the impact of their solutions on current issues and vice versa.
Ethics (Ethics)		Students should consider ethical situations inherent in the practice of engineering.
Teamwork (Team)		In K-12 engineering education, it is important to develop students' abilities to participate as a contributing team member.
Communication Related to Engineering (Comm-Engr)		Communication is the ability of a student to effectively take in information and to relay understandings to others in an engineering context.

Figure 1. Truncated version of the *Framework for a Quality K-12 Engineering Education* (reprinted from Moore, Tank, et al., 2015).

Additionally, the initial intention of that the framework was that it could be used as a tool for evaluating the degree to which academic standards, curricula, and teaching practices address the important components of a quality K-12 engineering education and therefore would need to be accessible to a broad range of audiences from educational researchers to practitioners. Therefore, a final step in this project was developing a more accessible version of this framework in a “handout” form that is provided to teachers, school level officials, policy makers, and researchers.

Following development of the framework, the research team conducted a content analysis of each state's mathematics and science standards for instances of requiring engineering to gain a better picture of the degree to which current academic standards address the important components of a quality K-12 engineering education. With the release of the Next Generation Science Standards (NGSS), we also analyzed those standards for their inclusion of engineering. At the time of this research, the assessment of the mathematics standards using the framework revealed that there was no significant inclusion of engineering in any of the states’ mathematics standards or in the Common Core Mathematics Standards. The assessment of all states’ science standards and the NGSS painted a different picture in terms of the inclusion of engineering.

The results of the content analysis revealed that within the 50 state science standards documents, there was evidence of engineering, in almost three-fourths of the states’ documents (74%) with a varying degree of presence throughout K-12. While indicators of engineering were identified in 37 out of the 50 state standards documents, at the time of this research, the majority of the references (24/50 states) were implicit with engineering indicators only explicitly called “engineering” in 13 of those state documents. Additionally, there was a concern in the small percentage of engineering that was present either explicitly or implicitly within the science standards documents across the country. In addition to the quantity of engineering that was currently present in the science standards, it was also important to look at the quality of the engineering that was present in those 37 states with engineering in their state science standards and the extent to which they addressed the necessary key indicators identified in the Framework for Quality K-12 Engineering Education. The results of the analyses show that the quality of engineering-related standards that were present within the science standards documents were limited in scope due to the fact that many of the standards addressed only part of the key indicators captured in the Framework for Quality K-12 Engineering Education, and thereby failing to adequately address the necessary pieces to a complete and comprehensive engineering education at the K-12 level.

These results raised concerns about the differences in the extent and quality to which engineering was currently included in K-12 science across the country and the vision of integrating science and engineering that had been presented in the *Framework for K-12 Science Education* document (NRC, 2012) which was the basis for the NGSS (NGSS Lead States, 2013). This work suggests that while there were a number of states that had already included elements of engineering in their standards documents, the larger picture suggested that for a quality and comprehensive engineering education program to be introduced, effort was needed to scale up the elements of engineering in a majority of these states’ science documents. For example, the high levels of application of science, engineering, and mathematics (SEM) knowledge in these documents could serve as a foundation to make students go through the complete Processes of Design while at the same time providing avenues for students to engage in Teamwork and Engineering Communication. The findings indicated that the inclusion of engineering would

require a major change in the way that we currently viewed K-12 science education. Therefore, if we wanted to better prepare our students for success, we needed to include a more comprehensive approach to teaching engineering at the K-12 level. The journal article about the assessment of the science standards and NGSS is published in the *Journal for Research in Science Teaching* (Moore, Tank, et al., 2015).

PictureSTEM. The second thread of research resulted in PictureSTEM, which is a curricular project that resulted from work that had been completed in the first thread looking at the extent to which curricula, standards, policy documents, and teacher practice integrated engineering in the elementary setting through a STEM integration lens. Through this work, the definition was then used to help with the framing and development of curricula for elementary classrooms. Originally units were conceived for all grade levels in K-5. However, through participation in the NSF-funded I-Corps-L program [NSF #1519387], the focus for the units became K-2. The resulting K-2 curricula are called Designing Paper Baskets, Designing Hamster Habitats, and Designing Toy Box Organizers. These instructional units for K-2 classrooms utilize engineering design and picture books to teach young students about mathematics, science, engineering, technology, computational thinking, and reading in an integrated manner. Each of the modules in the PictureSTEM curriculum was developed using the curriculum design method described by Clements' Curriculum Research Framework (Clements, 2007), which follows three stages: Stage 1: Initial Development, Stage 2: Pilot and Teaching Experiment, and Stage 3: Classroom Implementation. The purpose of this work related to the CAREER/PECASE award was to research the effectiveness of these STEM integration curricula that utilize engineering design as a foundational component and map them to the standards.

There are four foundational components that underlie these STEM+C integrated units: 1) engineering design as the interdisciplinary glue, 2) realistic engineering contexts to promote student engagement, 3) high-quality literature to facilitate meaningful connections, and 4) instruction of specific STEM+C content within an integrated approach. The units have an overarching engineering design project that provides the scaffolding for all learning in the unit. The engineering design learning highlights problem scoping and solution generation as an iterative process that requires learning about client needs and relevant background knowledge and applying these to their solution. The context of the units revolves around having a client who has asked for the students' help with a problem. The contexts have multiple ways the students can get interested in the problem, such as providing a challenge, helping them to making personal connections, or highlighting the realistic nature of the work that engineers do. In recognizing the large emphasis on reading in elementary classrooms, these units build upon the rich literature in STEM and reading integration to support the learning of literacy skills, as well as providing students with background knowledge and real-world contexts through the use of high-quality STEM-focused literature. Each of the units includes science, mathematics, computational thinking, picture books, and an engineering design challenge to integrate STEM+C learning. STEM+C activities throughout the unit help students develop their prototypes or make evidence-based decisions while designing. The focus on engineering and reading allows for a rich environment in which students can explore the interdisciplinary nature of learning engineering, science, mathematics, and computational thinking. Following development of the curriculum, the next steps examined the implementation of these STEM integration units that were driven by engineering design and picture books and we found that students and teachers were engaging in these curricula in meaningful ways across the four

foundational components (Tank et al., in press). In one classroom, kindergarten students showed evidence of applying the science knowledge that was learned in the curriculum into two different settings, a field trip to a local nature center and a different science unit (Tank, Pettis, Moore, & Fehr, 2013). In a different set of three Kindergarten classrooms, we observed implementation of the unit to examine the evidence of engineering learning that was present at different times throughout the unit. Implementation of a previous version of a PictureSTEM unit within a fifth-grade classroom, revealed that students were able to make connections to both mathematics and science content when the engineering design challenge was integrated throughout the unit (Farmer, Moore, & Tank, 2015; Tank, Moore, & Strnat, 2015). The work mentioned here has been included in a further NSF STEM+C project called *Integrated STEM and Computing Learning in Formal and Informal Settings for Kindergarten to Grade 2* [NSF # 1543175].

Conclusions

The movement to add engineering in K-12 classrooms through national and state documents makes defining engineering in K-12 settings, STEM+C integration, and new models of STEM learning a relevant endeavor. STEM+C integration with a focus on engineering has the potential to increase student interest in STEM+C subjects and, therefore, increase the strength and number of students with pathways to enter STEM fields. As more states adopt the Next Generation Science Standards or add engineering into their K-12 academic standards and as the teachers and schools in these states look at models of STEM learning for their classrooms, there is a clear need for a definition of engineering that goes beyond the surface provided in the standards and a need for flexible curricula that can act as a model for effective STEM+C teaching and learning. By researching the implementation of K-12 engineering standards, this project added to the theoretical basis for student learning in STEM integration environments. Additionally, given the focus on developing literacy skills in the early grades, curriculum with a STEM+C and a literacy focus will not only help to integrate engineering into classroom instruction, but it will also promote meaningful and intentional connections between STEM content fields and an interdisciplinary approach to learning. This project advances pedagogical understanding about how to teach, assess, and evaluate engineering and STEM in an interdisciplinary manner and how to translate these evidence-based research findings into broad classroom practice through the framework and through curricular units.

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