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A Framework for Quality K-12 Engineering Education: Research and Development

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Abstract

Recent U.S. national documents have laid the foundation for highlighting the connection between science, technology, engineering and mathematics at the K-12 level. However, there is not a clear definition or a well-established tradition of what constitutes a quality engineering education at the K-12 level. The purpose of the current work has been the development of a framework for describing what constitutes a quality K-12 engineering education. The framework presented in this paper is the result of a research project focused on understanding and identifying the ways in which teachers and schools implement engineering and engineering design in their classrooms. The development of the key indicators that are included in the framework were determined based on an extensive review of the literature, established criteria for undergraduate and professional organizations, document content analysis of state academic content standards in science, mathematics, and technology, and in consultation with experts in the fields of engineering and engineering education. The framework is 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. Additionally, this framework can be used to inform the development and structure of future K-12 engineering and STEM education standards and initiatives.

Keywords: definition of K-12 engineering, design-based research

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Introduction

STEM (science, technology, engineering, and mathematics) integration at the K-12 level is gaining national and international attention. Many U.S. national documents have laid the foundation for highlighting the connections between

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STEM disciplines (National Research Council [NRC], 2009; 2010), and engineering has great potential for facilitating this integration. However, there is not a clear definition or a well-established tradition of what constitutes a quality engineering education at the K-12 level (Chandler, Fontenot, & Tate, 2011). ABET (2008), the recognized accreditor for postsecondary programs in applied science, computing, engineering, and engineering technology, has guided the development of undergraduate engineering programs, but there is no similar process at the K-12 level. The U.S. national report *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* (NRC, 2009) stated, "The absence of standards or an agreed-upon framework for organizing and sequencing the essential knowledge and skills to be developed through engineering education at the elementary and secondary school levels limits our ability to develop a comprehensive definition of K-12 engineering education" (p. 151). As a result, a number of questions remain about the best methods by which to effectively teach engineering at the K-12 level and how they play into the integration of other STEM disciplines.

The purpose of this research was to address the need for a clear definition of engineering at the elementary and secondary levels through the development of a framework for describing, creating, and evaluating engineering in K-12 settings. Such a definition could help to guide the development of robust engineering and STEM education initiatives and inquiries into their effectiveness. The framework presented in this paper was developed through a design-research paradigm to answer the research question: *What constitutes a quality and comprehensive engineering education at the K-12 level?* This framework was developed as part of a larger research project focused on understanding how engineering and engineering design are implemented in K-12 environments at the classroom, school, district, and state levels. The key indicators of a quality K-12 engineering education that are included in the framework were developed to outline the essential elements of K-12 engineering education. The indicators were determined based on an extensive literature review, established criteria for undergraduate engineering programs and professional organizations, document content analysis of state academic standards, evaluation of classroom practice and curriculum implementation, and in consultation with experts in the fields of engineering and engineering education. The framework is designed with two purposes in mind. First, it is intended as an evaluation tool for examining the degree to which academic standards, curricula, and teaching practices address the important components of a quality K-12 engineering education. Additionally, this framework can be used to inform the development and structure of future K-12 engineering and STEM education standards and initiatives.

This paper presents the current version of the Framework for Quality K-12 Engineering Education. Following the presentation of the framework itself, the paper provides the development of the framework that followed a design-based research paradigm along with descriptions of the iterations. The detailed explanation of the process, as well as the different versions of the framework, is intended to provide a more complete picture of how the framework was developed, provide evidence that supports each stage of development, and explain the design decisions made along the way.

Why is a Framework for Quality K-12 Engineering Education Needed?

STEM and STEM integration have come into sharp focus in precollege education. Policy documents, international student achievement data, and the fast-paced changes in today's technology-based economy have been catalysts for this focus. Many U.S. policy documents have been written and are influencing this focus on STEM education (e.g., NRC, 2009; 2010; 2012; NGSS Lead States, 2013). All of these documents highlight the importance of improving STEM education in order to develop future generations of creative and competitive STEM professionals. *Prepare and Inspire: K-12 Education in Science Technology, Engineering, and Mathematics (STEM) for America's Future* (President's Council of Advisors on Science and Technology, 2010) indicates the need to produce individuals with strong STEM backgrounds in order to be competitive internationally. *Rising Above the Gathering Storm* (NRC, 2007) notes that economic growth and national security are related to well-trained people in STEM fields.

STEM integration can provide students with one of the best opportunities to experience learning in real-world situations, rather than learning STEM subjects in silos (Tsupros, Kohler, & Hallinen, 2009). However, the most prevalent methods of structuring and implementing STEM education do not "reflect the natural interconnectedness of the four STEM components in the real world of research and technology development" (NRC, 2009, p. 150). This has severe consequences for student interest and performance in STEM education and their development of STEM literacy. Therefore, it is important to consider how the STEM components are interconnected. Because engineering requires the application of mathematics and science through the development of technologies, it can provide a way to integrate the STEM disciplines meaningfully.

Engineering is a natural integrator. Many STEM integration efforts revolve around using engineering and engineering design as the impetus for learning science, mathematics, and technology content. The National Research Council's *Framework for K-12 Science Education* (2012) articulates and discusses the role of engineering as a mechanism by which students can learn meaningful scientific concepts. This document moves the conversation from broad sweeping reforms and abstract ideas to the concrete by advocating for national science standards that include engineering.

Another influential national report that supports the integration of engineering into STEM disciplines, *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* (NRC, 2009), states 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)

In order to prepare students to address the problems of our increasingly technological society, it is necessary to provide students with opportunities to understand these problems through rich, engaging, and powerful experiences that integrate the disciplines of STEM, particularly using engineering (Roehrig, Moore, Wang, & Park, 2012). This will require a rethinking of ways of teaching and learning in STEM learning environments.

If the education community is to take up this challenge of improving STEM teaching and learning through the addition of engineering, it must decide what constitutes quality engineering education at the K-12 level. *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* (NRC, 2009) began this work when it detailed the scope of engineering at the K-12 level as of 2009 and made recommendations for moving forward. As part of those recommendations, the document provided three principles for the focus of K-12 engineering education: (1) emphasis on engineering design; (2) incorporation of important and developmentally appropriate mathematics, science, and technology knowledge and skills; and (3) promotion of engineering habits of mind. These principles outline some overarching goals of K-12 engineering education, but as the report points out a "parsing of engineering content appropriate for K-12 would lead to more coherence in teaching and learning" (NRC, 2009, p. 156).

In 2010, the NRC's Committee on Standards for K-12 Engineering took up the task of determining if stand-alone standards were a feasible and appropriate means of establishing the coherent view of engineering education called for in the 2009 report. Instead of advocating for such standards, the committee recommended embedding the necessary and relevant learning goals in engineering into the standards of other STEM disciplines. Thus drawing attention to the connections to engineering that already exists in other disciplines by mapping the big ideas from engineering onto the current standards in these other disciplines (NRC, 2010). As pointed out in the report, however, the first step in this process is to "develop a document describing the core ideas—concepts, skills, and dispositions—of engineering that are appropriate for K-12 students" (p. 37).

The *Framework for K-12 Science Education* document heeded the call to embed engineering into science content standards with its recommendation to include engineering design in future science standards; however, the document only describes the essential ideas of engineering design (NRC, 2012). Despite taking a big step toward widespread inclusion of engineering at the K-12 level, this document does not articulate a complete set of core ideas in engineering appropriate for K-12 students as the 2010 NRC report recommends. The science framework document provided the foundation for the creation of the Next Generation Science Standards (NGSS), where the limited treatment of engineering becomes even more clear in the disclaimer in Appendix I of the standards where the authors state:

> It is important to point out that the NGSS do not put forward a full set of standards for engineering education, but rather include only practices and ideas about engineering design that are considered necessary for literate citizens. The standards for engineering design reflect the three component ideas of the *Framework* and progress at each grade span. (NGSS Lead States, 2013 Appendix I, p. 3)

So while each of the preceding documents describes engineering and discusses what is needed for engineering education, each also acknowledges that a more thorough definition of engineering for K-12 audiences is needed.

Engineering is gaining status among the education community, and it is increasingly making its way into the K-12 classroom. At the same time the engineering education community has yet to frame the "core ideas" called for in the 2009 and 2010 NRC reports. In order to support the engineering within national science content standards such as the NGSS, and to fulfill the goal expressed in the 2009 and 2010 NRC reports, a clear articulation of the key components of K-12 engineering education is still needed. The purpose of this research is to develop a research-based document that meets the need for a comprehensive set of core ideas of engineering at the K-12 level. The goal is to produce 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; [and a] basis for research on learning progressions" (NRC, 2010, p. 38). Through the identification of key indicators and the clear statement of their definitions, the framework presented here was designed to meet this goal. The following section will describe the design-based research that was used to develop the framework.

Methods

The Framework for Quality K-12 Engineering Education was developed using a design-based research methodology (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Edelson, 2002; Kelly, Lesh, & Baek, 2008). Design research is an iterative process in which an educational theory is developed by first building on previous research and existing theories. The theory is then applied in a controlled setting (typically a learning environment, but in this case, in an educational system) to test conjectures and expose flaws or weaknesses, which lead to the next iteration. The theories produced using a design research methodology are often, as in this case, domain specific, and as a result the assumptions that guided the design must be made explicit.

The assumptions that guided this study were based on the design-research model as described by Hjalmarson and Lesh (2008). This included planning iterative cycles of revision using the phases of *problematic situation, conceptual foundation, product design*, and *system of use* to develop a robust and inclusive framework that encompasses the core ideas necessary for a quality and comprehensive engineering education at the K-12 level. The *problematic situation* for this design-research study has been addressed in the above section "Why is a Framework for Quality Engineering Education Needed?" Primarily, a framework such as this is needed to provide a concise, yet thorough, definition of engineering including its core ideas, concepts, skills, and dispositions for educators, researchers, and policy makers to use as a reference tool when trying to make decisions about how to represent engineering to K-12 students. The *conceptual foundation* for this study is grounded in the defining attributes of engineering that are used to ensure undergraduate engineering students are getting a comprehensive engineering education and through literature from K-12 education that supports developmentally appropriate versions of these same attributes. The *product design* for this study is a Framework for Quality K-12 Engineering Education – whose development is the focus of this paper. Moreover, the testing of this product is also a test of the underlying theories and conceptual foundations that went into its development. The *system of use* is the educational system(s) in which the product will be used. It is expected that the users of this will be educators in the broad sense (i.e., teachers, administrators, teacher educators, and those who make or influence educational policy) and educational researchers. The document will be used as a concise way to help educators gain a deeper understanding of engineering and the components that make up engineering. The document will also be a useful research tool for the development and evaluation of the inclusion of engineering in K-12 settings. Therefore, the framework will likely be used to provide a lens for educators and researchers when considering academic objectives related to engineering.

Design research requires iterative cycles of revision that include testing under controlled conditions. The framework has gone through five cycles of revision. For the purpose of development, the framework has been tested through engineering expert review, stakeholder feedback, and application to state academic standards, the results of which lead to the modifications and next iteration of the framework. Each of these tests required different research methods, which are explained within the descriptions of the iterations. Further testing with the framework has been conducted in classroom and curriculum development research, which will be described later. The next section presents the current version of the framework followed by a detailed description of each iteration during development.

The Framework for Quality K-12 Engineering Education

The Framework for Quality K-12 Engineering Education is intended for educators, researchers, and policy makers to use as a tool for informing the integration of engineering within their educational systems. It is designed to represent the engineering a student should understand if they have participated in engineering throughout their K-12 schooling. This requires the users to translate the ideas contained within the framework to developmentally appropriate levels for the intended learners and to consider vertical alignment from grade band to grade band within the K-12 scope and sequence.

The framework has 12 *key indicators* that, when taken together, summarize a quality engineering education for all students throughout their K-12 education. Figure 1 provides a concise list of the key indicators of the framework. The order of the key indicators within the framework was carefully chosen based on the degree to which the indicator is unique or central to engineering as compared to other disciplines. Key indicators that appear near the beginning (e.g., *Processes of Design*) are thought to be defining characteristics of engineering. Whereas, key indicators that appear later (e.g., *Teamwork*), although essential for engineering, are concepts that are required for success in multiple disciplines. Clear distinctions were made between the key indicators of the framework for evaluative and knowledge building purposes, although in reality many of the indicators and their uses overlap. The distinctions were made in an effort to help users understand how engineering is multifaceted, not to place value or pass judgment on different aspects of engineering education. The subsections below describe each key indicator in detail.

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)

Figure 1. The Framework for Quality K-12 Engineering Education.

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)

General problem solving skills are prerequisites to solving engineering problems. An engineering design process begins with the formulation or identification 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 brainstorming, developing multiple solution possibilities, and evaluating the pros and cons of competing solutions. In doing so, they must judge the relative importance of different constraints and trade-offs. 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. This likely involves generating testable hypotheses or questions and designing experiments to evaluate them. Students may conduct experiments and collect data (and/or be provided with data) to analyze graphically, numerically, or tabularly. 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. Because of the iterative nature of design, 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)

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 including the integration of these areas. Students should have the opportunity to apply developmentally appropriate mathematics or science in the context of solving engineering problems. This could occur within a mathematics or science classroom where students study mathematics or science concepts through engineering design problems. Or this could happen within an engineering course 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)

Engineers must be independent thinkers who are able to seek out new knowledge when problems arise. In the K-12 setting, engineering can help students learn to use informed judgment to make decisions, which can lead to informed citizenry. Students must be empowered to believe they can seek out and troubleshoot solutions to problems and develop new knowledge on their own. Engineering requires students to be independent, reflective, and metacognitive thinkers who understand that prior experience and learning from failure can ultimately lead to better solutions. 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)

K-12 students not only need to participate in engineering design processes but they should also come to an understanding of the discipline of engineering and the job of engineers. This includes some of the big ideas/conceptions of engineering, such as how their 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. Students studying engineering at the K-12 level need to become familiar and proficient with some of these techniques, skills, processes, and tools. Techniques are defined as step-by-step procedures for specific tasks (example: DNA isolation). Skills are the ability of a person to perform a task (examples: using Excel, creating flowcharts, drawing schematics). Tools are objects used to make work 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 and **excluding** engineering design process because it is a specific and foundational process covered in POD). K-12 students should be learning and implementing different techniques, skills, processes, and tools during their engineering education.

Issues, Solutions, and Impacts (ISI)

The problems that we face in today's society are increasingly complex and multidisciplinary in nature. 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 ever changing global economy.

Ethics

A well-designed K-12 engineering education should expose students to the ethical considerations inherent in the practice of engineering. They have the responsibility to use natural resources and their client's resources effectively and efficiently. Engineers must also consider the safety of those using or affected by a product, and they should consider the potential effects of the product on 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. Engineering curriculum and activities at the K-12 level should be designed to expose students to these issues, and as a result students should be aware of the importance of these issues in the field of engineering.

Teamwork (Team)

An important aspect of K-12 engineering education is developing the ability of students to participate as a contributing team member. This may include developing effective teamwork skills, participating in collaborative groups and activities that allow students to assume a variety of roles as a productive member of a team. This team can include partners or small groups where students are engaged in working together towards a common goal or project. 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, or learning to compromise and include all members of the team in the process.

Communication Related to Engineering (Comm-Engr)

K-12 engineering education should allow students to communicate in manners 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. With these two types of communication, engineers write client reports, create presentations, and perform explicit demonstrations. Engineers need to embody information through multiple representations. In addition to verbal communication, communication will take place by using symbolic representations, pictorial representations, and manipulatives all within a real-world context. For example, reports may not only contain written language but also drawings, plans, and schematics.

Development of the Framework

The Framework for Quality K-12 Engineering Education has gone through five iterations in the development process. Each of the five iterations, examples of those iterations, and the design-based research decisions that led to each subsequent iteration will be described below.

Iteration #1

At the commencement of this project, there was no established framework for K-12 engineering education, so in order to generate an initial version of the K-12 framework, the research team first looked toward established criteria for undergraduate and professional organizations. While several international criteria for engineering were considered, each was found to be very similar to the ABET (2008) Criterion 3: Student Outcomes (a)–(k) (Figure 2), so the ABET Criterion 3 was chosen as part of the conceptual foundation for the first iteration of the framework. The ABET Criteria are used to accredit U.S. and international post-secondary education programs in

(a) an ability to apply knowledge of mathematics, [technology,] science, and engineering.
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.
(d) an ability to function on multidisciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary forengineering practice.

Figure 2. ABET Criterion 3: Student Outcomes (ABET, 2008) ["technology" was added to Outcome (a) for iteration #1].

applied sciences, engineering, and technology and describe the desired characteristics of students who have completed accredited undergraduate engineering programs. The ABET student outcomes were chosen due to the importance and wide-spread use of these criteria in providing structure for quality engineering education at the undergraduate level. It was understood that these criteria would not necessarily translate directly to the K-12 level, but, in that they describe the desired characteristics of practicing engineers, these criteria provide a starting point from which to work backwards toward the key components of K-12 engineering education.

When considering the use of ABET as a conceptual foundation for a K-12 framework, the research team conducted a literature search of each of the ABET student outcomes in relation to K-12 engineering education. The literature was examined to determine themes in K-12 engineering as well as to establish the presence and/or applicability of the ABET student outcomes in K-12 situations. This review (Moore, Stohlmann, Kersten, Tank, & Glancy, 2012) revealed that the characteristics outlined in Criterion 3 were at least preliminarily consistent with the aspects of K-12 engineering education emphasized in the literature including but not limited to the 2009 and 2010 NRC reports discussed above.

To synthesize the relationship between the themes in the K-12 literature and the ABET student outcomes, the research team organized and summarized the literature according to the ABET criterion (a)–(k). These summaries helped to clarify how the ABET student outcomes would manifest themselves at the K-12 level, thus they became working definitions of the outcomes from a K-12 perspective. The ABET outcomes along with the summaries of the literature organized by outcome became the first iteration of the framework. With the exception of viewing each outcome through a K-12 lens via the literature summaries, the only significant change was the addition of "technology" to outcome (a) making it consistent with the emphasis in the literature on all STEM fields. Thus, with minimal changes, the ABET student outcomes became the first iteration of the framework.

Following the design-based research paradigm, the next step in developing the framework was to apply it in a controlled setting. As one of the potential uses of this framework would be to inform the development and evaluate the quality of K-12 standards, the research team tested the framework by applying it to the evaluation of existing K-12 engineering standards. The goal of this application was both to ensure that all essential aspects of engineering that appeared in the standards were reflected in the framework, and when elements of the framework were not found in the standards, that the researchers felt that this represented a gap in the standards and not an irrelevant or inappropriate student outcome in the framework. The researchers chose Massachusetts Science and Technology/ Engineering Learning Standards (Massachusetts Department of Education, 2009) for the first test of the framework since Massachusetts was the first state to include engineering in the science content standards as a core requirement for all students and due to the fact that these standards are highly regarded (Brophy, Klein, Portsmore, & Rogers, 2008).

Using the ABET criterion and the working definitions from the literature summaries, the research team coded the Massachusetts science standards. The coding process for this iteration was a two-step process. First, each standard or benchmark was considered individually, and each researcher coding the standard determined whether it explicitly contained elements of engineering. Second, if it was determined that a standard did contain engineering, each researcher examined the standard for evidence of the (a)–(k) student outcomes as described in iteration #1 of the framework. Individual results were recorded in a spreadsheet and compared with at least one other researcher after completing the coding of the standards document. Through discussion, any disagreements were resolved and final codes were recorded. Comparisons of the codes, analysis of the overall results, and discussions about the way engineering was represented within the standards allowed the researchers to test the conjectured framework. This revealed areas where the current working definitions of the ABET student outcomes needed modification to be appropriate for K-12 applications. The framework was then adjusted accordingly, resulting in the next iteration. The weaknesses revealed in the examination of the first iteration will be described in the next section.

Iteration #2

In the second iteration, the researchers set out to resolve the following issues that arose from testing the first iteration. First, the distinction between ABET student outcome (c), which focuses on engineering design, and student outcome (e), which focuses on solving engineering problems, was difficult to resolve when examining the Massachusetts academic standards because engineering design is a specific approach to solving problems in engineering. As a result, the researchers found no examples that were coded as engineering design exclusively without also being coded as solving engineering problems and vice versa. Additionally, although the literature supports an emphasis on engineering design, it does not support a clear distinction between engineering design and solving engineering problems for K-12 students, thus the distinction between outcome (c) and outcome (e) was deemed unnecessary within the framework. For these reasons, outcomes (c) and (e) were combined.

The second difficulty that needed to be resolved was the overlap between outcome (h), which centers on the impact of engineering solutions on important issues, and outcome (j), which focuses on a general knowledge of contemporary issues involving engineering as they appeared in the K-12 setting. Contemporary issues involving engineering and the impact of engineering solutions were always presented together in the literature and in the Massachusetts standards. For practicing engineers, these two outcomes form distinct and important aspects of their profession. However for K-12 students learning about engineering these two outcomes go hand-in-hand; it is not necessary to artificially separate them. For this reason, outcomes (h) and (j) were also combined.

As an additional test on the iteration #2 framework, the research team consulted with two experts in the field of engineering education who have extensive experience with the ABET student outcomes. One of the experts is the director of and faculty in an ABET-accredited, completely problem-based undergraduate engineering program, and the other expert is a full professor at a research-extensive university immersed in the engineering education research community. Specifically, the research team asked the experts if the initial literature-based descriptions of the ABET student outcomes in the framework represented the goals and intentions of the undergraduate ABET student outcomes. Furthermore, the experts were asked whether combining the framework outcomes as discussed above preserved the intent of the ABET criterion 3 while reframing them for use in K-12 settings. For both questions, the experts responded in the positive.

The revised version of the framework with these combined definitions for outcomes (c) and (e) and outcomes (h) and (j) became iteration #2 of the framework (Figure 3). Because this iteration marked a somewhat significant modification of the ABET Criterion 3: Student Outcomes (ABET, 2008), the outcomes were each renamed with appropriate descriptors. Furthermore, the researchers acknowledged that the term "outcome," although suitable for describing a student leaving an undergraduate program, does not reflect the developmental nature of students moving through a K-12 education. For this reason, the term "indicator" was adopted, and from this point forward, the elements of the framework will be referred to as "indicators." Furthermore, those indicators that appear in the final framework are referred to as "key indicators." Figure 3 lists the indicators for iteration #2 and the ABET student outcomes from which they evolved.

To continue with the design research paradigm, it was necessary to test the second iteration of the framework in a controlled setting. The researchers again applied the framework by using it to evaluate existing state standards documents. Carr, Bennett, and Strobel (2012) had been working on identifying states with engineering standards. Through collaborations with them, 15 states were identified to code, 11 of which had created their own engineering standards and 4 had adopted standards that were highly similar to the *Standards for Technological Literacy* from the International Technology and Engineering Educators Association (ITEEA). The explicit engineering standards appeared in mathematics, science, or career and technical

ABET Student Outcome	*Corresponding Indicator*
(a)	STEM
(b)	Inquiry & Data
(c) & (e)	Design Cycle / Problem Solving
(d)	Teamwork
(f)	Ethics
(g)	Communicate
(h) & (j)	Global, Economic, Environmental, Societal and/or Contemporary Issues
(i)	Life-Long Learner
(k)	Technology & Engineering Tools

Figure 3. Iteration #2. ABET Criterion 3: Student Outcomes (ABET, 2008) and the new corresponding indicators for the second iteration of the framework.

education content areas; therefore, those were the content standards examined by the researchers. Standards documents for each of these states were retrieved from the respective state department of education websites in the summer of 2011 and were current as of that point.

The science and technology standards from Massachusetts were the only standards to be coded by all graduate researchers; the other standards were coded in pairs by one science education graduate researcher and one mathematics education graduate researcher. Prior to coding, the researchers tasked with coding the standards for each state determined the unit of coding based on the structure of the standards document itself. In some cases the unit of coding was the "standard" while in others it was the "benchmark," depending on how each state interpreted those two concepts. Through the discussions to reach final agreement for the coding of these states' standards documents, further refinements and additions were made to the definitions of each indicator for this iteration. See Moore et al. (2012) for a complete description of the framework at this stage.

Iteration #3

The results from iteration #2 indicated the need to make major adjustments to the ABET-based framework in order to appropriately reflect and describe the K-12 setting. The changes represented in this iteration will be described in detail in this section. Figure 4 provides a list of the new indicators that resulted in this iteration.

Analysis of the standards from the fifteen states identified above, made it clear that combining indicators (c) and (e) into Design Cycle/Problem Solving (from the last iteration) did not completely capture the characteristics of engineering design that are central to solving engineering problems. Although combining indicators (c) and (e) made the coding of certain standards more clear, it also allowed some academic standards to meet that indicator frequently by focusing on aspects of design, like proposing design solutions, without truly requiring students to engage in a design cycle and therefore the indicator needed further description. Furthermore, it was determined that the simple combination of problem solving with engineering design failed to clearly convey the subtle yet important distinctions between problem solving in engineering and problem solving in other domains. This was seen as particularly problematic in situations where engineering is integrated into mathematics or science classrooms. In these cases, without clear distinctions, the practices of the primary discipline could easily overshadow the desired engineering practices.

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

Figure 4. Preliminary K-12 Framework (Iteration #3).

Additionally, the research team acknowledged that the intent of the *Inquiry & Data* indicator was that the skills represented by this indicator would be used while testing and evaluating a design solution not just in a purely scientific context. The indicator definition for *Inquiry & Data*, however, did not reflect that intention so it was decided that it would be highlighted as part of the testing and evaluating steps of engineering design. Furthermore, the indicators as they appeared in iteration #2 of the framework did not allow for the distinction of the use of the entire design process from the use of only a portion of the process. The ABET student outcomes indicate that engineering program graduates should be able to apply design processes, however, this ultimate goal does not reflect the stages of development or scaffolding necessary to acquire that ability for K-12 students. Although it is important for K-12 students to engage in complete processes of design during the course of their engineering education, focusing on portions of the design cycle can be helpful in building students' understanding.

To address the issues described above, both the *Design Cycle/Problem Solving* and *Inquiry & Data* indicators were eliminated and replaced with one new key indicator and three sub-indicators. It was determined that the previous indicators all represented different aspects of a design process and therefore, they were grouped under the new key indicator *Processes of Design (POD)*. In recognizing that there are multiple phases included in an engineering design process and to accommodate education environments in which portions of engineering design are highlighted, three sub-indicators were created. These sub-indicators represent different phases of engineering design: *Problem and Background (POD-PB), Plan and Implement (POD-PI)*, and *Test and Evaluate (POD-TE)*. Although it is acknowledged that there is variation in specific processes of design, the researchers found that models of design processes iterate on these three, broad phases in some form or another.

Analysis of the first fifteen states with iteration #2 of the framework also revealed that the *Life-Long Learner* indicator, as stated, was not developmentally appropriate for the K-12 setting. ABET outcome (i), *Life-Long Learning*, describes the characteristics exhibited by graduates of a degree-awarding program, and the merit of the program can be judged (in part) by the extent to which graduates exhibit these characteristics (ABET, 2008). Thus producing "life-long learners" is an appropriate goal for an undergraduate program. However, the Framework for Quality K-12 Engineering Education is meant to guide and evaluate the learning activities and opportunities afforded to the students during their K-12 education and classroom experiences. Although many activities in primary and secondary classrooms do in fact encourage students to be life-long learners, rarely is that the stated goal of the activity or represented in academic standards. For this reason, *Life-Long Learner* was eliminated as a separate indicator, and the thrust of the indicator remains as a part of two new indicators discussed below.

Results from iteration #2 also revealed that some important aspects of a K-12 engineering education were reflected in practice but were not, as of yet, addressed in the framework. For this reason, two new key indicators were created. The first was *Conceptions of Engineers and Engineering (CEE)*. K-12 students often do not have well developed conceptions of engineering or what engineers do, and what is more problematic, they often have misconceptions (Knight & Cunningham, 2004). For this reason, it is important that K-12 students are given opportunities to learn about engineering as a profession and what it takes to be an engineer (Brophy et al., 2008; Cunningham, Lachapelle, & Lindgren-Streicher, 2005). These findings are the basis for this new indicator.

Additionally, one of the three recommendations from the 2009 National Research Council report calls for the promotion of engineering habits of mind. While collaboration, communication, and attention to ethical considerations were already present in the framework, systems thinking, creativity, and optimism were still missing. Furthermore, while the Processes of Design indicator encompasses a large part of how engineers approach problems, the types of thinking involved in solving engineering problems are not limited to design processes. Therefore, the *Engineering Thinking (EThink)* key indicator was added to include the remaining habits of mind from the NRC (2009) report as well as other valued engineering thinking skills such as learning from failure and reflective thinking.

Testing of the framework from iteration #2 also revealed that a distinction was necessary between general communication skills (such as the ability to explain one's ideas, or present background information) and engineering-specific communication skills (such as the ability to communicate technical information both to other engineers and to the client). An important outcome in many disciplines of K-12 education is to develop students who are able to communicate using a variety of forms. However, these general communication skills do not capture the specialized types of communication skills that are commonly used in engineering professions. This inspired the modification of the *Communication* indicator into one indicator (*Comm*) with two sub-indicators: *Engineering Communication (Comm-Engr)* and *General Education Communication Skills (Comm-Edu)*.

The next iteration also included several other minor changes to the framework. Most significantly, the decision to include technology in the *STEM* indicator was reversed. Although application of one's technological knowledge is an important aspect of engineering, at the K-12 level students typically focus more on learning about and how to use the technologies than on applying them. This approach to technology education is more appropriately addressed in the *Technology & Engineering Tools* indicator. This shift resulted in renaming the *Science, Technology, Engineering, and Mathematics (STEM)* indicator to *Apply Science, Engineering, and Mathematics Knowledge (SEM)*. Also, the *Technology & Engineering Tools* indicator was simplified to *Engineering Tools (ETool)*. The final change in this iteration was to rename the *Global, Economic, Environmental, Societal and/or Contemporary Issues* indicator with the new name *Issues, Solutions, and Impacts (ISI)*.

The significant changes to the framework within this iteration warranted further evaluation beyond the research team's expertise. Experts in the field of engineering education were consulted to complete a review of this iteration. One of the experts has extensive research experience writing and implementing engineering curricula at the K-12 level through work at an informal learning institution. The second expert is a full professor at a research-extensive university immersed in the engineering education research community. Specifically, the research team asked the experts if the third iteration of the framework was representative of the research literature around K-12 engineering education, and if the modifications to the ABET student outcomes seemed appropriate for K-12 while still maintaining the spirit of the original criterion. With this updated version of the framework, the researchers again coded (as described in previous iterations) the same fifteen states as had been done previously to ensure that the modifications were more completely representative of a quality K-12 engineering education. Finally, this iteration was presented at the American Society for Engineering Education conference within the K-12 and Precollege Engineering Division where the research team solicited feedback from the audience on the framework. Feedback was provided by five participants, one of which was fairly extensive.

Iteration #4

Iteration #4 resulted in changes from iteration #3 based on the second analysis of the standards from those 15 states and the feedback from the expert reviewers and stakeholders present during the conference presentation mentioned above. The most significant change was to reorder the indicators. The previous order of the indicators simply reflected the evolution of the framework from the original ABET student outcomes and not any valuation of the relative importance of the indicators. Reviewers commented, however, that despite the lack of intent to rank the indicators, the fact that they appear in some order implied a ranking. For that reason, the order of the indicators within the framework was carefully rearranged based on the degree to which the indicator is a unique or central aspect of engineering compared to skills, processes, and ways of thinking used across several disciplines. The rearrangement of the framework occurred in close consultation with the expert reviewers from previous iterations. Indicators that appear near the beginning (e.g., *POD*) are thought to be defining characteristics of engineering. Whereas, those indicators that appear later (e.g., *Teamwork*), although essential for engineering education, are concepts that are required for success in multiple disciplines. The final framework presented above (Figure 1) reflects the ordering at this stage.

Additional reviewer comments and the analysis of our second coding prompted several additions to the definitions. These additions were intended to provide more detailed descriptions of the indicators. The most significant of these was the addition of engineering processes to the *ETool* indicator. These processes include things like manufacturing processes as well as concepts like the "universal systems model" that are important components of engineering. This key indicator was renamed again to *Engineering Tools & Processes (ETool)*. Along with that, minor modifications to several of the indicators were made. For example, additional aspects of engineering thinking like considering product reliability and managing uncertainty and risk were added to the *EThink* indicator.

The changes described above marked the penultimate version of the framework. With this iteration (iteration #4), the testing of the framework was expanded to include the evaluation of the science standards documents for all 50 states. The science standards for each of the original 15 were re-coded along with the science standards for the remaining 35 states. For the results of the analysis of science standards from all 50 states see (Moore, Tank, Glancy, Kersten, & Ntow, 2013).

Iteration #5

Application of iteration #4 of the framework to all 50 states' science standards documents identified a few final changes that will be described below and resulted in the current version of the Framework for Quality K-12 Engineering Education presented above (Figure 1). The first change was related to the communication indicators, and it was determined that general communication skills, while important, were not unique to engineering so therefore did not belong in a framework that was meant to define engineering for K-12 learners. For this reason *Comm-Edu* was removed. Without that indicator, there was no longer a need for the overall *Comm* indicator so that was also removed. The second change was related to the *Processes of Design* indicator, which was renamed to *Complete Processes of Design* (*POD*) to distinguish it more clearly from the sub-indicators beneath it. Finally, the detailed definitions, examples, and clarifying statements that the research team had been using for coding were incorporated directly into the indicator definitions themselves. The final key indicators as well as their definitions are reflected in the *Framework for Quality K-12 Engineering Education* section above.

As these modifications did not alter the content of the definitions, only their presentation, the testing of the fifth iteration of the framework did not include another round of coding of state standards documents and instead the testing of the current iteration was extended to include additional aspects of the educational system. This application helps to ensure that educators, researchers, and policy makers can use the framework more broadly for the inclusion of engineering in various K-12 settings. The additional aspects that were included for this round of testing included the application of the framework to evaluate classroom practice and for use in the development and evaluation of a research-based curriculum.

The fifth iteration of the framework was applied in classroom settings by using it as an evaluation tool for describing how and to what extent high school science teachers implementing an integrated STEM module represented engineering in their classroom. Kersten (2013) used the framework as a means to describe the comprehensiveness and quality of modules, which resulted in a demonstration of varying levels of quality among modules and their implementation. The classrooms in which the research took place included required and not required science courses, differing levels of students of color (as high as 75%, as low as 10%), and varying percentages of students receiving free and reduced lunch (as high as 62% and as low as 29%). Her work included parsing out key indicators of the framework into three groups: (1) indicators central to engineering and engineering education (POD [POD-PB, POD-PI, POD-TE], SEM, and EThink), (2) indicators important to the development of students' understanding of engineering (CEE and ETools), and (3) indicators that promote important professional skills used by engineers (ISI, Ethics, Team, and Comm-Engr). Her results indicated that in order for a module to be of adequate quality, it needed to include all of three of the indicators central to engineering (POD, SEM, and EThink). She found that when these were not present, "a project can merely become a craft or tinkering project, rather than an engineering design project" (p. 243). Her results also indicated that the Team and Comm-Engr indicators are required for the module to be considered adequate quality. Her findings suggested that the indicators important to the development of students' understanding of engineering (CEE and ETools), and the ISI and Ethics indicators are not required for a quality engineering unit, but that when they are added, the projects are more authentic. Kersten's work increased the understanding of how the framework could be useful in the classroom setting.

Additionally, the fifth iteration of the framework was applied to the development and subsequent evaluation of an integrated STEM curricular unit. In this case, the framework provided a lens for researchers when considering the inclusion of the necessary engineering learning objectives at the elementary level. The PictureSTEM Project (Moore, 2010–2015) is a design-based K-5 curriculum development project that explores the use of engineering and literature to facilitate the meaningful learning of STEM content through the integration of these disciplines. The application of the framework to one of the K-2 grade band units, *Designing Hamster Habitats* (Tank, Pettis, Moore, & Fehr, 2013), ensured that this STEM integration curricular unit was accurately representing core ideas, skills, and dispositions of engineering throughout the unit. This unit has been adopted by a highly diverse, urban school district for use with all kindergarten students. This district is an inner-ring metropolitan district with 11,000 students in grades K-12, 41% of students of color, 42% of students receive free or reduced-price lunch, and 35 different languages are spoken by the students and their families.

The application of the framework to this early elementary unit also helped the researchers assess the use of the framework for application with younger students in elementary settings. Upon evaluation of the K-2 grade band unit with the framework, it was found that the curricular unit addressed 10 of the 12 key indicators identified in the framework. When implemented in classrooms, the curricular module also met the same indicators. Therefore, with the successful application of the framework to elementary academic state standards and the development of an elementary curricular unit and its implementation, it was determined that at the current time the framework did not need to be further modified for use in elementary settings.

The ultimate goal of the project was to create a document that could be used to help educators gain a deeper understanding of engineering and the components that make up engineering, and as a research tool for evaluating the inclusion of engineering in K-12 settings. Therefore, the extended application of the current framework for evaluating classroom teaching practices and curriculum helped to expand the system of use for this framework into educational settings beyond academic state standards documents. Additionally, the classroom implementations of the framework described above helped to demonstrate that the framework is applicable across K-12 grade levels and for a diverse set of students.

Conclusion

This paper describes the Framework for Quality K-12 Engineering Education and its development in order to provide a research-based justification for its structure and content. The framework was created in order to meet the growing need for a clear and concise definition of quality K-12 engineering education to be used in guiding development of curricula, classroom implementation, standards, and policy around engineering in integrated K-12 STEM education settings. As we look towards the future of STEM education, there is a need for continued research about how engineering is and should be implemented at the K-12 level.

The framework has uses as an evaluation and development tool for policy and research regarding K-12 engineering and STEM education. The framework has been used to assess the current status of engineering in all 50 U.S. state's academic science standards (Moore, Tank, et al., 2013) and is also being applied to the national career and technical education standards to gain a picture of how engineering is currently represented in our K-12 educational system. It has also been used to assess the public drafts of the Next Generation Science Standards (NGSS Lead States, 2013) as a feedback mechanism for writers of the standards. The framework has been presented to the National Academy of Engineering's Committee on Integrated STEM Education (Moore, 2012) for their work on developing a national strategic research agenda for determining the approaches and conditions most likely to lead to positive outcomes of an integrated STEM education. Lastly, the framework has been applied to student-level engineering content assessments to be used in research to assure a comprehensive view of engineering was present (Moore, Imbertson, Guzey, Roehrig, & Davis, 2013–2018). These uses provide an overview to the possibilities of how the framework might be used to evaluate existing engineering education initiatives.

Furthermore, the framework can be useful for curriculum development both for the development of units of instruction and for the development of scope and sequencing throughout K-12 curricula. Teachers who have been introduced to the framework through professional development opportunities have used this framework as a guide to ensure their curricular units faithfully represent the complexities of engineering (Brown, Roehrig, & Moore, in press). One school district has used the framework to guide the development of programs of instruction around STEM integration (Burrell, Moore, & Roehrig, 2008–2014). However, the authors want to caution the readers here. This framework was intended to ensure a quality engineering education over the course of a student's K-12 education. Not every lesson or unit that a student encounters in engineering education needs to address every key indicator of the framework. These uses show the potential for applying this framework as a guide for school-level engineering education reform.

Many questions have yet to be answered about engineering in K-12 and its role in integrated STEM education. Most of these require a definition and means of operationalizing the conceptions of engineering at the K-12 level (NRC, 2010). The Framework for Quality K-12 Engineering Education offers a collection of key indicators for a comprehensive K-12 engineering education and a means to develop those key indicators through systematic definitions of each indicator. Furthermore, the framework has potential as a research instrument that can lead to deeper understandings of learning and instruction in K-12 engineering education.

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