A Framework for Implementing Quality K-12 Engineering Education

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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 the connections between the disciplines[1, 2]. Engineering can be considered the integrator in STEM 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[3]. At the college level, the Accreditation Board for Engineering and Technology[4] (ABET) has guided the development of engineering programs through its accreditation process, 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*[1] 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, we are left with a number of questions about the best methods by which to effectively teach engineering at the K-12 level and how that plays into the integration of the other STEM disciplines.

The purpose of the current research has been the development of a framework for describing and evaluating engineering at the K-12 level in order to help further our understanding and development of robust engineering and STEM education standards and initiatives. The framework presented in this paper is the result of a larger research project focused on understanding how engineering and engineering design are implemented in K-12 classrooms at the classroom, school, district and state levels. The development of the key indicators of a quality K-12 engineering education that are included in the framework were determined based on an extensive literature review, established criterion for undergraduate engineering programs and professional organizations, document content analysis of state academic 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.

This paper presents the final version of the Framework for Quality K-12 Engineering Education, as well as the detailed reporting of the iterations of the framework through a design-based research paradigm. These results give a more complete picture of how the framework was developed and provide evidence that supports each stage of development.

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

STEM and STEM integration have become an essential focus of precollege education worldwide. Policy documents, international student achievement data, and the fast-paced changes in our technology-based economy have been catalysts to this focus. Many U.S. policy documents have been written and are influencing this focus on STEM education. All of these documents highlight the importance of improving STEM education in order to develop a future generation of creative and competitive STEM professionals. *Prepare and Inspire: K-12 Education in Science Technology, Engineering, and Mathematics (STEM) for America's Future*[5] indicates the need to produce individuals with a strong STEM background in order to be competitive internationally. *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*[6] 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[7]. 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"[1] (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 use of mathematics and science and results in products that are technologies, it can provide a way to do STEM integration meaningfully.

Engineering is a natural integrator. Most 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*[8] articulates and discusses the role of engineering as a mechanism by which students can learn meaningful scientific concepts. This document moves the conversation from the abstract and broad sweeping reform ideas to the concrete by advocating 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*[1], 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[9].

If we are to take this challenge up, we must decide what constitutes a quality engineering education at the K-12 level. *Engineering in K-12 Education: Understanding the Status and Improving the Prospects*[1] 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. However, this is not a robust enough definition of engineering at the K-12 level to be implemented by practitioners. As we look towards providing a more comprehensive definition of K-12 engineering education in an era of standards-based reform, we need to establish clear, coherent, and important content as developmentally appropriate learning outcomes. The document *Standards for K-12 Engineering Education?*[2] concludes that the first step toward improving the quality and consistency in K-12 engineering education is to "articulate the essential core ideas" (p. 37) of engineering that are appropriate for students at this level. The research presented here reports the development of the Framework for Quality K-12 Engineering Education, which was designed to meet the growing need for a clear definition of quality K-12 engineering education.

Methods

The Framework for Quality K-12 Engineering Education was developed using a design-based research methodology[10-12]. For the design of the Framework, the researchers planned iterative cycles of revision in order to get a robust and inclusive framework that encompasses the core ideas necessary for a quality engineering education. Here, we first describe the final framework, and then the development process from the initial version based on a modified ABET Criterion 3: Student Outcomes a-k[4] for K-12 students through to the final version. For each iteration, academic standards from a sample of states were coded by multiple researchers using the framework, and the results of the coding from that iteration were compared and discussed. To facilitate the content analysis of the standards documents, a detailed coding protocol for each iteration of the Framework was developed. This coding protocol was designed to guide the research team and to ensure the validity and reliability of the review process. The iterations of the framework were also evaluated through peer and expert review at key times within the design research cycles. These research cycles will be described in detail in each of the corresponding sections below.

Presentation of the Framework

We begin by presenting the Framework for Quality K-12 Engineering Education in its final form. The Framework has 12 key indicators that, when taken together, summarize a quality engineering education for all students throughout their K-12 education. The following is the introduction to the framework, which is followed by the framework itself (Figure 1):

> *Definition of engineering*
> Throughout this introduction and this framework we define engineering to be the design, manufacture, and operation of efficient and economical technologies (i.e. structures machines, processes, and systems) to purposeful ends through a creative and carefully planned application of scientific and mathematical principles.
>
> *Purpose and intended use of the K-12 framework for engineering*
> This framework was created to meet the growing need for a clear definition of quality K-12 engineering education. It 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 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 education standards and initiatives.
>
> *Development of the K-12 framework for engineering*
> The framework's key indicators for a quality K-12 engineering education were determined based on an extensive review of the literature, established criterion for undergraduate and professional organizations, and in consultation with experts in the fields of engineering and engineering education. The order of the key indicators within the framework was carefully chosen based on the degree to which the benchmark 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., *Communication*), although essential for engineering education, are concepts that are required for success in multiple disciplines.
>
> Clear distinctions were made between the key indicators of the framework for evaluative purposes, although in reality many of the indicators and their uses overlap. The distinctions between the indicators allow the users of the framework to more precisely identify the strengths and weaknesses within the work being evaluated. The distinctions were made in an effort to simplify the evaluation

process, not to place value or pass judgment on different aspects of engineering education.

Engineering context within academic standards, curricula, & teaching practices
The use of this framework for the development or assessment of academic standards, curricula, or teaching practices that promote a quality K-12 engineering education is only appropriate when an engineering context is present, either explicitly or implicitly stated. For example, an experiment could be considered part of the testing phase within engineering design or as part of a scientific investigation. The context in which the student does the experiment determines whether or not the framework is applicable. A student is considered to be *doing engineering* when they are engaged in a complete or partial process of design, or activities that involve the student in engineering thinking and habits of mind. A student is considered to be *learning about engineering* when they are studying design processes, conceptions of engineers and engineering, and closely related skills and topics. Either *doing engineering* or *learning about engineering* can satisfy the requirement of an *engineering context.*

Figure 1 provides the 12 key indicators that make up the final framework as well as the descriptions of the indicators, which includes how the framework is to be applied.

The Framework for a Quality K-12 Engineering Education		
Key Indicator		**Description**
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 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.
Sub-indicators of POD	**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 weaknesses 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, 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 **(ETool)**	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 a step-by-step procedure for a specific task (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 on and 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 **(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 do 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.

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

Development of the framework

The research team involved in the development of the framework consisted of one professor of STEM education and four graduate researchers. Two of the graduate researchers were from mathematics education and two were from science education – one of the science education researchers also had a master's degree in engineering. Additionally, each member of the research team had K-12 teaching experience.

Although several sets of standards or expectations exist for undergraduate engineering programs, as noted above, no established framework for K-12 engineering education existed prior to this study. To generate an initial version of the K-12 framework, the research team began by comparing the literature on K-12 engineering education with established criteria for undergraduate and professional organizations.

The initial framework was based on the Accreditation Board for Engineering and Technology (ABET) Criterion 3: Student Outcomes (a)-(k)[4] (Figure 2), which describe the desired characteristics of student who have completed accredited undergraduate engineering programs. The ABET Criteria are used to accredit U.S. and international post-secondary education programs in applied sciences, engineering, and technology. 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.

Initial ABET-based framework (*Iteration #1*)
Before applying the ABET Criterion 3[4] directly to K-12 standards and learning materials, we conducted an extensive review of the literature on K-12 engineering education (see Moore, Stohlmann, Kersten, Tank, and Glancy[13] for this review). The literature was examined for connections to the outcomes (a)-(k) within Criterion 3. This review revealed that the characteristics outlined in Criterion 3 were consistent with the aspects of K-12 engineering education emphasized in the literature. Based on the literature, we then created K-12 focused interpretations of the ABET student outcomes which marked the first iteration of the framework. Besides viewing each outcome through a K-12 lens, 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.

(a) an ability to apply knowledge of mathematics, 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 for engineering practice.

Figure 2. ABET Criterion 3: Student Outcomes[4]

Following the extensive review of the literature, the literature was summarized and organized into working definitions for each of the student outcomes that related to K-12 engineering education. In order to test the degree to which these reformulated student outcomes would apply to the K-12 setting, our research team coded the Massachusetts science standards[14] as a group with the ABET-based framework. Massachusetts was selected because it was the first state to require engineering at all levels. The coding process for this iteration, and each subsequent iteration, was a two-step process. First, each standard or benchmark to be coded was considered individually, and each researcher coding the standard first determined whether it contained any engineering. Second, if it was determined that a standard did contain engineering, each researcher examined the standard for evidence of the outcomes as described in the current iteration of the framework. Individual results were recorded in a spreadsheet and compared with another researcher after completing the coding of the standards document. Through discussion, any disagreements were resolved and final codes were recorded. Comparisons of our codes and analysis of the overall results revealed areas where the current working definitions of the ABET student outcomes needed further modification to be appropriate for K-12 applications. The framework was then adjusted accordingly resulting in the next iteration.

Modified ABET-based framework (Iteration #2)

In this iteration, we set out to resolve the following issues. First, the distinction between outcome (c), which focuses on engineering design, and outcome (e), which focuses on solving engineering problems, was difficult to resolve when examining the Massachusetts standards because engineering design is a specific approach to problem-solving. As a result, we found few examples of standards that were coded as engineering design but not problem solving and vice versa. Furthermore, identifying and formulating problems is an important part of the engineering design process, and the literature does not reflect a clear distinction between the two for K-12 students. For these reasons, outcomes (c) and (e) were combined. Likewise, outcome (h), which centers on the impact of engineering solutions on important issues, and outcome (j), which focuses on the knowledge of those issues, were determined to be very similar. In the context of engineering, when contemporary issues appear within the literature or the standards the issue itself is discussed in conjunction with the solutions (or possible solutions) to the problem. For this reason, outcomes (h) and (j) were also combined. In both of these cases we consulted with experts in the field of engineering education who were very familiar with the ABET student outcomes to confirm and clarify our interpretations of those outcomes.

The revised version of the framework with these collapsed definitions for outcomes (c) and (e) and outcomes (h) and (j) became the next iteration of the framework (Figure 3). Because this iteration marked a somewhat significant modification of the ABET Criterion 3: Student Outcomes[4], we adopted our own names for each of the outcomes. Furthermore, we acknowledged that the term "outcome," although appropriate 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, we adopted the term "indicator," and from this point forward, we will refer to the elements of the framework as "indicators." Furthermore, those indicators that appear in the final framework will be referred to as "key indicators." Figure 3 lists the indicators for the 2nd iteration and the ABET student outcomes from which they evolved. At this point we also created a coding protocol by compiling example standards and descriptions of how those standards met the working definitions of the indicators. This protocol was used to examine fourteen additional states' science standards. This expanded application helped us to develop the definitions of the framework in a way that worked to establish consistency in coding, despite the large variation in the structure and layout of each of the state standards documents. The fourteen states were chosen based on their identification by Strobel, Carr, Martinez-Lopez, and Bravo[15] as having explicit engineering in their academic state standards. Standards documents for each of these states were retrieved from the respective state department of education websites in the fall of 2011 and were current as of that point. Massachusetts was the only state to be coded by all four graduate researchers; the other fourteen states were coded in pairs by one of the science education graduate researchers and one of the mathematics education graduate researchers. Through the discussions to reach final agreement for these fourteen states, further refinements and additions were made to the definitions of each indicator for this iteration (see Moore et al.[13] for a complete description of the framework at this stage).

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: Evolution of the ABET Criterion 3: Student Outcomes[4] within the Framework

Preliminary K-12 framework (Iteration #3)

After reviewing codes for fifteen states, the results indicated the need to make major adjustments to the ABET-based framework in order to appropriately reflect the K-12 classroom/setting. Figure 4 provides a list of the new indicators for this iteration. The changes represented in this iteration will be described in detail in this section. First, it became clear that combining indicators (c) and (e) into *Design Cycle/Problem Solving* did not completely resolve the issue stated above. Although doing so made the coding of certain standards more clear, it also allowed states to meet that indicator often by focusing heavily on problem solving without truly requiring students to engage in the process of design. Additionally, we acknowledged that the intent of the *Inquiry & Data* indicator was that these skills would be used while testing and evaluating a design solution not just in a purely scientific context, but the indicator definition did not reflect that. Furthermore, this iteration of the framework did not allow us to distinguish standards that addressed the entire design process from those that only addressed a portion of the process. For these reasons, we eliminated the *Design Cycle/Problem Solving* and *Inquiry & Data* indicators and replaced them with one new key indicator and three sub-indicators. We 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 a design process and to accommodate those standards that dealt with design but not an entire design process, we create three sub-indicators. These sub-indicators represent different phases of design: *Problem and Background (POD-PB), Plan and Implement (POD-PI),* and *Test and Evaluate (POD-TE).* Although we acknowledge the variation in specific processes of design, we contend that any design process will pass iterate on these three, broad phases in some form or another.

Indicator
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 (Ethics)
Communication Skills (Comm)
Engineering Communication Skills (Comm-Engr)
General Communication Skills (Comm-Edu)

Figure 4: Preliminary K-12 Framework

Analysis of the first fifteen states with the modified ABET-based framework also revealed that the *Life-Long Learner* indicator, as stated, was not 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. The Framework for Quality K-12 Engineering Education, however, is meant to guide and evaluate the learning activities and opportunities afforded to the students during their K-12 education and classroom experiences. For this reason, we eliminated the *Life-Long Learner* indicator, although the thrust of the indicator remains as a part of two new indicators discussed below.

In order to better address the developmentally appropriate learning opportunities provided to K-12 students, we felt that the ABET-based framework was missing some key developmental pieces necessary for a comprehensive engineering education. The first new key indicator that we created was *Conceptions of Engineers and Engineering (CEE).* Students in an undergraduate engineering program have already made a choice to pursue engineering in some form, and it is fair to assume that they have more developed conceptions of engineering and the work of engineers. Thus, it is not surprising that this is absent in the ABET outcomes which are designed for undergraduate engineering programs. K-12 students, however, may not have such conceptions, and what is more problematic, they may have misconceptions about the nature of engineering[16]. For this reason, it is important that students are given opportunities to learn about engineering as a profession and what it takes to be an engineer[17, 18]. These concepts are the basis for the indicator.

Engineering habits of mind and ways of thinking were also noticeably absent from earlier version of the framework. One of the three recommendations from the 2009 National Research Council report[1] calls for the promotion of engineering habits of mind and, while the Processes of Design encompass a large part of how engineers approach problems, the types of thinking involved in solving an engineering problem are not limited to design processes. For this reason, we added the *Engineering Thinking (EThink)* key indicator to include ideas like learning from failure and reflective thinking.

Application of the second iteration of the framework to the state standards 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 were not specific enough for the types of communication skills that are more specialized for use 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)*. If a standard or learning activity gave students the opportunity to develop both types of communications skills it was coded as only *Comm*.

At this point, we also made several other minor changes to the framework. Most significantly, we reversed our previous decision to include technology in the *STEM* indicator. Although application of one's technological knowledge is an important aspect of engineering, at the K-12 level students focus more on learning about and how to use the technologies than applying them. We felt this was 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)*. We also renamed the *Technology & Engineering Tools* indicator to simply *Engineering Tools (ETool)*. The last change was to rename the *Global, Economic, Environmental, Societal and/or Contemporary Issues* indicator with the new name *Issues, Solutions, and Impacts (ISI)*. The list of indicators as of the 3rd iteration are shown in Figure 4. With this updated version of the framework we again coded (as described above) the same fifteen states as had been done previously and to ensure that our modifications were more completely representing a quality K-12 engineering education.

Framework prototype (Iteration #4)

Throughout the course of this second coding of the fifteen states identified by Strobel et al.[15] as having explicit engineering standards, we refined the working definitions for each indicator. We also compiled lists of key-phrases and specific concepts that fell under each indicator into a *code-book*. The *code-book*, including the definitions, phrases, and examples was sent to several experts in the fields of engineering and engineering education for review and feedback.

Based on our second review of the standards from those 15 states and the feedback from the expert reviewers, we modified the framework even further. 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 our 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 chosen based on the degree to which the indicator is a unique or central aspect of engineering as compared to other disciplines. 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., *Comm*), 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 that this stage.

Additional reviewer comments and the analysis of previous coding results prompted us to make several additions to the definitions and clarifying examples in the code-book to provide more detailed definitions. The most significant of these was the addition of engineering processes to the *ETool* indicator. These include things like manufacturing processes as well as concepts like the "universal systems model." This indicator was renamed again to *Engineering Tools & Processes (ETool)*. Along with that we made minor modifications to several of the indicators. For example we added concepts like safety factors and considerations of product reliability to *EThink*.

The last issue that we resolved based on reviewers feedback, was the question about what criteria we were using to determine if a standard satisfied our requirement of engineering context. Throughout the coding process, we had been using an informal, working understanding of *engineering context.* Many of the skills listed in the framework are not unique to engineering or are very similar to skills in other disciplines. For example, formulating problems, analyzing data, and considering the ethical implications of work are all important aspect of science as well. This framework, however, is designed specifically to evaluate education materials focused on engineering. Thus, an activity or learning opportunity may encourage or develop a skill that appears in the framework, but it does not meet the criteria set by the framework if it does not do so within an engineering context. For this to be clear, we determined that is was necessary to add introductory material to the framework outlining the definition of engineering on which it is based, the intended use of the framework, and the definition of engineering context used in developing it. We will describe this introductory material in the following paragraphs.

In defining engineering context, we first developed a definition of engineering based on discussion with experts and review of definitions in the literature. The National Academy of Engineering (NAE) and National Research Council (NRC) published a report in 2009, which looked at the scope and status of teaching engineering in K-12 schools, and their definition included that engineering is a “body of knowledge about the design and creation of human-made products and a process for solving problems”[1] (p.17). Further expansion on that definition included that engineering is “design under constraint”[19] with a fundamental constraint being the laws of nature, and the recognition that engineering utilizes concepts in science and mathematics[1, 2]. Brophy, Klein, Portsmore, and Rogers[17] highlight that “engineering requires applying content knowledge and cognitive processes to design, analyze and troubleshoot complex systems in order to meet society’s needs” (p. 371). For the purposes of this framework, we define engineering to be the creative and carefully planned application of scientific and mathematical principles to purposeful ends through the design, manufacture, and operation of efficient and economical technologies (i.e. structures, machines, processes, and systems). Based on that definition, our understanding of engineering context is any learning activity or material that allows the student to do engineering or learn about engineering. Students are doing engineering when they are engaged in a complete or partial design process or in activities that involve engineering thinking and habits of mind. Students are learning about engineering when they are studying design processes, conceptions of engineers and engineering, and closely related skills and topics.

The changes described above marked the penultimate version of the framework. With this iteration, we expanded our coding and analysis of the science standards 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.

Final framework (Iteration #5)

After coding and analyzing all 50 states with the fourth iteration of the framework, a few final changes were made resulting in the Framework for Quality K-12 Engineering Education presented above (Figure 1). First, it was determined that general communication skills were distinct enough from the essential engineering communication skills that they did not belong in the framework. 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 *Processes of Design* indicator was also renamed to *Complete Processes of Design* (*POD*) to distinguish it more clearly from the sub-indicators beneath it. The final changes were the incorporation of the examples and clarifying statements in the code-book directly into the indicator definitions themselves. As these modifications did not alter the content of the definitions, only their presentation, we did not need to complete another round of coding. For the result of the analysis of science standards from all 50 states see[20]. The final key indicators as well as their definitions are reflected in Figure 1.

Conclusion

In this paper, we have described the development of the Framework for Quality K-12 Engineering Education 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 definition of quality K-12 engineering education. Additionally, the framework is intended to provide guidance for the development of curricula, system changes, and policy with regards to using engineering in an integrated STEM education at the K-12. As we look towards the future of STEM education, there is a need for continued research about how engineering is 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[20] and will also be 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[21] as a feedback mechanism for writers of the standards. We have presented the framework to the National Academy of Engineering's Committee on Integrated STEM Education[22] 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 the development of student-level engineering content assessments to be used in future research[23]. 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 the K-12 curricula. Teachers who have been introduced to the framework through professional development opportunities have used this framework as a guide to ensuring their curricular units represent the complexities of engineering (e.g., Brown, Roehrig, and Moore[24]). One school district has used the framework to guide the development of programs of instruction around STEM integration[25]. However, we want to caution the readers here. This framework was intended to guarantee 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 using 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 some kind of a definition and means of operationalizing that concept[2]. The Framework for Quality K-12 Engineering Education offers both key indicators for a comprehensive K-12 engineering education and a means to develop those key indicators through thorough definitions of each. It has potential as a research instrument that in future studies can lead to deeper understandings of learning and instruction in K-12 engineering education.

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