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Nature and Extent of Science and Engineering Practices Coverage in K-12 Engineering Curriculum Materials*

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The integration of science and engineering practices in K-12 science education is currently an area of growing national interest in the United States, as evidenced in the recently published document titled *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. However, to date, little is known about the extent to which these practices are covered in the widely used K-12 engineering programs. As a response to the dearth of research in this area, this study investigated the nature and extent to which science and engineering practices are covered in the widely used K-12 engineering programs in the United States. Nine programs that are widely used in the United States were analyzed via document content analysis method using the K-12 science education framework. The results revealed important findings showing the similarities and disparities in the coverage of science and engineering practices in the analyzed programs, grade levels, and in different science discipline units. This study is significant because an understanding of the current status of science and engineering practices coverage would be helpful to educators and curriculum designers as they strive to further the development of integrated science and engineering curricula, as well as shaping the scope and sequence of engineering design thinking learning activities in the K-12 science curriculum.

Keywords: engineering practices; science practices; K-12 engineering education; K-12 science curriculum

1. Introduction

The integration of engineering design in K-12 science education is currently an area of growing national interest in the United States [1] and in other nations [2]. Integrating engineering in K-12 science curricula has been viewed as one of the ways to enhance students' learning and promote interest in STEM subjects [3, 4, 5]. In the United States, the push for this integration is evident in the three national documents recently published by the National Academy of Engineering and National Research Council, which include: *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* [5]; *STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research* [6]. *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas* [7]. The above documents have fostered a connection between engineering and science education to help better prepare students and society to address current and future challenges of our modern and technological society [5, 7, 8]. Particularly, the National Research Council released the New Framework for K-12 Science Education that has three main dimensions: *Science and engineering practices*, C*rosscutting concepts*, and C*ore ideas in science disciplines* [7]. These dimensions outline the knowledge and practices of science and engineering that all students should learn by the end of high school. In this paper, the focus is on the science and engineering practices which include: asking questions (for science) and defining problems (for engineering); developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematics and computational thinking; constructing explanations (for science) and designing solutions (for engineering); engaging in argument from evidence; and obtaining, evaluating, and communicating information.

Engaging K-12 students in science and engineering practices can "help students see how science and engineering are instrumental in addressing major challenges that confront society today" [7, p. 6]. Other researchers have argued that integrating engineering practices in STEM curricula have benefits for both learning outcomes and students' interest in the STEM subjects [1, 9–11]. Engaging students in the practices of science and engineering would help them understand how scientific knowledge develops, understand the work of engineers, and understand the links between engineering and science. Furthermore, these practices can help students develop meaningful understanding of concepts and how those concepts can be used to solve engineering problems facing society. Generally speaking, scientific inquiry practices involves conducting experiments to answer the given question by gathering experimental data, analyze and interpret that data, and use models to explain the observed phenomena [11]. These science practices are critical prerequisites to learning in an engineering design

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context, which include defining engineering problems, and determining possible solutions to the problems [12].

To date, a few studies have been conducted that shed light on the current status of engineering in K-12 science education [4, 13]. Moore et al [4] surveyed the status of engineering standards present in state science standards and the Next Generation Science Standards in K-12 science, using the *Framework for a Quality K-12 Engineering Education* [14]. The key indicators in this framework included the following engineering design processes—problem and background, plan and implement, test and evaluate, application of science/engineering/math knowledge, engineering thinking, conceptions of engineers and engineering, engineering tools and processes, issues/solutions and impacts, ethics, teamwork, and engineering communication. Their results revealed these trends: (a) the emphasis of engineering in the above key indicators of engineering design process were as follows (note that the percentages provided were rounded off to the nearest whole number): 5% (problem and background), 24% plan and implement, 28% test and evaluate, 38% application of science/engineering/math knowledge, 15% engineering thinking, 10% conceptions of engineers and engineering, 12% engineering tools and processes, 20% issues/solutions and impacts, ethics, and 10% engineering communication. (b) Number of engineering related standards at different grade levels were 11% (K-2), 23% (3–5), 28% (6–8), and 35% (9–12). In another study, Meyer et al [13] reviewed over 300 activities across a variety of content areas and grade bands to explore how specific inquiry based activity structures (i.e. Protocol, Design Challenge, Product Testing, Black Box, Discrepant Event, Intrinsic Data Space, Taxonomy, and Modeling), are better suited to emphasizing engineering in the K-12 science classrooms. Their results revealed that (a) fewer activities included engineering practices, and more included science inquiry activities. (b) The Design Challenge activities included more engineering practices and promoted inquiry-based learning best.

Despite some research efforts cited above, there is a dearth of research investigating the nature and extent to which the science and engineering practices stipulated in the current K-12 science education framework are covered in the widely used K-12 engineering programs in USA and elsewhere in the world. In fact, at the time we conducted this study, we did not come across any empirical study that had attempted to analyze K-12 curricula for the coverage of science and engineering practices outlined in the Next Generation Science Standards in the new K-12 science education framework. The absence of research in this area has been the rationale for our current study. At this juncture, we remind readers that we are not starting out with the assumption that all K-12 engineering curricula must necessarily include all the science and engineering practices, nor are we assuming that these practices must be synergistically integrated. Instead, we recognize that depending on the learning objectives, topic or concept being taught/learned, some practices would be more prominent than others.

Therefore, the purpose of this study was to determine the nature and extent of science and engineering practices coverage in widely used K-12 engineering programs. The research questions that guided this study were: (1) To what extent are science and engineering practices covered in selected K-12 engineering programs? (2) What is the coverage of science and engineering practices across grade levels (elementary, middle and high school)? (3) What is the coverage of science and engineering practices across discipline-specific subjects (i.e. life science, physical science, and earth/space science units)?

This study is significant because as interests in integrating engineering practices and design in science curriculum continues to increase, there is need to know which practices are addressed and to *what extent* they are addressed in existing K-12 curriculum materials. This knowledge is critical, as it would inform K-12 engineering curriculum developers, STEM teacher education programs, and K-12 teachers on which practices to consider during curriculum design and development of learning experiences for students. Furthermore, an understanding of the current status of science and engineering practices would be helpful in furthering the development of robust integrated science and engineering curricula, as well as shaping the scope and sequence of engineering design and engineering thinking learning activities in the K-12 science curriculum.

2. Methodology

2.1 Data sources & selection criteria

At the time this study was conducted (2014–2015 academic year), there are several existing K-12 engineering programs (both formal and informal non-school organizations), whose focus has been developing engineering-based curriculum materials in the USA [3, 15–17]. To locate the relevant programs, we consulted the 2009 report published by the NAE (National Academy of Engineering (NAE) and National Research Council (NRC)—"*Engineering in K-12 Education: Understanding the Status and Improving the Prospects*" that compiled a comprehensive list and brief notes of about twenty engineering-focused programs [5, p. 189–207]. Out

Table 1. K-12 engineering programs analyzed

Program & developer	**Maturity, Impact/Diffusion**
Elementary School (grades K–5) ***Engineering is Elementary (EiE)*** (By Boston Museum of Science)	Started in 2003. To date, 20 units have been developed, field tested, and published. Being used by about 15,000 elementary teachers and have impacted about one million students. *Website*: http://www.eie.org
City Technology (CT) (By City College of New York)	Earlier curriculum guides were published in 2002 but did not have an engineering component. However, currently Force & Motion and Energy Systems are developed which integrate engineering. Earlier series were field-tested in 19 US states & 49 teachers have been trained to provide professional development in 16 states across the country. Website: http://www.citytechnology.org/stuff-that-works/home
Middle School (Grades 6–8) ***Engineering by Design^{TM} (EbD)*** (By International Technology Education Association-ITEA)	Is a national Standards-Based Model Program built on the constructivist model that engages students in authentic, problem-based environment. EbD has a wider readership and implementers. *Website*: http://www.iteaconnect.org/EbD/ebd.html
Gateway to Technology (GT) (By Project Lead the Way)	Over 1,400 schools in 50 US states & District of Columbia are participating in PLTW program. Analysis of 171 college transcripts showed 40% of students that completed PLTW pursued further education in technology and engineering fields in college. *Website:* http://www.pltw.org/our-programs/gateway
Learning by Design (LbD) (By Georgia Institute of Technology)	Several articles and presentations have been documented between 1995–2004. Has been used among many students and teachers, though no exact numbers are given. *Website*: http://www.cc.gatech.edu/projects/lbd/home.html
A World in Motion (AWIM) (By Society for Automotive Engineers)	Started in 1996. Used in all 50 US states and in 10 of Canada's 13provinces. Over 60,000 kits have been shipped to schools since1990. About 4 million students across North America have participated. More than 15,000 volunteer engineers have been involved in AWIM programs. *Website:* http://www.awim.org/
Engineering for Today's Intermediate School (ETIS) (By Infinity)	Developed in 1999. Has trained over a thousand instructors. Currently being used in about 543 middle and high Schools in 38 USA States and 9 Countries. Has impacted thousands of students as they apply key concepts through hands-on engineering design projects. *Website:* http://www.smu.edu/Lyle/Institutes/CaruthInstitute/K-12Programs/InfinityProject
High School (grades 9–12) ***Principles of Engineering (PoE)*** (By Project Lead The Way)	Over 1,400 schools in 50 US states & District of Columbia have participated. Analysis of 171 college transcripts showed 40% of students that completed PLTW classes pursued further education in technology and engineering fields as first year college students. *Website:* http://www.pltw.org/our-programs/engineering/engineering-curriculum
Math for Innovators (MfI) (By Infinity)	Developed in 1999. Has trained over a thousand instructors. Currently being used in about 543 middle/ high Schools in 38 USA States and 9 Countries. *Website:* http://www.smu.edu/Lyle/Institutes/CaruthInstitute/K-12Programs/InfinityProject

of these, we selected nine programs (see Table 1) using the following criteria: should have a science and engineering education focus; should be within the K-12 grade band; should have lesson materials, activities and outlines accessible online or by reasonable purchase; and most importantly, should have evidence that it has been widely implemented among students and teachers in the USA.

2.2 *Units of analysis*

The units of analysis in this study were lesson units. Each program has several lesson units. Whilst it would have been ideal to analyze all units per program, we selected three units per program based on the science content focus (i.e. life science, physical science, and earth/space science). Our justification for not analyzing all units in a given program is that each program has a specific learning/lesson progression for all units. These specified lesson progressions enabled us to be confident that we were less likely to overlook some science/engineering practices within the selected curricula. Furthermore, we chose three units per program so that we could focus on sample topics from different science disciplines and be rigorous enough at the same time. The following are examples of some lesson progressions of some programs. At the core of each unit in Engineering is Elementary program, there is a story that features different people (the characters), a problematic situation (the setting), a pursuit of a resolution to a technical problem (the plot), and ultimately, a viable solution (the conclusion). City Technology program units are presented in form of lesson series, each intended for at least one class period. Each lesson is organized into all or most of the following sections: overview that provides a brief statement of the purpose of lesson, list of materials needed for the lesson, lesson plan procedures including worksheets, focused inquiry questions and prompts for writing entries in the science notebooks, suggested assessment methods for student learning outcomes, and extensions that provide additional scientific investigations and engineering design challenges.

The selection of the three curriculum units analyzed was based on two criteria: (a) If the K-12 program covered all science disciplines (i.e. life science, physical science, and earth/space science), then one unit from each of the disciplines was selected. For example, Engineering is Elementary covers topics from all three disciplines, and one unit from each discipline was chosen. (b) If the K-12 program only covered two science disciplines (e.g. life and physical sciences), we chose two or one unit from either. (c) If the program only covered one science discipline such as physical science for A World in Motion program, we chose three different lessons covering different topics within the discipline. Table 2 shows the three units of analysis sampled from each of the nine program curricula (total of 27 lesson units).

2.3 Content analysis framework

The K-12 science education framework developed by National Research Council [7] was used as the analysis framework. It outlined the science and engineering practices, with specific indicator phrases or words for each practice (See highlighted text in Table 3). This framework was used as a rubric for identifying the presence of the science and engineering practices in each program units.

2.4 Data analysis

Document content analysis suggested by Krippendorff [18] was used to analyze the extent to which the eight science and engineering practices stipulated in the K-12 science education framework were addressed. Content analysis was conducted using line-by-line analysis of learning units' goals, prominent activities and assessments.

The anchoring *phrases or words* for each description of the practices (see Table 3) served as descriptors and guided coders in what to look for during the coding process. An example from Engineering is Elementary program unit on "Just Passing through: Designing Model Membranes", the phrase *Explore the properties of a biological membrane* was categorized under the science practice, planning and conducting investigations in science. Another example from Gateway to Technology program unit on "Flight and Space" phrase *calculate fuel consumption and range of an airplane given speed and fuel*

Table 2. Curriculum Units & Science foci for K-12 Engineering programs analyzed

Grade level	K-12 Program	Lesson units selected for analysis & science foci
Elementary School (Grades K–5)	Engineering is Elementary	– Unit 1: Just passing through: designing model membranes (LS) – Unit 2: To get to the other side: designing bridges (PS) – Unit 3: Water, water everywhere: designing water filters (ESS)
	City Technology	– Unit 1: MechAnimations (Force and Motion—PS) – Unit 2: Invent-a-Wheel (Energy Systems—PS) – Unit 3: ElectroCity units (Energy systems—PS)
Middle School (Grades 6–8)	Engineering by Design	– Unit 1: Technological systems: how they work (PS) – Unit 2: Technological systems: issues and impacts (PS) – Unit 3: Technological systems interactions (PS)
	Gateway to Technology	– Unit 1: Energy and the environment (PS) – Unit 2: Flight and space (ESS) – Unit 3: Medical detectives (LS)
	Learning by Design	– Unit 1: Apollo 13 (engineering design process) (PS) – Unit 2: Vehicles in Motion (PS) – Unit 3: Tunneling across Georgia (ESS).
	A World in Motion	– Unit 1: Gravity cruiser (PS) – Unit 2: Motorized Toy Car (PS) – Unit 3: Glider (PS)
	Engineering for the Intermediate School	– Unit 1: Sound engineering: making great sounds (PS) – Unit 2: Engineering in the Natural World (ESS) – Unit 3: Engineering the Human Machine (LS)
High School (Grades 9–12)	Principles of Engineering	– Unit 1: Energy & power (PS) – Unit 2: Materials & Structures (PS) – Unit 3: Control systems (PS)
	Math for Innovators	– Unit 1; Engineering our Environment (ESS) – Unit 2: The Human Body as a Biomachine (LS) – Unit 3: Sounds of a Digital Age (PS)

Note: LS = Life Science; PS = Physical Science; ESS = Earth/Space Science.

Table 3. Science & Engineering practices with specific indicator phrases

1. Asking questions and defining problems	
Science begins with a question about a phenomenon, such as "Why is the sky blue?" or "What causes cancer?" and seeks to develop theories that can provide explanatory answers to such questions. A basic practice of the scientist is formulating empirically answerable questions about phenomena, establishing what is already known, and determining what questions have yet to be satisfactorily answered.	**Engineering** begins with a problem, need, or desire that suggests an engineering problem that needs to be solved. A societal problem such as reducing the nation's dependence on fossil fuels may engender a variety of engineering problems, such as designing more efficient transportation systems, or alternative power generation devices such as improved solar cells. Engineers ask questions to define the engineering problem, determine criteria for a successful solution, and identify constraints.
Example: LbD unit 2—Vehicles in Motion: As students investigate the effects of different ways of applying forces in the rubber band car, they are *asked to generate questions* about the effective features which can improve the performance and design of the car.	*Example:* EiE unit 1—Just passing Through-Designing Model Membranes: *Lesson 1 introduces a problem* that needed to be solved which was to help a frog survive by keeping its skin moist.
2. Developing and using models	
Science often involves the construction and use of a wide variety of models and simulations to help develop explanations about natural phenomena. Models make it possible to go beyond observables and imagine a world not yet seen. Models enable predictions of the form "if . . . then . . . therefore" to be made in order to test hypothetical explanations.	**Engineering** makes use of models and simulations to analyze existing systems so as to see where flaws might occur or to test possible solutions to a new problem. Engineers also call on models of various sorts to test proposed systems and to recognize the strengths and limitations of their designs.
Example: MfI unit 2—The human body as a biomachine. Design a *system to monitor heart rate and respiration while a person is exercising.*	*Example:* EbD unit 1—Technological systems: How they work: *Disassemble a common product and identify the common systems and subsystems found inside*.
3. Planning and carrying out investigations	
Scientists is planning and carrying out a systematic investigation, which requires the identification of what is to be recorded (gather data) and, if applicable, what are to be treated as the dependent and independent variables (control of variables). Observations and data collected from such work are used to test existing theories and explanations or to revise and develop new ones.	**Engineers** use investigation both to gain data essential for specifying design criteria or parameters and to test their designs. Like scientists, engineers must identify relevant variables, decide how they will be measured, and collect data for analysis. Their investigations help them to identify how effective, efficient, and durable their designs may be under a range of conditions.
Example: EiE unit 3—To get to the other side: Designing bridges. Lesson 2 requires students to *investigate* the pushing and pulling forces that act on structures.	*Example:* CT unit 1—Mechanaimations. Lesson 1 requires students to analyze manufactured mechanisms, look at their characteristics and properties that would inform the criteria for their new and improved designs.
4. Analyzing and interpreting data	
Scientific **investigations** produce data that must be analyzed in order to derive meaning. Because data usually do not speak for themselves, scientists use a range of tools including tabulation, graphical interpretation, visualization, and statistical analysis to identify the significant features and patterns in the data. Sources of error are identified and the degree of certainty calculated. Modern technology makes the collection of large data sets much easier, thus providing many secondary sources for analysis.	Engineers analyze data collected in the tests of their designs and investigations; this allows them to compare different solutions and determine how well each one meets specific design criteria—that is, which design best solves the problem within the given constraints. Like scientists, engineers require a range of tools to identify the major patterns and interpret the results.
5. Using mathematics and computational thinking	
In **science,** mathematics and computation are fundamental tools for representing physical variables and their relationships. They are used for a range of tasks, such as constructing simulations, statistically analyzing data, and recognizing, expressing, and applying quantitative relationships. Mathematical and computational approaches enable predictions of the behavior of physical systems, along with the testing of such predictions. Moreover, statistical techniques are invaluable for assessing the significance of patterns or correlations.	In **engineering,** mathematical and computational representations of established relationships and principles are an integral part of design. For example, structural engineers create mathematically based analyses of designs to calculate whether they can stand up to the expected stresses of use and if they can be completed within acceptable budgets. Moreover, simulations of designs provide an effective test bed for the development of designs and their improvement.
Example: PoE unit 1—Energy & Power. Calculate work and power in mechanical systems.	*Example:* GT unit 1—Energy & the Environment. Evaluate a design to reduce heat transfer by *weighing the amount of ice remaining*, and propose improvements for the design.

Table 3 (*continued*)

6. Constructing explanations & designing solutions	
The goal of **science** is the construction of theories that can provide explanatory accounts of features of the world. A theory becomes accepted when it has been shown to be superior to other explanations in the breadth of phenomena it accounts for and in its explanatory coherence and parsimony. Scientific explanations are explicit applications of theory to a specific situation or phenomenon, perhaps with the intermediary of a theory-based model for the system under study. The goal for students is to construct logically coherent explanations of phenomena that incorporate their current understanding of science, or a model that represents it, and are consistent with the available evidence.	**Engineering design,** a systematic process for solving engineering problems, is based on scientific knowledge and models of the material world. Each proposed solution results from a process of balancing competing criteria of desired functions, technological feasibility, cost, safety, esthetics, and compliance with legal requirements. There is usually no single best solution but rather a range of solutions. Which one is the optimal choice depends on the criteria used for making evaluations.
7. Engaging in argument from evidence	
In **science,** reasoning and argument are essential for identifying the strengths and weaknesses of a line of reasoning and for finding the best explanation for a natural phenomenon. Scientists must defend their explanations, formulate evidence based on a solid foundation of data, examine their own understanding in light of the evidence and comments offered by others, and collaborate with peers in searching for the best explanation for the phenomenon being investigated. *Example*: LbD unit 1—Apollo 13: After watching an introductory 1995 movie about the aborted mission to the moon, students are asked to provide convincing argument for or against continuation of the space program in a mock letter to their senator.	In **engineering,** reasoning and argument are essential for finding the best possible solution to a problem. Engineers collaborate with their peers throughout the design process, with a critical stage being the selection of the most promising solution among a field of competing ideas. Engineers use systematic methods to compare alternatives, formulate evidence based on test data, make arguments from evidence to defend their conclusions, evaluate critically the ideas of others, and revise their designs in order to achieve the best solution to the problem at hand.
8. Obtaining, evaluating, and communicating information	
Science cannot advance if scientists are unable to communicate their findings clearly and persuasively or to learn about the findings of others. A major practice of science is thus the communication of ideas and the results of inquiry—orally, in writing, with the use of tables, diagrams, graphs, and equations, and by engaging in extended discussions with scientific peers. Science requires the ability to derive meaning from scientific texts (such as papers, the Internet, symposia, and lectures), to evaluate the scientific validity of the information thus acquired, and to integrate that information.	**Engineers** cannot produce new or improved technologies if the advantages of their designs are not communicated clearly and persuasively. Engineers need to be able to express their ideas, orally and in writing, with the use of tables, graphs, drawings, or models and by engaging in extended discussions with peers. Moreover, as with scientists, they need to be able to derive meaning from colleagues' texts, evaluate the information, and apply it usefully. In engineering and science alike, new technologies are now routinely available that extend the possibilities for collaboration and communication. *Example:* CT unit 1—Mechanimations: Lesson 4 requires students to represent their mechanisms designs by a diagram.

Notes: Text highlighted in grey represents the **phrases** anchoring the given practice, and served as analysis guide during coding.

capacity, was coded as a *mathematics and computational thinking* practice in science.

The research team consisted of two science education professors, one engineering education professor, and one STEM education graduate student. The analysis process consisted of two initial phases of coding and rating of three randomly selected program curricula for coders to get familiar with the process. The inter-rater reliability was established between three coders. Due to the presence of the phrase/word as anchors and clearly highlighted in the framework, the coding process was quite consistent. As such, raters were not constrained by the process. The coefficient of inter coder agreement was calculated [19]. Traditionally, this method is seen as overlooking the possibility of chance agreement. However, since all three coders coded every unit for a total of eight practices, the effect of chance on the overall reliability is diminished. The coders were in agreement on average of 82.52% of the time. After coding, the practices were scored for their presence and extent of coverage.

When determining the coverage level of the practices among all the nine programs and across grade levels and science disciplines, the following threshold percentages were used: If the practice was addressed by 70%–100% of the programs, it was described as *high coverage*; if it was addressed by 40%–69% of the programs, it was described as *medium coverage*; if it was addressed by 1%–39% of the programs, the practice was described as *low coverage*; and if no program addressed it, it was described *no coverage.*

3. Results

3.1 Overall coverage of science and engineering practices

According to Table 4, the coverage of science and engineering practices revealed the following trends. High coverage was found in the two science practices (*developing and using models*, and *planning and carrying out investigations*), and none in engineering. Medium coverage was found in two science practices (*analyzing and interpreting data*, and *constructing explanations and designing solutions*), and in five engineering practices (*developing & using models, planning & carrying out investigations, analyzing & interpreting data, constructing explanations & designing solutions, and obtaining, evaluating, and communicating information*). Low coverage was found in four science practices (*asking questions and defining problems, using mathematics and computational thinking, engaging in argument from evidence*, and *Obtaining, evaluating & communicating information*), and in three engineering practices (*asking questions and defining problems, using mathematics and computational thinking*, and *engaging in argument from evidence*). A salient observation was that the science and engineering practices that had low coverage were mostly found in middle school programs, and rarely in elementary and high school programs.

3.2 Coverage of science and engineering practices across grade levels

Table 5 shows the coverage of science and engineering practices across grade levels. At elementary school level, most of the science and engineering practices had either high or medium coverage. However, there was no coverage for two science practices (i.e. *asking questions and defining problems*, and *using mathematics & computational thinking*), and for two engineering practices (*developing and*

Table 4. Coverage status of science & engineering practices

Extent of coverage	Science practice	K-12 programs	Program Abbreviation	Engineering practice	K-12 programs	Program Abbreviation
High Coverage	Developing & using models	7 (78%)	EiE, CT, LbD, GT, ETIS, PoE, MfI	None	None	
	Planning & carrying out investigations	7 (78%)	EiE, CT, LbD, GT, AWIM, PoE, MfI			
Medium Coverage	Analyzing & interpreting data	6 (67%)	EiE, CT, LbD, GT, AWIM, PoE,	Developing & using models	4 (44%)	LbD, GT, AWIM, PoE
	Constructing explanations & designing solutions	5 (56%)	EiE, CT, LbD, GT, PoE	Planning & carrying out investigations	6 (67%)	CT, LbD, GT, EbD, AWIM, PoE
				Analyzing & interpreting data	5 (56%)	CT, LbD, EbD, AWIM, PoE
				Constructing explanations & designing solutions	6 (67%)	EiE, CT, LbD, GT, AWIM, PoE
				Obtaining, evaluating & communicating information	6 (67%)	CT, LbD, GT, EbD, AWIM, PoE
Low Coverage	Asking questions & defining problems	1 (11%)	LbD	Asking questions & defining problems	3 (33%)	EiE, LbD, EbD
	Using mathematics & computational thinking	3 (33%)	CT, GT, PoE	Using mathematics & computational thinking	3 (33%)	GT, AWIM, PoE
	Engaging in argument from evidence	3 (33%)	CT, LbD, GT	Engaging in argument from evidence	3 (33%)	CT, LbD, AWIM
	Obtaining, evaluating & communicating information	3 (33%)	CT, LbD, GT			

Elementary level: EiE = Engineering is Elementary; CT = City Technology; Middle school level: LbD = Learning by Design; GT = Gateway to Technology; EbD = Engineering by Design; ETIS = Engineering for Today's Intermediate School; AWIM = A World In Motion; High school level: PoE = Principles of Engineering; MfI=Math for Innovators.

Table 5. Coverage of science and engineering practices across grade levels

Science practice coverage by grade level	**Elem (n = 2)**	**Middle (n = 5)**	**High (n = 2)**
Developing & using models	2 (100%)	3 (60%)	2 (100%)
Planning & carrying out investigations	2 (100%)	3 (60%)	2 (100%)
Analyzing & interpreting data	2 (100%)	3 (60%)	1 (50%)
Constructing explanations & designing solutions	2 (100%)	2 (40%)	1 (50%)
Asking questions & defining problems	–	1 (20%)	–
Using mathematics & computational thinking	–	2 (40%)	1 (50%)
Engaging in argument from evidence	1 (50%)	2 (40%)	–
Obtaining, evaluating, and communicating information	1 (50%)	2 (40%)	–
Engineering practices coverage by grade level	**Elem (n = 2)**	**Middle (n = 5)**	**High (n = 2)**
Developing & using models	–	3 (60%)	1 (50%)
Planning & carrying out investigations	1 (50%)	4 (80%)	1 (50%)
Analyzing & interpreting data	1 (50%)	–	1 (50%)
Constructing explanations & designing solutions	2 (100%)	3 (60%)	1 (50%)
Obtaining, evaluating &communicating information	1 (50%)	3 (60%)	1 (50%)
Asking questions & defining problems	1 (50%)	2 (40%)	–
Using mathematics & computational thinking	–	2 (40%)	1 (50%)
Engaging in argument from evidence	1 (50%)	2 (40%)	–

using models, and *using mathematics & computational thinking*). At middle school level, nearly all science and engineering practices had at least medium coverage. Notable observations were low coverage for one science practice (*asking questions and defining problems*), and no coverage for one engineering practice (*analyzing and interpreting data*). At high school level, most science and engineering practices had at least medium coverage. However, there was no coverage for three science practices (*asking questions and defining problems, engaging in argument from evidence*, and *Obtaining, evaluating, and communicating information*), and in two engineering practices (*asking questions and defining problems*, and *engaging in argument from evidence*).

3.3 Coverage of science and engineering practices across discipline-specific units

According to Table 6, the following findings were revealed. (a) Majority of the units developed so far in existing K-12 engineering curricula have a physical science-orientation, followed by earth/space science, and lastly life science. (b) Across all science disciplines units, the coverage of science practices was similar in that there was high to medium coverage of four practices (*developing and using models, planning and carrying out investigations, analyzing and interpreting data, and constructing explanations & designing solutions*), low coverage for three practices (*using mathematics and computational thinking, engaging in argument from evidence*, and *Obtaining, evaluating, and communicating information*), and no coverage for asking questions and defining problems. (c) Across all science disciplines, the coverage of engineering practices varied: in life science, all engineering practices had no coverage except for two that had low coverage (i.e. *constructing explanations & designing solutions*, and *asking questions and defining problem*). In Physical science, all engineering practices were covered, but to varying degrees. High to medium coverage was found in three practices (*Obtaining, evaluating, and communicating information, planning and carrying out investigations*, and *analyzing and interpreting data*), and low coverage in five practices (*developing and using models, constructing explanations & designing solutions, Obtaining, evaluating, and communicating information, using mathematics & computational thinking*, and *engaging in argument from evidence*). In earth/space science, three practices had medium coverage (*planning and carrying out investigations, constructing explanations & designing solutions*, and *asking questions and defining problems*), two had low coverage (*using mathematics & computational thinking*, and *engaging in argument from evidence*), and no coverage in three practices (*developing and using models, analyzing and interpreting data*, and *Obtaining, evaluating, and communicating information*).

4. Discussion

The primary goal of this content analysis was to determine the nature and extent of science and engineering practices coverage in widely used K-12 engineering programs. As we discuss the results, we would like readers to know that at the time our study was conducted, there was no known study that had investigated the coverage of science and engineering practices stipulated in the Next Generation Science Standards outlined in the new K-12 science education framework. Therefore, our dis-

Table 6. Coverage of science and engineering practices across discipline-specific units

Science practices	**Life Science units (n = 4)**		**Physical science units (n = 18)**		**Earth/space science units (n = 5)**	
Developing & using models	3 (75%)	EiE^{1}, ETIS^{3} & MfI^{2}	9 (50%)	CT^{1,3}, LbD^{1,2} , GT^{1}, ETIS^{1}, PoE^{1,3} & MfI^{3}	4 (80%)	LbD^{3}, GT^{2}, ETIS^{2} & MfI^{1}
Planning & carrying out investigations	2 (50%)	EiE^{1} & GT^{3}	9 (50%)	EiE^{2}, CT^{2}, LbD^{1,2}, GT^{1}, AWIM^{3}, PoE^{1,2} & MfI^{3}	4 (80%)	EiE^{3}, LbD^{3}, GT^{2} & MfI^{1}
Analyzing & interpreting data	2 (50%)	EiE^{1} & GT^{3}	9 (50%)	EiE^{2}, CT^{2}, LbD^{1,2}, GT^{1}, AWIM^{1,3} & PoE^{1,2}	4 (80%)	EiE^{3}, CT^{3}, LbD^{3} & GT^{2}
Constructing explanations & designing solutions	2 (50%)	EiE^{1} & GT^{3}	9 (50%)	EiE^{2}, CT^{2}, LbD^{1,2}, GT^{1}, AWIM^{1,3} & PoE^{1,2}	3 (60%)	EiE^{3}, LbD^{3} & GT^{2}
Asking questions & defining problems	–	–	1 (6%)	LbD^{1}	–	–
Using mathematics & computational thinking	1 (25%)	GT^{3}	4 (22%)	CT^{2}, GT^{1} & PoE^{1,2}	1 (20%)	GT^{2}
Engaging in argument from evidence	1 (25%)	GT^{3}	3 (17%)	CT^{2} & LbD^{1,2}	1 (20%)	LbD^{3}
Obtaining, evaluating & communicating information	1 (25%)	GT^{3}	4 (22%)	CT^{1,2} & LbD^{1,2}	1 (20%)	LbD^{3}
Engineering practices	**Life Science units (n = 4)**		**Physical science units (n = 18)**		**Earth/space science units (n = 5)**	
Developing & using models	–	–	4 (22%)	LbD^{2}, GT^{1}, AWIM^{1} & PoE^{2}	–	–
Planning & carrying out investigations	–	–	9 (50%)	CT^{1}, LbD^{1,2}, GT^{1}, EbD^{1,2,3}, AWIM^{3} & PoE^{3}	2 (40%)	LbD^{3}, GT^{2}
Analyzing & interpreting data	–	–	8 (44%)	CT^{1}, LbD^{2}, EbD^{1,2,3}, AWIM^{3} & PoE^{1,3}	–	–
Constructing explanations & designing solutions	1 (25%)	EiE^{1}	7 (38%)	EiE^{2}, CT^{2}, LbD^{1,2}, GT^{1}, AWIM^{1} & PoE^{2}	3 (60%)	EiE^{3}, LbD^{3} & GT^{2}
Obtaining, evaluating & communicating information	–	–	13 (72%)	CT^{1,2}, LbD^{1,2,3}, GT^{1}, EbD^{3}, AWIM^{1,2,3} & PoE^{1,2,3}	–	–
Asking questions & defining problems	1 (25%)	EiE^{1}	6 (33%)	EiE^{2}, LbD^{1,2} & EbD^{1,2,3}	2 (40%)	EiE^{3} & LbD^{3}
Using mathematics & computational thinking	–	–	3 (17%)	AWIM^{1,2} & PoE^{2}	1 (20%)	GT^{2}
Engaging in argument from evidence	–	–	5 (28%)	CT^{1}, LbD^{1,2} & AWIM^{1,2}	1 (20%)	LbD^{3}

Note: Superscripts represent number of lesson unit. For example EiE^{1} represents Engineering is Elementary unit 1. For a complete list of lesson unit numbers, see Table 2.

cussion will draw comparisons from some studies that investigated some aspects of engineering standards in K-12 science curriculum. Our study revealed the following trends:

(a) Across all programs, high to medium coverage for both science and engineering practices was found in four practices (*developing and using models, planning and carrying out investigations, analyzing and interpreting data*, and *constructing explanations and designing solutions*), whereas low coverage was found in three practices (*asking questions and defining problems, using mathematics and computational thinking, engaging in argument from evidence*). However, there was a disparity in the coverage of the practice *Obtaining, evaluating & communicating information* in that it had low coverage for science, but a medium coverage for engineering. Our findings are dissimilar to what Moore et al [4] found in their survey of the status of engineering design processes in K-12 state science standards, in that all their coverage ranges fell in the "low coverage" zone according to our scale. Specifically, Moore et al found that 5%, 24%, 28%, 38%, 15%, 20%, and 10% of the standards addressed problem and background, plan and implement, test and evaluate, application of science/engineering/math knowledge, engineering thinking, issues/solutions and impacts, and engineering communication, respectively. The disparities in percentages between our findings and Moore et al could be attributed to that fact that our study investigated K-12 engineering programs, whose main goals are to develop engineering integrated learning units and thus have more engineering processes addressed at a higher level compared to simply looking at standards which may not be as robust and elaborative as the curriculum units we analyzed.

(b) Across all grade levels, there was low to no coverage for four science practices (*asking questions and defining problems, using mathematics and computational thinking, engaging in argument from evidence*, and *Obtaining, evaluating, and communicating information*), and in five engineering practices (*asking questions and defining problems, using mathematics & computational thinking, engaging in argument from evidence, analyzing and interpreting data*, and *developing and using models*). Our results could be related to Meyer et al. [13], who also found that across grade bands, the prevalence of activities that included engineering practices lagged behind the prevalence of those including science practices.

(c) A striking observation was that the science and engineering practices with low coverage were mostly addressed in middle school programs, and rarely in elementary and high school programs. Similarly, a recent empirical study by Moore et al [4] has also found that the percentage distribution of engineering-related standards across grade levels varied, with less for elementary (i.e. 11% for K-2, and 23% for 3–5), but tended to increase for middle school (28% for 6–8), and high school (35% for 9–12). Although it may not be appropriate to compare these percentage ranges due to differences in research goals, Moore et al's percentages could be interpreted as having low engineering coverage at elementary level, with increasing coverage at middle and even more increases at high school level. These interpretations are both similar and dissimilar to our results in that we had low coverage of engineering practices at elementary and high school levels, but more coverage at middle school levels.

(d) Across all science disciplines units, the coverage of science practices was similar. That is, there was high to medium coverage of four science practices (*developing and using models, planning and carrying out investigations, analyzing and interpreting data, and constructing explanations & designing solutions*), low coverage for three practices (*using mathematics and computational thinking, engaging in argument from evidence*, and *Obtaining, evaluating, and communicating information*), and no coverage for *asking questions and defining problems*.

(e) The coverage of engineering practices varied across all science disciplines. Specifically, all science and engineering practices were covered in physical science units, though to varying degrees. In life science units, all engineering practices had no coverage except for two that had low coverage (i.e. *constructing explanations & designing solutions*, and *asking questions and defining problem*). In earth/space science, majority of the engineering practices had low to no coverage (*developing and using models, analyzing and interpreting data, using mathematics and computational thinking, engaging in argument from evidence*, and *Obtaining, evaluating, and communicating information*). With respect to physical and earth/space units, our findings are dissimilar to Meyer et al [13] who found that earth/Space Science topics were more fruitful in providing opportunities for engineering practices than physical science topics.

(f) Majority of the existing units developed thus far in K-12 engineering curricula have physical science-orientation, followed by earth/space science, and lastly life science.

Based on our findings, the following aspects merit discussion. First, our results show that existing K-12 engineering programs tend to overlook what we consider to be the "basic and foundational" practices, which are critical in initiating scientific investigations and in framing the engineering design problems. Two of the foundational practices, which had low to no coverage across programs, grades levels and science discipline units were *asking questions in science*, and *defining problems in engineering*. We argue that for students to be able to work through the rest of the scientific practices, they need to have well-crafted inquiry questions that aid in planning and investigations, analyzing and interpreting data, or construct explanations. Similarly, without well-defined engineering problems, students may not be able to successfully embark on higher order engineering practices such as designing appropriate engineering solutions. Other current studies have also alluded to the idea that general problem solving skills are prerequisites to solving engineering problems, and students should be able to formulate a design plan as well as identify the need for engineering solutions [4].

Second, for students to be adept at applying the science and engineering practices as they progress through the education spectra, it is critical that these practices are introduced at all grade levels. Unfortunately, our study revealed that most of the science and engineering practices with low coverage were addressed in middle school programs, and that some practices had low to no coverage at elementary and high school levels. Any student can navigate through these practices, provided the science concepts at hand are grade-level appropriate. Introducing these practices from the young age would ensure that the learning progression is continuous for students.

Third, all discipline units covered the science practices in the similar manner, but varied in the coverage of engineering practices. A salient observation was that all engineering practices were covered in physical science units to varying degrees; in life science, nearly all were not covered; and in earth/space science majority had low to no coverage. Another notable observation was that most of the K-12 engineering materials analyzed have a physical science orientation—a situation that would erroneously sway students to believe that engineering is only relatable to physical science concepts, and not other science disciplines. As such, this may limit the young learners' career pathways; let alone developing wider perspectives on how to solve societal problems that are rooted in knowledge from other science disciplines.

5. Implications for curriculum design and instruction approaches

Our study revealed disparities in the coverage of science and engineering practices, which raise concerns about the design of STEM curriculum materials and instruction approaches. We argue that scientific and engineering problems in society are multidisciplinary and multifaceted in nature. As such, K-12 science education should aim at nurturing young and adult problem-solvers who can conceptualize problems and solutions in various contexts. Additionally, K-12 science or STEM curriculum materials should be designed in such a way that science and engineering practices are integrated and represented in all STEM disciplines for students to have a wider sense-making context. Other researchers have also stated that learning experiences should be designed to enhance coherency among the science and engineering practices [20]. In light of this, one of our proposed instruction and curriculum design model would be an integrated science and engineering design (iSED) approach, which would ensure that there is both content and context integration of science and engineering practices. Our rationales for this proposal is backed by recent studies which showed that (a) many teachers may find it difficult for to recognize the potential connections between science and engineering due to little or no explicit exposure to engineering design [4, 21–23], and (b) many existing K-12 engineering curriculum materials do not specifically address the science standards so that students are also prepared for standardized assessment tests as they engage in engineering design [24].

Our proposed iSED approach would provide teachers with explicit ways in which to integrate science and engineering practices within STEM *content* areas, and students with an integrated sense-making *context* and continuous learning progression. Moore et al [25] defines *context* integration as the integration of engineering design as a pedagogy and motivator to teach disciplinary content such as science and/or math, and help students learn the content; and *content* integration as the integration of engineering thinking and disciplinary content, in which engineering design content is part of the learning objectives for the activity/unit. Why is our proposed model appropriate and significant at this time when the new K-12 science education framework is just starting to be implemented in schools? If the integration of engineering practices in science curriculum is to be receptive to teachers, students and school systems, there should be *explicit alignments* with science concepts and inquiry skills outlined in state standards, and engineering design practices. Whereas scientists seek to understand why something is happening via questions, investigations, analyzing, interpreting and constructing explanations from data; engineers define societal problems and develop engineering solutions. Given these different perspectives of science and engineering, it is crucial that science instructional approaches engage students *explicitly* in grappling with the underlying scientific concepts and puzzling over why something is happening, and then apply the knowledge to their engineering design tasks. Every engineering design task in the science curriculum must predictably and explicitly lead students to a deeper understanding of specific scientific concept(s) outlined in the State and National Science Standards. The emphasis in the learning sequence must also aim at ensuring that students construct proper scientific explanations that demonstrate that they have mastered the underlying science concepts, rather than simply designing a successful engineering solution. Therefore, a conceptual view of iSED learning experiences should include relevant sense-making contexts for the engineering design tasks, which students can personally relate, and make use of appropriate science content [26, 27]. This need for relevancy implies that an iSED instructional approach should be holistic and explicitly link the concepts, inquiry skills, and engineering design experiences so that they are connected, focused, meaningful, and relevant to students. The relevancy aspect of engineering design experiences was reinforced by some authors who stated that one of the less discussed dimensions in engineering education literature is diversity in and how to connect with students' cultural and linguistic resources [28]. In our study, the immediate diversities included variations in the coverage of science and engineering practices across grade levels (elementary, middle and high school), and science discipline units (life, physical and earth/space sciences). Although reform documents stress that science and engineering practices should begin in the very earliest grades and then progress through middle to high school, engaging students in more complex sophisticated levels of performances [7], our results revealed that this is not the case in existing curriculum materials. Therefore, we argue that at all grade levels and science discipline units, there is need to introduce science and engineering practices, with sense-making contexts and scaffolds that explicitly integrate both science and engineering practices. For lower grades and unfamiliar disciplines, the learning contexts can be teacher-driven; whereas for higher grades and familiar disciplines, learning structure can emerge from students' own questions or from authentic investigations of agreed upon questions and engineering problems. Engaging students in sense-making contexts can help students engage with conceptual knowledge, procedural knowledge, and epistemic knowledge that can help develop explicit understandings of how science and engineering concepts are dependent on each other.

6. Conclusions

For the integration of engineering practices to serve as an anchoring context for science learning, curriculum materials should address both science and engineering practices. Simply addressing the practices is not enough if there is no explicit integration between the two sets of practices. For example, in order for students to conduct investigations, analyze and interpret data or construct scientific explanations and design engineering solutions, there must be good science questions asked, and well defined engineering problems. However, the low coverage of the practice, *asking questions and defining problems,* would pose a drawback to the effective integration of engineering design skills and practices in science classrooms. Therefore, these findings should communicate to science teachers about the importance of involving students in both science and engineering practices if meaningful and relevant learning is to occur, and consequently help learners with the transfer of knowledge. If students are not very clear about the science questions and an articulate engineering problem from the onset, they may not learn as intended by the new K-12 science education framework. Despite the limited number of K-12 engineering programs analyzed in our study, the results have provided a basic overview of the coverage status of science and engineering practices, which could serve as a guide for science and engineering education researchers, educators, teachers and curriculum designers as they continue to develop curriculum materials that meaningfully integrate these practices. Particular considerations for these stakeholders would be to develop curricula and learning experiences that address both science and engineering practices, and highlight how both practices inform and are dependent on each other.

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