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Keywords

P-12 engineering education, content taxonomy, engineering literacy

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Establishing a Content Taxonomy for the Coherent Study of Engineering in P-12 Schools

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Abstract

Engineering education has increasingly become an area of interest at the P-12 level, yet attempts to align engineering knowledge, skills, and habits to existing elementary and secondary educational programming have been parochial in nature (e.g., for a specific context, grade, or initiative). Consequently, a need exists to establish a coherent P-12 content framework for engineering teaching and learning, which would serve as both an epistemological foundation for the subject and a guide for the design of developmentally appropriate educational standards, performance expectations, learning progressions, and assessments. A comprehensive framework for P-12 engineering education would include a compelling rationale and vision for the inclusion of engineering as a compulsory subject, content organization for the dimensions of engineering literacy, and a plan for the realization of this vision. The absence of such a framework could yield inconsistency in authentically educating students in engineering. In response, this study was conducted to establish a taxonomy of concepts related to both engineering knowledge and practices to support the development of a P-12 curricular framework. A modified Delphi method and a series of focus groups—which included teachers, professors, industry professionals, and other relevant stakeholders—were used to reach a consensus on engineering concepts deemed appropriate for secondary study. As a result, a content taxonomy for knowledge and practices appropriate for P-12 engineering emerged through multiple rounds of refinement. This article details the efforts to develop this taxonomy, and discusses how it can be used for standards creation, curriculum development, assessment of learning, and teacher preparation.

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Introduction

Current initiatives in P-12 engineering education are encouraging: progress has been made to incorporate engineering into the Next Generation Science Standards (NGSS Lead States, 2013), programs such as Engineering is Elementary continue to expand, and the inclusion of engineering design has permeated all subject areas through integrated science, technology, engineering, and mathematics (STEM) education practices. Relatedly, calls have even been made for the creation of P-12 engineering educational standards (Carr, Bennett, & Strobel, 2012; Grubbs, Strimel, & Huffman, 2018). However, preceding such standards, and the corresponding development of curricula and formative or summative assessments of learning, is a coherent curricular framework that is developmentally sequenced for P-12 students. Supporting this claim, a National Academy of Engineering (2017) report states that "one need is for a better understanding of what engineering content knowledge teachers need for different grade bands" (p. 15). In addition, the *Building Capacity for Teaching Engineering in K-12 Education* report (National Academies of Sciences, Engineering, & Medicine [NASEM], 2020) recommends research efforts to (1) describe the subject-matter and pedagogical content knowledge required for the high-quality teaching of engineering across grades and (2) document age-appropriate expectations and progressions of learning for K-12 engineering education. Without such a framework and clear vision, teachers may find the implementation of P-12 engineering education challenging and face difficulty in teaching in-depth and authentic practices of engineering.

To address this concern, the National Academy of Engineering (2017) recommends that content experts work with grade-level experts to develop a content *taxonomy* for P-12 engineering education. In response, the authors of this study initiated a collaborative community of experts to establish a content taxonomy capable of supporting a coherent framework for P-12 engineering teaching and learning. More specifically, the authors sought to provide an epistemological foundation for the study of engineering at the P-12 level by establishing a taxonomy of (1) concepts and (2) sub-concepts. This taxonomy would inform the development of age-appropriate *progressions of learning* to be implemented and tested in schools. This effort, and the focus of this article, involved research and developmental work to form the taxonomic structure and identify the appropriate concepts of engineering knowledge and practice. To do so, the authors followed the recommendations of the National Academy of Engineering (2010) and employed a modified Delphi method, as well as a series of focus groups involving teachers, professors, industry professionals, and other relevant stakeholders, to reach a consensus on the engineering concepts deemed appropriate for the secondary study of engineering. Through these efforts, the authors expected to provide information to answer the broader question of "If engineering becomes a compulsory subject in school to achieve engineering literacy for all students, what should teachers teach?" The lack of such information can continue to contribute to the unevenness, inconsistency, and inequity of engineering learning across the country (National Academy of Engineering & National Research Council, 2009). Therefore, the ultimate goal of this work is to ensure that *every* child is given the opportunity to think, learn, and act like an engineer.

Engineering in P-12 Education

The educational benefits of engaging P-12 students in engineering experiences continue to be promoted (Strimel, Bartholomew, Kim, & Cantu, 2018; Strimel, Bartholomew, Kim, & Zhang, 2018; Strimel, Grubbs, & Wells, 2016). However, minimal attempts in the United States have been made by the educational community to establish a deliberate and coherent study of engineering on a national level. Specifically, few efforts have been undertaken to identify developmentally appropriate content and practices for scaffolding the teaching of engineering at the P-12 level (National Academy of Engineering, 2017). As Reed (2018) stated, "engineering is well-defined at the postsecondary level but still evolving in P-12 education" (p. 19). While related educational standards in science education (Next Generations Science Standards) and technology education (Standards for Technological Literacy) have included engineering practices and content to facilitate learning experiences, there is still vast uncertainty as to how engineering should be intentionally taught in elementary and secondary schools. In addition, the science and technology education standards may provide a limited view of authentic engineering, specifically with concern to engineering content and competencies beyond design. This potential lack of authenticity may lead to a misrepresentation of what engineering is and is not. As discussed by the Executive Director of the American Society for Engineering Education, Norman Fortenberry (2018), knowledge of how to authentically teach engineering is intimately tied to the understanding of engineering as a discipline. However, there are currently no national content frameworks or learning progressions that aim to wholly define P-12 engineering as a stand-alone school subject and to explicitly guide the development of elementary, middle, and high school engineering education programs.

In 2009, Rodger Bybee, a renowned educator, researcher, and leader in science education, argued that the timing is right for the emergence of P-12 engineering education and the potential creation of engineering educational standards. However, the 2010 National Academy of Engineering's *Committee on Standards for K-12 Engineering Education* decided to oppose the development of stand-alone standards at the time. The committee's report highlighted multiple reasons, including schools' relatively limited experience with K-12 engineering education, a lack of teachers qualified to deliver engineering instruction, and uncertainty over the impact of standards-based educational reforms on student learning. Instead, the committee recommended the integration of engineering content into current school curriculum as they believed it to be the quickest and least difficult way to begin exposing more K-12 students to engineering. However, following that report, many have supported the development of a true engineering content structure as P-12 engineering programs have become more widespread. For example, Pinelli and Haynie (2010) stated "it is imperative that engineering should be included in the K-12 school curriculum, both as a discipline and as a source of enrichment and context for teaching other subjects." Subsequently, after their study of state standards in engineering across the United States, Carr et al. (2012) concluded that "now is the time to move forward in the formation of national standards based on the state standards identified in this study" (p. 539). Samuels and Seymour (2015) emphasized the need for engineering coursework and called on the country's engineering and educational communities to create a set of foundational concepts establishing engineering as a stand-alone topic in the nation's schools. Strimel and Grubbs (2016) recommended a true focus on engineering as a core disciplinary subject. Then, in 2017, the National Academy of Engineering explicitly called for a better understanding of what engineering content knowledge teachers need for different grades. Lastly, the NASEM (2020) stressed the need to better support teachers preparing to teach engineering, as well as the importance of more formal accreditation guidelines to build the capacity to guide all students toward engineering literacy. It is evident that, over the last decade, support and efforts have increased to purposefully include engineering at the P-12 level.

In response to these various "calls to action," there have been a few studies published that aimed toward identifying concepts, skills, and dispositions appropriate to P-12 engineering education. While some studies have focused on analyzing existing literature, others employed Delphi study approaches to help collect and build a consensus on experts' opinions (National Academy of Engineering, 2010). For example, the National Academy of Engineering (2010) examined eight such studies and identified a total of 33 concepts, skills, and dispositions. These included design, engineering and society, constraints, communication, modeling, optimization, and analysis as big ideas in engineering at the P-12 level. While several of these studies involved the participation of both engineering educators and engineers, some lacked the contribution from a wider range of stakeholders, including K-12 teachers, policymakers, and school administrators. Further deficiencies included discussions on how to communicate the findings with key audiences and develop or implement learning materials—which is recommended by the National Academy of Engineering in their 2017 report titled *Increasing the roles and significance of teachers in policymaking for K-12 engineering education*. However, in 2014 Moore and colleagues did investigate how teachers and schools implement engineering and engineering design in their classrooms to create the first framework aimed toward providing a clear definition of what constitutes quality K-12 engineering education (Moore et al., 2014). The resulting framework presented key indicators for engineering education that have been demonstrated as useful to educators, predominately for evaluation purposes. While these findings have established a strong foundation for defining quality engineering education at the P-12 level, the key indicators can be improved by adding specificity of concepts. This could help to guide the organization of teachable and learnable engineering content over multiple grades at increasing levels of depth and sophistication (similar to Core Ideas for Science Education, A Framework for K-12 Science Education, 2012, p. 31). Accordingly, Moore and colleagues (2014) highlighted the need for continued research into how engineering is implemented at the P-12 level in order to further operationalize conceptions of engineering through the systematic definitions of each of their key indicators. Therefore, the authors posit that the development of a content taxonomy and progressions of learning for both engineering knowledge and practices, at a level of specificity which would allow schools and teachers to establish engineering learning pathways, is needed (National Academy of Engineering, 2017; NASEM, 2020). These efforts could help to extend the framework developed by Moore and colleagues (2014) and further define engineering literacy for *all* P-12 learners.

Engineering Literacy for All P-12 Learners

As the demand for high-quality engineers and related STEM professionals continues to increase (Change the Equation, 2016; Manpowergroup, 2015), achieving engineering literacy for *all* students should be at the forefront of any engineering education effort. The Bureau of Labor Statistics presented a projection in 2014 that the overall STEM employment would grow by 13% from 2012 to 2022—with occupations related to engineering and technology growing the fastest (Noonan, 2017). However, only a small portion of the nation's youth are intentionally taught the concepts necessary to become engineering literate throughout their educational experiences. This is evidenced by the results of the first National Assessment of Educational Progress in Technology and Engineering Literacy (2016), which revealed that less than half of the nation's eighth graders were on track to become engineering literate. Moreover, the results of this national assessment revealed that low-income and underserved minority students lagged the furthest behind in regard to engineering literacy, as they typically have the least exposure to core engineering fundamentals during school. Unfortunately, a student's exposure to engineering seems to be completely left to chance based on their zip code, family's income, and ethnicity, as only schools with abundant resources implement engineering programs as a superfluity rather than an obligation for all students (Change the Equation, 2016). This great disservice to the nation's youth can be attributed to the lack of a defined sequence of learning progressions across and within each grade level, which would provide a roadmap toward achieving engineering literacy (Samuels & Seymour, 2015).

Engineering literacy can be viewed as closely related to technological literacy. However, the term "technological literacy" is often confused or misrepresented as "technology literacy" or even "computer literacy" by policymakers (Ollis & Pearson, 2006) and in school systems (Wicklein, 2006). With the rise of computer science education in P-12 schools, this distortion will likely continue to grow. Whereas technological literacy represents an understanding of the destination of human ingenuity (e.g., construction, manufacturing, medical, and transportation) and the human interactions with those technologies (National Academy of Engineering & National Research Council, 2002), engineering literacy is concerned with the participation of inventors, innovators, makers, designers, and literate citizens in improving and interacting with the world's systems, products, and services. These interactions require that an engineering-literate person become familiar with associated scientific, mathematical, and technical knowledge. As such, engineering literacy can be described as the confluence of content knowledge, habits, and practices merged with the ability to read, write, listen, speak, think critically, and perform in a way that is meaningful within the context of engineering (Lent, 2015; Wisconsin Department of Public Instruction, 2011). Equivalent to the idea of three-dimensional learning presented in the Next Generation Science Standards (NGSS Lead States, 2013), engineering literacy (see Figure 1) can be described as: (Dimension 1) engineering habits of mind, (Dimension 2) engineering practices, and (Dimension 3) engineering knowledge (National Academy of Engineering & National Research Council, 2006; Sneider & Rosen, 2009).

The three dimensions of engineering literacy include: (1) habits students should develop over time through repetition and conditioning; (2) practices in which students should become competent; and (3) knowledge that students should be able to recognize and potentially access, when appropriate, to inform their practices. These three dimensions help to determine how a pupil's educational progress may be measured (see Figure 2). The habits of mind can be described as the traits or ways of thinking that influence how a person looks at the world or reacts to a challenge. These habits should become part of a student's everyday thinking and allow them to routinely devise solutions to problems or improvements to current technologies or processes. Engineering knowledge can consist of the concepts that situate habits and practices in a conceptual domain, as well as enable sophistication in engineering practice. Engineering practices can be described as the skills and knowledge that enable a student to authentically act or behave like an engineer. While several efforts have been made to identify the big ideas of each engineering-literacy dimension, there is still a need to specify and reach a consensus on the concepts and corresponding age-appropriate learning progressions (National Academy of Engineering, 2010, 2017). Table 1 provides a summary of proposed "big ideas" for each engineering-literacy dimension founded on previous literature. However, based on the recommendations from the National Academy of Engineering (2017), the authors believe that it is necessary to extend these big ideas for engineering knowledge and practice to establish a taxonomy of engineering concepts and sub-concepts and to make appropriate connections with the engineering habits of mind.

Problem Statement

Our world is full of seemingly insurmountable challenges: poverty, food security, and climate change to name a few. Historically, engineering has provided solutions to the world's most daunting problems. Paramount among these challenges is the need to prepare the next generation of global citizens to solve issues of the ensuing century. While the demands of our world require creative, capable, and diverse problem solving, our children continue to have limited opportunities to engage in authentic engineering as part of a typical educational environment. This may not only be detrimental to our regional, national, and global economic and security success, but also for cultivating informed and participating citizens. Therefore, to solve the most difficult economic, environmental, and societal challenges of the future, one should be driven to advocate for *all* students to engage in engineering in order to meet these challenges. Such a formidable initiative results in political and economic trials of its own: budget constraints, space in the current school schedule, and teacher professional

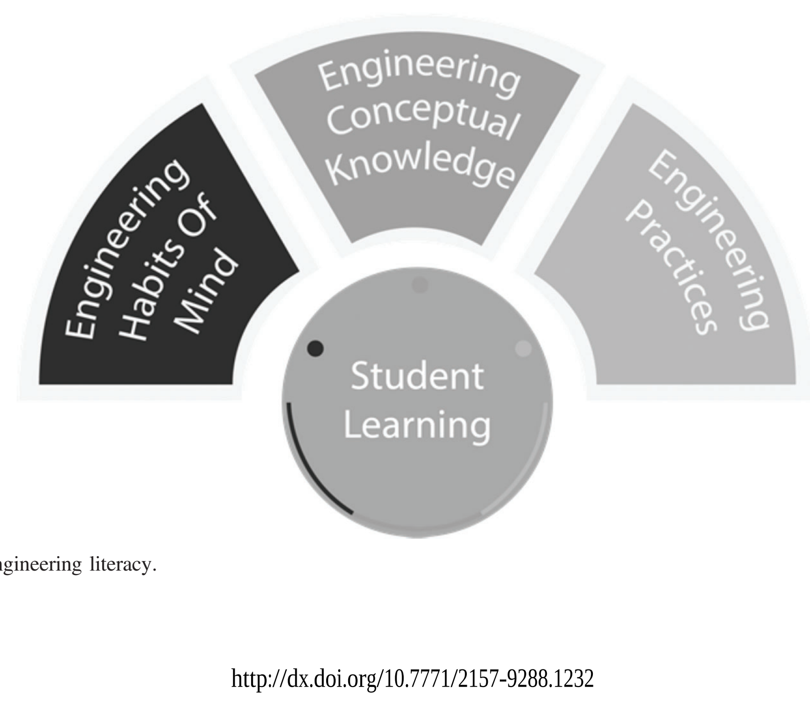

Figure 1. Dimensions of engineering literacy.

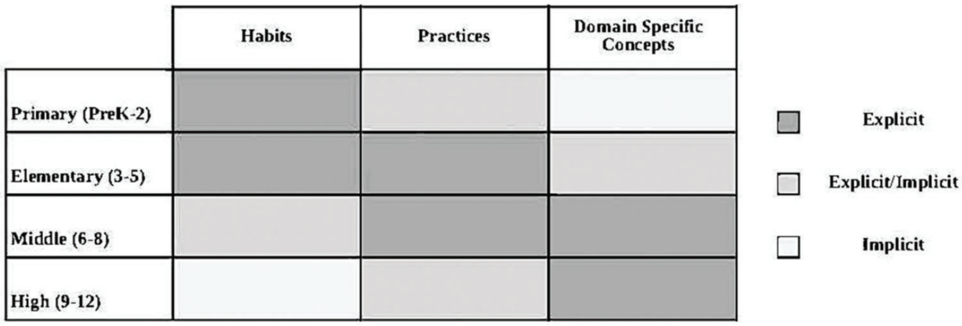

Figure 2. A proposed scaffolding of engineering dimensions of literacy across grade levels.

Table 1
Proposed draft of the dimensions of engineering literacy.

Dimension	**Big ideas**
Engineering knowledge	• Engineering design is an approach to solving problems or achieving goals • Technology is a fundamental attribute of human culture • Science and engineering differ in terms of goals, processes, and products
Engineering practices	• Designing under constraints • Using tools and materials • Engineering graphics • Developing physical models and/or prototypes • Research and investigation • Technical writing • Mathematical reasoning • Project management
Engineering habits of mind	• Systems thinking • Creativity • Optimism • Collaboration • Conscientiousness • Persistence

Note. The dimensions of literacy are based on the following works: International Technology Education Association (1996); National Academy of Engineering & National Research Council (2002, 2006). The big ideas are synthesized from the following works: Carr et al. (2012, p. 101); Merrill, Custer, Daugherty, Westrick, and Zeng (2009); National Academy of Engineering (2009, pp. 151–152; 2010, pp. 35–36); Sneider and Rosen (2009, p. 131). The engineering habits of mind definitions are provided by the National Academy of Engineering's (2019) LinkEngineering Educator's Exchange.

development that influence educational practice. Even with these obstacles, the last decade has seen the proliferation of engineering in U.S. elementary, middle, and high schools. However, while engineering education is an emerging trend in P-12 schools, there is a lack of a defined and cohesive educational sequence to potentially serve as the foundation for national P-12 engineering learning progressions and standards. This seems specifically true in regard to the depth of content related to engineering knowledge and practice dimensions of engineering literacy. Therefore, the authors set out to provide educators with the primary components of a viable engineering taxonomic structure for use in P-12 engineering programs to ensure that every child is given the opportunity to think, learn, and act like an engineer. Specifically, this investigation sought to establish agreed-upon concepts and sub-concepts for the development of progressions of learning to articulate and evaluate a sequence of knowledge and practices that students should learn as they progress toward engineering literacy. It is important to note that this study did not include an investigation on the engineering habits of mind, as significant work has already taken place to define and describe these habits.

Research Objective

This study sought to answer the question: "If engineering becomes a compulsory subject in school to achieve engineering literacy for all students, what do teachers teach?" In turn, the research was structured to establish a potential epistemological foundation for the study of engineering across P-12 schools, by determining the (1) content organizers, (2) concepts, and (3) sub-concepts for the development of an engineering content taxonomy. This taxonomy can be viewed as necessary for the creation of age-appropriate progressions of learning to be implemented and tested in P-12 classrooms.

Methods

This study employed a modified Delphi method which included a variety of stakeholders involved in the engineering, engineering education, technology and engineering education, and also teacher education communities. The modified Delphi is a semi-structured mixed methods approach involving one qualitative round of investigation followed by two or more quantitative rounds (Helmer & Rescher, 1959). The technique attempts to build a consensus of opinion by asking experts a round of questions, developing more refined questions that are returned to the respondents, and so on. The main reason for the selection of this research methodology was that it provides a feasible approach to develop a consensus among different experts. Hartman and Bell (2017) claim that the Delphi approach is particularly suitable for research projects aiming toward curriculum development for relatively new fields, such as P-12 engineering education, without the existence of prior frameworks. Another advantage considered in this study is that the modified Delphi can be conducted without a face-to-face group meeting through the use of surveys. This advantage allows researchers to involve more experts who would be unable to centrally convene (Delbecq, van de Ven, & Gustafson, 1975). For these advantages, the Delphi methodology has been used in multiple curriculum studies (Bolte, 2008; Hartman, 2016; Kloser, 2014; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003). However, to improve the utility of the Delphi results for the development of progressions of learning, the authors took a more unique approach that involved a series of focus groups as the final round, allowing the relevant stakeholders to debate and refine the results.

In this study, a total of 40 participants—with various professional experiences—were selected and invited across secondary education, post-secondary education, and engineering-related professions (based on the recommendations of national organizations). The participants included teachers and administrators for secondary education; faculty members or administrators in engineering or teacher-education programs; coordinators of P-12 engineering outreach; and technologists, engineers, scientists, or mathematicians working in engineering-related professions. Also, professionals in association administration or leadership, curriculum specialists, state education administrators, and graduate students majoring in engineering and technology education were invited to diversify the expertise for a content structure of P-12 engineering. The details of the selection criteria for each participant group are described in Table 2. Many participants crossed several of the areas of professional experiences. As the modified Delphi process includes multiple rounds usually involving approximately 30 participants (Paré, Cameron, Poba-Nzaou, & Templier, 2013), the authors initially invited 40 individuals who satisfied the selection criteria, anticipating the possibility that some participants may not complete all rounds.

Employing the modified Delphi, this study involved three rounds in survey format and one final Refinement and Development round in a face-to-face focus group setting. In the survey, both core concept and sub-concept were defined and described to the participants. A core concept is a primary idea the participant felt represented the content area. Sub-concepts are content subdivisions that each core concept could be broken into as the next level in structural hierarchy. Throughout the four rounds, the participants were asked to identify, rate, and then verify core concepts and corresponding sub-concepts for both the knowledge and practices dimensions of engineering literacy. The four rounds consisted of:

Round 1: Concept Discovery (identifying important concepts and sub-concepts).
Round 2: Concept Prioritization.
Round 3: Concept Rating.
Final Round: Concept Verifying and Refinement (involving focus groups).

Table 2
Selection criteria for participants.

Criteria	Secondary education	Post-secondary education	Professional experience
Education	• Bachelor's degree in science, engineering/technology, or mathematics education as well as professional development experiences in the teaching of engineering	• PhD in engineering, science, or mathematics • PhD in engineering/technology education or curriculum and instruction	• Bachelor's degree in science, mathematics, engineering, technology, or engineering technology
Professional background	• Teaching engineering or technology at secondary level • P-12 education administration related to coordination of STEM curriculum	• Teaching or research in engineering, at post-secondary level • Engineering administration • Teaching or research in teacher education • Teacher education administration • Engineering outreach coordination	• Working in engineering-related fields • Working in engineering technology or technology fields

Table 3
Participant backgrounds overall and for rounds 1, 2, 3, and 4.

Professional experience	Invited	Round 1	Round 2	Round 3	Final round
Secondary education	26	9	13	15	21
• Engineering/technology teacher					
• Science teacher					
• Mathematics teacher					
• K-12 administrator					
• Other					
Post-secondary education	23	18	14	12	17
• Engineering faculty					
• Teacher education faculty					
• Science faculty					
• Mathematics faculty					
• Engineering administrator					
• Teacher education administrator					
• Outreach coordinator					
• Other					
Professional	22	5	5	4	17
• Engineering technologist/technician					
• Civil engineer					
• Mechanical engineer					
• Electrical/computer engineer					
• Biomedical engineer					
• Industrial engineer					
• Scientist					
• Mathematician					
• Other					
Other	15	2	6	5	13
• Professional association administration/leadership					
• Outreach/curriculum specialist					
• Other (state education administrator, graduate student)					
Total participants	40	22	24	26	32

Note. Many participants crossed several of professional experience categories.

The survey questions for the initial three Delphi rounds were answered anonymously through an online survey tool. For these initial rounds, an average of 26 participants completed each questionnaire. For the final round, eight focus groups involving 32 participants were organized in consideration of their professional experiences. Table 3 presents the overall participant backgrounds for each round of the study.

For Round 1, the *concept discovery questionnaire* in Appendix A was sent to the participants, who were given one week to submit their responses. The questionnaire was developed based on the Delphi approach enacted by Wells (1992) to establish a taxonomy for the study of biotechnology in secondary school. The questionnaire provided a brief overview of the study as well as several links to open resources for review such as the National Academies Taxonomy of Fields and Sub-Fields, the Fundamentals of Engineering Exam Resources, and the National Academy of Engineering's Standards for K-12 Engineering Education Report. Also, the questionnaire presented a potential taxonomic structure for the knowledge and practice dimensions of engineering literacy which is provided in Figure 3. As seen in Figure 3, the knowledge dimension included the four content areas of mechanical, electrical, civil, and chemical, and the practice dimension included the four content areas of engineering design, material processing, quantitative analysis, and ethics and society (later renamed professional conventions). The structure was founded on the synthesis of relevant literature (Carr et al., 2012; Custer & Erekson, 2008; Merrill et al., 2009; National Academy of Engineering, 2009, 2010; Sneider & Rosen, 2009) as well as the National Academies' Taxonomy of Engineering (NASEM, 2006), the Fundamentals of Engineering Exams (National Council of Examiners for Engineering & Surveying, 2017), first-year engineering programs (Strimel, Krause, Hensel, Kim, & Grubbs, 2018) and the Accreditation Board for Engineering and Technology disciplines of engineering, engineering technology, and computing (Engineering Accreditation Commission, 2016). The Delphi participants reviewed the taxonomic structure and identified and prioritized the core concepts and sub-concepts for each content area to serve as a foundation for the knowledge and practice dimensions of engineering literacy.

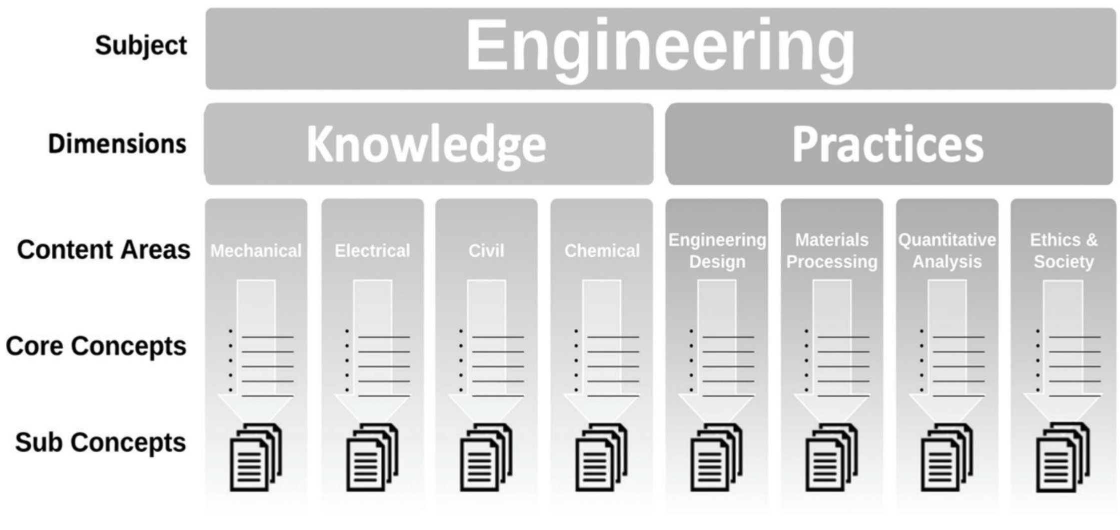

Figure 3. Potential taxonomic structure for the knowledge and practice dimensions of engineering literacy.

Accordingly, for Round 1, the participants were asked to identify core concepts and corresponding sub-concepts for each of the eight content areas through the following questions:

- What are the main core concepts you feel represent the conceptual knowledge of each content area appropriate for the secondary study of engineering?
- Under each of the designated concepts for each content area, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy?

Also, the participants could provide feedback on, or suggest modifications for, the content areas that were identified for the potential taxonomic structure. A total of 22 participants responded to the Round 1 survey. The authors combined the participants' qualitative answers to create the list of concepts and corresponding sub-concepts for each content area for Round 2.

For Round 2, the *concept prioritization questionnaire* was sent to the participants and they were given one week to submit their responses. Based on the Round 1 results, the Round 2 *concept prioritization questionnaire* asked the participants to review and then rate each of the concepts and sub-concepts for every content area on a six-point Likert scale (1 = not important to 6 = critical). Also, the participants could add a justification or clarification for any item, as needed, in the comment sections. A total of 24 participants completed the Round 2 questionnaire. The authors calculated the mean and standard deviation of each concept/sub-concept and collected the qualitative responses for the next round. The items rated below 3.00 were to be eliminated for Round 3.

For Round 3, the *concept-rating questionnaire* was sent to the participants and they were, again, given one week to provide their response. The Round 3 *concept-rating questionnaire* was developed based on the participants' quantitative and qualitative responses to Round 2. Thus, the questionnaire included revised lists of concepts and sub-concepts for each content area and the mean and standard deviation of each concept. Then, the participants were asked to rate each concept again for its importance and to add comments, if needed, in the same way as Round 2. A total of 26 participants responded to the Round 3 questionnaire. The mean and standard deviation were calculated for each concept and collected qualitative responses for the final round. The items rated below 3.00 were to be eliminated for the final round.

Lastly, the final round involved eight focus groups. These focus groups were essential to this project and differentiate this study from others conducted previously. Oftentimes, Delphi studies are done within a vacuum without direct debate between both content experts and practicing educators. This may be one reason why previous efforts have not been widely employed in the classroom. Additionally, the focus groups enabled the research team to solicit participation of much needed broader expertise in areas of elementary education and curriculum development. The focus groups brought together 32 experts from the education, engineering education, technology education, and engineering communities. Experts were invited based on participation from the preceding Delphi study (20) and recommendations from various stakeholders (e.g., ITEEA, ASEE, and National Academy of Engineering) with an interest in the research (12). The participants were regionally diverse with representation from Connecticut, Delaware, Indiana, Iowa, Maryland, New Jersey, North Carolina, Pennsylvania, Utah, Virginia, West Virginia, and the District of Columbia. Participant selection ensured demographic variety in two primary ways. First was diversity of gender. Of the 32 participants, 18 were female and 14 were male. The second primary demographic was career experience (e.g., teacher, engineer, post-secondary educator, curriculum developer). A majority of the participants were active secondary (4) or elementary (2) teachers or had previous experience as a secondary (11) or elementary (4) classroom teacher. Nineteen participants had an engineering undergraduate degree, with 11 having industry experience. Fifteen participants currently held positions at post-secondary institutions, including colleges/schools of engineering, technology, and education. Eight participants were actively engaged in curriculum development. Many participants crossed several of these demographics. Therefore, this study organized focus groups, based on the participants' backgrounds, that comprised at least one of the following: secondary teacher, curriculum developer, and engineer or engineering educator. Each group was provided with the results of the Delphi study and worked on one of the four knowledge areas and one of the four practice areas to refine the content taxonomy. Each group spent two-and-a-half hours for each content area. With the Delphi results, the focus groups were asked to review and revise the concepts and sub-concepts for each content area based on the following guiding questions:

- Is this a fundamental core concept or sub-concept of engineering? Justify through narrative.
- Is this core concept or sub-concept appropriate for secondary learners? Justify through narrative.
- How is this core concept or sub-concept connected to one or more engineering habits of mind?

Lastly, it is important to note that this modified-Delphi study followed a unique approach wherein 40 panelists were invited and agreed to participate across the four rounds, the final round consisting of a series of focus groups in which the panelists agreed to attend. The 40 panelists were invited based on their expertise and involvement with engineering education as well as their diversity in terms of their occupations and demographics. Throughout these four rounds, the response rate varied: Round 1 had a 55% response rate, Round 2 had a 60% response rate, Round 3 had a 65% response rate, and the final round had an 82% response rate. As it was always the intention to bring the panelists together in a development workshop setting to deliberate on the identified concepts and sub-concepts, the entire group of panelists were retained throughout the study, regardless of their participation in Round 1. Therefore, the panelist participation did increase across each round. However, the majority of panelists from Round 1 were consistent throughout the subsequent rounds. To account for this potential limitation, the concept-rating value for retaining the identified concepts between rounds was set to a mean of three, meaning that all concepts considered "neutral to critical" were retained to ensure maximum exposure of the identified concepts to the panelists across all four rounds. Then, the rating values were used by the panelists to inform the revision of the taxonomy of concepts during the final round wherein the highest participation rate was planned and achieved. However, to retain the anonymity of the panelists through the final round deliberations, only minimal descriptions of the participants by round could be provided.

Findings

Findings from Round 1 included potential core concepts and sub-concepts for the eight identified content areas of engineering knowledge and practice. In Round 1, participants were asked to list concepts and sub-concepts which they felt represent the fundamental content of each area. On average, participants identified 7.75 concepts and 45.75 sub-concepts across the content areas. The items that all the participants had identified were integrated and, in the process, minor wording changes were made. Then, following identification in Round 1, all items were rated by participants in the second round. The items rated below 3.00 were to be eliminated for the third round. However, all identified items received a rating of 3.00 or higher, although some of the items listed in Round 2 had been duplicated across different content areas. Based on the results of Round 2, duplicated items that had the highest rating were retained while the others were eliminated. Also, considering participants' qualitative comments, four additional sub-concepts were added into the list for the third round. Then, the finalized items were shared in Round 3 and rated by participants. The results of the three rounds are summarized in Table 4, and the details of the items and ratings for each round can be found in Appendix B. Lastly, the emerging content taxonomy resulting from Rounds 1 through 3 is presented in Tables 5 and 6.

After the three Delphi rounds were completed and an initial taxonomy emerged, eight focus groups were organized to deliberate the results in the final round. While reviewing and answering the provided guiding questions, the participants recommended the following overarching revisions to improve the utility of the taxonomy: (a) general improvements in regards to the wording or structures of concepts, (b) removing the "career-focused" content areas within the *Engineering Knowledge* dimension (mechanical, electrical, civil, and chemical), and (c) integrating the duplicated/overlapping concepts across the content areas to form crosscutting concepts. These revisions were recommended to (a) improve the taxonomy terminology, (b) avoid the potential confusion and concerns related to these content areas being

Table 4
Summary of Delphi study results.

Content area			Round 1	Round 2		Round 3
			Number of concepts	Number of concepts	Average of ratings	Average of ratings
Engineering knowledge dimension	Mechanical	Core concepts	7	67	4.61	4.48
		Sub-concepts	43	43	4.14	4.07
	Electrical	Core concepts	8	8	4.64	4.72
		Sub-concepts	63	63	4.22	4.18
	Civil	Core concepts	8	8	4.37	4.28
		Sub-concepts	50	51	4.05	4.11
	Chemical	Core concepts	10	10	4.32	4.22
		Sub-concepts	53	53	3.98	3.87
Engineering practice dimension	Engineering design	Core concepts	9	9	5.47	5.55
		Sub-concepts	51	52	5.10	5.20
	Material processing	Core concepts	8	8	4.49	4.54
		Sub-concepts	34	35	4.16	4.22
	Quantitative analysis	Core concepts	6	6	5.29	5.25
		Sub-concepts	34	34	4.77	4.71
	Professional conventions	Core concepts	6	6	4.81	4.68
		Sub-concepts	38	39	4.46	4.33

Note. The rating scale: 1–6 (1 = not important; 6 = critical).

viewed as specific engineering careers rather than just a means to organize content, and (c) reduce the overwhelming number of concepts and sub-concepts. Accordingly, the biggest recommended change involved the removal of the content areas for the *Engineering Knowledge* dimension. However, it is important to note that these content area labels were viewed as a necessary structure to initially determine what concepts were important across each area. However, once the concepts important to each content area were determined through the initial rounds, the content area titles could be removed and the crosscutting concepts could be identified—allowing the removal of duplicated concepts. Figure 4 illustrates an example of how the emerging taxonomy was revised, wherein the crosscutting concepts relating to the field of statics (i.e., force systems, equilibrium, inertia) were converged from the mechanical and civil content areas to form a single core concept. Removing the content area classifications and creating a combined core concept, in this case the field of statics, can allow for more flexibility in development of progressions of learning. The complete revised taxonomy is provided in Tables 7 and 8.

Discussions

Utility of the Taxonomy

While millions of students participate in formal P-12 engineering coursework (Marshall & Berland, 2012), a major problem has been the lack of broadly accepted P-12 engineering standards and a shared understanding of the role of engineering within primary and secondary schools (Chandler, Fontenot, & Tate, 2011). As an operationalized and sequenced progression of engineering learning continues to be lacking at the P-12 level, the authors hope that the taxonomy resulting from this study can serve as the kernel for expanding the definition of engineering literacy. Moreover, such consistency is expected to ensure a more equitable approach to the delivery of engineering at the P-12 level, as teacher preparation programs, professional development opportunities, and alternative licensures programs can be built around this framework for the most comprehensive support model possible. As such, this work can ultimately help set the foundation for the development of learning progressions and standards to establish coherent educational pathways in engineering. However, one may question how this work differs from some previous studies. Therefore, it is important to further discuss the context of this study, which provides several reasons why this work can be considered unique and why the results can have utility value for P-12 classrooms.

First, the methods were established to specifically address the recommendations set forth by the National Academy of Engineering (2010), which included bringing content experts and grade-level experts together. To do so, this work enacted a strategy that enabled participants to identify engineering concepts individually while also affording an opportunity to refine the concepts through debate and deliberation in focus group settings. As stated by the National Academy of Engineering (2017), "the historical lack of involvement by K-12 teachers in education policy and decision making is particularly

Table 5
Emerging content taxonomy for engineering knowledge.

Mechanical	Electrical	Civil	Chemical
Engineering Sciences for Mechanical Engineering	Engineering Sciences for Electrical Engineering	Engineering Sciences for Civil Engineering	Engineering Sciences for Chemical Engineering
Force Systems	Properties of Materials (chemical, electrical, mechanical and thermal)	Force	Applications of Inorganic Chemistry
Equilibrium	Current, Voltage, Charge, Energy, and Power	Equilibrium	Applications of Organic Chemistry (e.g., biofuels)
Inertia	Forces (e.g., charges, conductors)	Inertia	Chemical, Electrical, Mechanical and Physical Properties (including potential hazards)
Friction	Voltage and Work	Friction	Material Types and Compatibilities
Centroids and Moments	Electrical Power	Centroids and Moments	Corrosion
Particles	Force	Rigid Bodies	Membrane Science
Rigid bodies	Motors and Generators	Resultant Calculations	Chemical Reaction and Catalysis
Newton's Second Law	Electrical Materials	Shear and Moment Diagrams	Reaction rate, Rate Constant, and Order
Work and Energy	Electro-magnetics	Hydrologic Systems	Conversion, Yield, and Selectivity
Impulse-Momentum	Voltage Regulation	Hydrology and Hydraulics	Chemical Equilibrium
Mechanics of Materials	Transmission and Distribution	Water Distribution and Collection Systems	Fluid Mechanics and Dynamics
Stress Types (axial, bending, torsion, shear) and Transformations	Circuit Analysis	Watershed Analysis	Bernoulli's Principle
Material Characteristics, Properties, and Composition	Series and Parallel Equivalent Circuits	Open Channel	Flow
Stress-Strain Analysis	Ohm's Laws and Kirchhoff's Laws	Closed Conduits (pressurized)	Pumps, Turbines, and Compressors
Static Equilibrium	Power and Energy	Pumping Stations	Fluid Properties
Material Deformations	Resistance, Capacitance, and Inductance	Laboratory and Field Tests	Heat Transfer
Material Equations	Wave Forms	Structural Analysis	Conductive, Convective, and Radiative Heat
Phase Diagrams	Analog vs. Digital Signals	Physical Properties of Building Materials	Heat Transfer Coefficients
Heat Treating	Electronics	Deflection	Energy
Dynamics and Vibrations	Instrumentation and Components (physical components and measurement devices)	Deformations	Work, Energy, and Power
Scalars	Semiconductor	Column and Beam Analysis	Energy Balance
Vectors	Amplifiers	Mohr's Circle (2D graphical representation of the transformation law for the Cauchy stress tensor)	Fuels
Resistance	Control Systems	Implementation of Design Codes	Energy Transfer
Gears	Sensors	Infrastructure	Thermodynamics
Mechanical Design	Closed and Open Loop and Feedback (systems, system response)	Street, Highway, and Intersection Design	Thermodynamic Properties, Laws, and Processes
Manufacturing Processes	Block Diagramming	Transportation Planning and Control (safety, capacity, flow)	Equilibrium
Machine Elements (springs, pressure vessels, beams, piping, cams and gears, threads and fasteners, power transmission, electromechanical components)	Digital Systems	Traffic Design	Gas Properties
Machine Control	Programmable Logic Devices	Pavement Design	Power Cycles and Efficiency
Electro-mechanical Systems	Logic Simplification (Boolean logic, K-mapping)	Surveying	Mass Transfer and Separation
Basic Electricity	Number Systems	Topographical Surveys	Molecular Diffusions
Circuits	Logic State and Gate Arrays	Route Survey	Separation Systems
Motors and Generators	State Machine Design (microcontrollers/programming)	Leveling	Equilibrium State Methods
Electric Charge	Communication Technology	Coordinate System	Humidification and Drying
Magnetism	Digital Communications	Project Management in Civil Engineering	Continuous Contact Methods
Fluid Mechanics	Telecommunications	Project Planning and Management	Convective Mass Transfer
Fluid Properties	Fiber Optics (photonics)	Economics	Process Design
Lift, Drag, and Fluid Resistance	Computer Systems	Safety	Process Controls and Systems
Fluid Statics and Motion (Bernoulli's equation)	Computer Hardware	Project Delivery	Process Flow, Piping, and Instrumentation Diagrams
Hydraulics	Computer Software	Human Resource Management	Recycle and Bypass Processes
Pneumatics	Integrated Circuits	Verifying Local Codes	Industrial Chemical Operations
Thermodynamics	Processors and Microprocessors	Geotechnical Engineering	Biological/Chemical Applications
Thermodynamic Properties, Laws, and Processes	Interfacing	Laboratory and Field Tests	Bio-molecular Engineering
Energy Transfer	Algorithms	Erosion Control	Biotechnology
Thermal Equilibrium	Networks	Geological Properties and Classifications	Biochemical Engineering
Thermal Resistance	Memory	Soil Characteristics	Pharmaceuticals
Gas Properties	Programming Languages	Bearing Capacity	
Power Cycles and Efficiency	Emerging Fields in Electrical Engineering	Drainage Systems	
Heat Exchangers	Biomedical Engineering Applications (instrumentation, imaging, biometrics)	Foundations and Retaining Walls	
HVAC Processes	Virtual System	Slope Stability	
Psychometrics	Artificial Intelligence	Environmental Engineering	
Emerging Mechanical Engineering	Cybersecurity	Ground and Surface Water Quality	
Mechatronics and Robotics		Wastewater Management (disposal)	
Bio-mechanics		Environmental Impact Regulations and Tests	
Nanotechnology		Natural Systems	
Ocean Engineering			

Table 6
Emerging content taxonomy for engineering practice.

Engineering design	Material processing	Quantitative analysis	Professional Conventions
Problem Scoping	Measurement and Precision	Computational Thinking	Professional Ethics
Identifying design parameters	Measurement instrumentations	Programming and algorithms (including flowcharting)	Morals, values, and ethics continuum
Problem statement development	Accurate layout and precise measurement	Programming (script programming languages)	Code of ethics
Research	Units and significant figures	Software design, implementation, and testing	Legal vs. ethical considerations
Information gathering	Manufacturing	Computational Tools	Professional Practice
Data collection and organization methods	Design for manufacture	Spreadsheet computations (e.g., MS Excel)	Public health, safety, and welfare
Information quality assessment	Additive manufacturing	Scripting languages (e.g., MATLAB, LabView)	Responsible conduct of research
Ideation	Subtractive manufacturing	Data visualization (e.g., charts, graphs, etc.)	Workplace culture
Spatial visualization (e.g., sketching)	Fabrication	Data Collection, Analysis and Communication	Ethical business operations
Divergent thinking (e.g., brainstorming)	Tool selection	Techniques of data collection (e.g., sampling methods)	Agreements and contracts
Convergent thinking (e.g., functional decomposition)	Product assembly	Data-driven decisions	Public policy and regulation
Prototyping	Hand tools	Creating graphs and documents	Professional liability
Testing and modification (virtual and physical)	Equipment and machines	Reporting data	Honoring Intellectual Property
Material selection	Quality and reliability	Systems Analysis	Patents, copyright, and licensure
Manufacturing processes	Material Classification	Inputs and outputs	Referencing sources
Computer-aided design and manufacturing	Metals and alloys	Feedback loops	Intellectual and physical property
Decision Making	Composites	Optimization	Impacts of Technology
Evidence/data/reason-driven decisions	Polymers	Product life cycle	Environmental impacts
Apply STEM principles	Ceramics	Modeling and Simulation	Global impacts
Balance trade-offs	Joining	Physical models	Social impacts
Use decision-making Tools	Fastening	Computational simulations	Culture impacts
Group decision making	Soldering	Mathematical models	Economic impacts
Design Communication	Adhesion	Failure analysis and destructive testing	Individual impacts
Technical writing	Welding	Design validation through calculations	Political impacts
Presentation tools	Brazing	Engineering Algebra	Role of Society in Technology Development
Information graphics	Forming	Recognizing, selecting, and applying appropriate algebraic concepts and practices	Addressing societal needs and desires
Visual design	Forging	Manipulation of algebraic equations	Design sustainability
Project Management	Extruding	Curve fitting	Technology design in cultures
Initiating and planning	Rolling	Linear algebra	Scaling of technology
Scope, time, and cost management	Machining	2D and 3D coordinate systems	Appropriate technology
Risk, quality, teams, and procurement	Drilling	Engineering Geometry	Inclusion and accessibility
Design Methodologies	Cutting	Recognizing, selecting, and applying appropriate geometric concepts and practices	Public participation in decision making
Iterative cycles	Milling	Manipulation of geometric equations	Careers in Engineering
User-centered design	Turning	Trigonometry	Professional licensing
Systems design	Grinding	Vector analysis	Recognition of engineering-related careers
Troubleshooting	Reaming	Engineering Statistics and Probability	Trade Organizations
Reverse engineering	Finishing	Recognizing, selecting, and applying appropriate probability and statistics concepts and practices	Entrepreneurship
Engineering Graphics	Adhesion	Basic statistics (normal distributions, percentiles)	
Engineering drawings	Grinding	Probability	
Dimensioning and tolerances	Polishing	Regression	
2D CADD	Burnishing	Inferential statistics and tests of significance (e.g., *t*-tests, statistical tolerance)	
3D parametric modeling	General Safety	Engineering Calculus	
	Laboratory guidelines	Differential and integral calculus	
	Machine-specific safety	Differential equations and multivariable calculus	
	Attire and equipment		

a problem for education in engineering" (p. vii). Second, the project was framed in a manner to move beyond identifying only "broad" engineering concepts (e.g., teamwork, problem-solving, design, creativity, and communication) to classifying and recognizing the in-depth fundamental engineering knowledge that informs engineering practice, as well as the technical concepts to perform such practices with increased sophistication (e.g., problem framing, decision-making techniques, fabrication processes, computational thinking and tools, mechanics of materials,

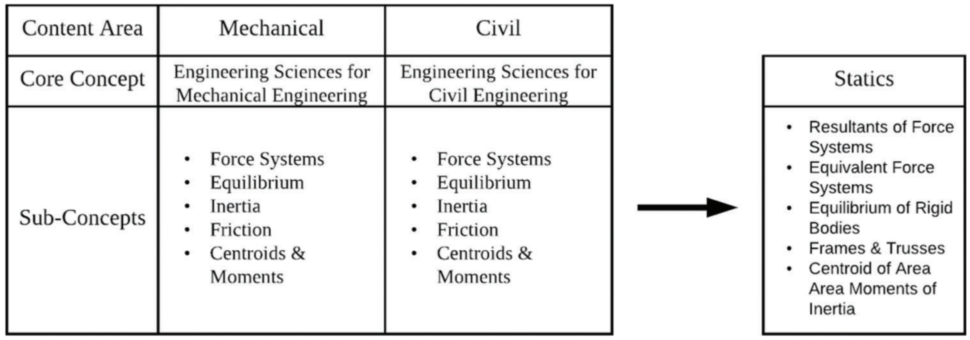

Figure 4. Example of revising the taxonomy by removing the content area classifications and merging duplicate core concepts to produce a refined crosscutting concept.

thermodynamics, mass transfer and separation, and hydrologic systems). This also aligns, and supplements, the content components of the *Standards for preparation and professional development for teachers of engineering* (Farmer, Klein-Gardner, & Nadelson, 2014). Third, the study was framed in a use-inspired context, wherein the results of the process were to be implemented and tested in schools through a research–practitioner partnership leveraging the curriculum space provided by the Technology and Engineering Education school subject in a state in which it was required for graduation. Through this approach, the authors hope to enhance the utility value of the study's results and support achieving engineering literacy for all students.

Defining Engineering Literacy

As mentioned, the taxonomy established through this research and development work can help to further define engineering literacy and, as such, provide a cohesive lens in which to bind the concepts, practices, and habits of mind that can be intentionally taught for learners to become engineering literate. When considering how the results from this study may help define engineering literacy for all students, it is necessary to discuss the term "core concepts." While the concepts identified in this study were originally conceived as "core" to engineering learning, it is reasonable to suggest that not all the scientific, mathematical, and technical concepts identified are essential for fundamental engineering literacy. The *Engineering Knowledge* dimension could be further defined as the scientific, mathematical, and technical concepts that students should appreciate and be able to draw upon, when appropriate, to better perform the practices of engineering. One would not expect a student to fully understand each of the *Engineering Knowledge* concepts in depth by the end of secondary school. However, to be engineering-literate individuals, they must be able to deploy their *Engineering Habits of Mind* as the thinking strategies to acquire and apply the appropriate *Engineering Knowledge*, along with their competence in *Engineering Practice*, to confront and solve the problems in which they encounter. For example, Table 9 outlines a proposed draft for a blueprint toward engineering literacy that leverages the results of this study to extend the depth in which the dimensions of literacy are defined. As a result, this blueprint can help provide a lens, not for compliance but for coherence, in conducting research to investigate and improve the impact of engineering education in P-12 settings. This can be important as the impact of engineering within P-12 schools needs to be well documented in the literature to continue garnering support from the general public and through legislation. As Chandler et al. (2011) indicate, there has been limited research that demonstrates how P-12 engineering curricula can help all students to develop the "habits of mind" or the engineering skill sets that can contribute to a technically proficient and informed citizenry for the 21st century.

Addressing Coherence to Achieve Engineering Literacy for All

The National Assessment of Educational Progress (2016) indicates that only a small portion of the nation's youth are intentionally taught the concepts of engineering and design throughout their educational experiences. Change the Equation (2016) also states that less than half of the nation's eighth graders were on track to become proficient in using engineering concepts and practices to conceive optimal solutions for authentic problems. Therefore, a major objective of developing a content taxonomy of engineering is to help educators develop and implement curriculum and instruction that allows for coherent educational pathways across the country based on a consistent, operational definition of engineering literacy. As an

Table 7
Revised content taxonomy for engineering knowledge.

Concepts	Sub-concepts	
Statics	• Resultants of force systems • Equivalent force systems • Equilibrium of rigid bodies	• Frames and trusses • Centroid of area • Area moments of inertia
Dynamics	• Kinematics (e.g., particles and rigid bodies) • Mass moments of inertia • Force acceleration (e.g., particles and rigid bodies)	• Impulse momentum (e.g., particles and rigid bodies) • Work, energy, and power (e.g., particles and rigid bodies)
Mechanics of materials	• Stress types and transformations • Material characteristics, properties, and composition (e.g., heat treating) • Stress-strain analysis • Material deformations	• Material equations • Phase diagrams • Mohr's circle • Young's modulus
Fluid mechanics	• Fluid properties • Pumps, turbines, and compressors • Lift, drag, and fluid resistance	• Fluid statics and motion (Bernoulli's equation) • Pneumatics and hydraulics
Mechanical design	• Machine elements (e.g., springs, pressure vessels, beams, piping, cams, and gears)	• Manufacturing processes • Machine control
Circuit theory	• Series and parallel circuits • Ohm's laws • Kirchhoff's laws • Resistance, capacitance, and inductance	• Wave forms • Signals • Current, voltage, charge, energy, power, and work
Electrical power	• Motors and generators • AC and DC • Electrical materials • Electro-magnetics	• Voltage regulation • Transmission and distribution • Magnetism
Electronics	• Instrumentation • Components • Integrated circuits	• Closed and open loop and feedback (systems, system response) • Digital electronics (e.g., gates and logic)
Communication technologies	• Digital communications • Telecommunications	• Photonics • Networks
Computer architecture	• Computer hardware • Computer software • Processors and microprocessors	• Interfacing • Memory
Thermodynamics	• Thermodynamic properties, laws, and processes • Equilibrium	• Gas properties • Power cycles and efficiency • Heat exchangers
Mass transfer and separation	• Molecular diffusions • Separation systems • Equilibrium state methods	• Humidification and drying • Continuous contact methods • Convective mass transfer
Chemical applications	• Applications of inorganic chemistry • Applications of organic chemistry • Chemical, electrical, mechanical, and physical properties (including potential hazards)	• Material types and compatibilities • Corrosion • Membrane science
Chemical reactions and catalysts	• Reaction rate, rate constant, and order • Conversion, yield, and selectivity	• Chemical equilibrium • Fuels
Process design	• Process controls and systems • Process flow, piping, and instrumentation diagrams	• Recycle and bypass processes • Industrial chemical operations
Structural analysis	• Physical properties of building materials • Deflection	• Deformations • Column and beam analysis • Implementation of design codes
Hydrologic systems	• Hydrology • Water distribution and collection systems • Watershed analysis	• Open channel • Closed conduits (pressurized) • Pumping stations • Laboratory and field tests
Infrastructure	• Street, highway, and intersection design • Transportation planning and control (safety, capacity, flow)	• Traffic design • Pavement design
Geotechnics	• Laboratory and field tests • Erosion control • Geological properties and classifications • Soil characteristics	• Bearing capacity • Drainage systems • Foundations and retaining walls • Slope stability
Environmental considerations	• Ground and surface water quality • Wastewater management	• Environmental impact regulations and tests

Table 8
Revised content taxonomy for engineering practice.

	Core concepts	Sub-concepts	
Engineering Design	Problem framing	• Identifying design parameters • Problem statement development	• Considering alternatives
	Research and investigation	• Information gathering • Data collection and organization methods	• Information quality assessment
	Ideation	• Spatial visualization (e.g., sketching) • Divergent thinking (e.g., brainstorming)	• Convergent thinking (e.g., functional decomposition)
	Prototyping	• Testing and modification (digital and physical) • Material selection	• Manufacturing processes • Computer-aided design and manufacturing
	Decision making	• Evidence/data-driven decisions • Application of STEM principles • Balancing trade-offs	• Using decision-making tools • Group decision making
	Project management	• Initiating and planning • Scope, time, and cost management	• Risk, quality, teams, and procurement • Product life cycle management
	Design methods	• Iterative cycles • User-centered design • Systems design	• Troubleshooting • Reverse engineering
	Engineering communication	• Engineering graphics • Dimensioning and tolerances • 2D computer-aided design	• 3D parametric modeling • Technical writing
Materials Processing	Measurement and precision	• Measurement instrumentation • Accurate layout and precision measurement	• Units and significant figures
	Manufacturing	• Design for manufacture • Additive manufacturing	• Subtractive manufacturing
	Fabrication	• Tool selection • Product assembly • Hand tools	• Equipment and machines • Quality and reliability
	Material classification	• Metals and alloys • Composites	• Polymers • Ceramics
	Joining	• Fastening • Soldering • Adhesion	• Welding • Brazing
	Forming	• Forging • Extruding	• Rolling
	Machining	• Drilling • Cutting • Milling	• Turning • Grinding • Reaming
	Finishing	• Grinding • Polishing	• Burnishing
	General safety	• Laboratory guidelines • Machine safety	• Attire and equipment
Quantitative Analysis	Computational thinking	• Programming and algorithms (including flowcharting) • Programming languages	• Software design, implementation, and testing
	Computational tools	• Spreadsheet computations (e.g., Microsoft Excel) • Data visualization	• Scripting languages (e.g., MATLAB, LabView)
	Data Collection, Analysis, and Communication	• Techniques of data collection (e.g. sampling methods) • Data-driven decisions	• Creating graphs and technical documents • Reporting data • Estimation
	System analytics	• Inputs and outputs • Feedback loops	• Optimization
	Modeling and Simulation	• Physical models • Computational simulations • Mathematical models	• Failure analysis and destructive testing • Design validation through calculations
	Engineering algebra	• Recognizing, selecting, and applying appropriate algebraic concepts and practices • Manipulation of algebraic equations	• Curve fitting • Linear algebra • 2D and 3D coordinate systems
	Engineering geometry	• Recognizing, selecting, and applying appropriate geometric concepts and practices • Manipulation of geometric equations	• Application of trigonometry • Vector analysis
	Engineering statistics and probability	• Recognizing, selecting, and applying appropriate probability and statistical concepts and practices • Applications of basic statistics (normal distributions, percentiles)	• Probability • Regression • Inferential statistics and tests of significance (e.g., *t*-tests, statistical tolerance)
	Engineering calculus	• Derivatives • Integrals	• Differential equations • Vectors (dot product and cross product)

Table 8
(Continued)

	Core concepts	Sub-concepts	
Professional Conventions	Professional ethics	• Morals, values, and the ethics continuum • Code of ethics	• Legal vs. ethical considerations
	Professionalism	• Public health, safety, and welfare • Responsible conduct of research • Workplace culture • Ethical business operations	• Agreements and contracts • Public policy and regulation • Professional liability
	Honoring intellectual property	• Patents, copyright, and licensure • Referencing sources	• Intellectual and physical property
	Impacts of technology	• Environmental impacts • Global impacts • Social impacts • Cultural impacts	• Economic impacts • Individual impacts • Political impacts
	Role of society in technological development	• Addressing societal needs and desires • Design for sustainability • Technology design in culture • Scaling of technology	• Appropriate technology • Inclusion and accessibility • Public participation in decision making
	Careers in engineering	• Professional licensing • Recognition of engineering-related careers	• Trade organizations • Entrepreneurship

effort to resolve the paucity of clarity, this study highlights the importance of a consistent epistemic basis for engineering and proposes a foundation for a coherent framework for P-12 engineering learning.

These results can be valuable in promoting diversity in engineering by modeling equity and inclusion through the development and implementation of comprehensive learning progressions of engineering concepts from kindergarten to grade 12 and beyond. This attention to coherence between grade bands can ensure that any curricular framework or standards reflect all the key stages in a learning progression that will not require additional, out-of-school opportunities to fill knowledge gaps—which put students without these experiences at a disadvantage (K-12 Computer Science Framework, 2016). Also, the way in which these results are used for the development of a curricular framework should intentionally model learning experiences that are contextualized in ways that are socially relevant and culturally responsive to students. This can play a major role in addressing the misperceptions around careers in engineering and can help guide the creation of educational experiences that reach all students.

A Foundation for Progressions of Learning in Engineering

As researchers and practitioners leverage the taxonomy in this paper to advance quality P-12 engineering education (Figure 5), effective engineering curricula and instruction will require an understanding of how students engage with and learn engineering habits of mind, practices, and concepts and sub-concepts. As discussed earlier, research on student learning of engineering is limited. Understanding how students progress through learning is paramount to guide P-12 engineering education when considering framework, curriculum, and instruction development and refinement. A major objective of this research was to establish an engineering content taxonomy to support the creation of developmentally appropriate student progressions of learning for P-12 schools. These progressions of learning can provide a defined and cohesive educational sequence to help guide engineering curriculum and instruction. As detailed in Figure 2, this could aid in scaffolding instruction to build from explicitly developing engineering habits at a young age to teaching in-depth concepts to inform engineering practice in high school.

Progressions of learning are defined as a sequenced set of subskills or bodies of enabling knowledge that students must master to achieve a curriculum target (Popham, 2008). Marzano (2010) posits that, "national and state standards often do not provide guidance in regards to the building blocks necessary to reach the designated learning goals" (p. 3). Therefore, progressions of learning will be necessary for the planning and assessment of engineering literacy at the P-12 level. Aligning to the work of Fonger and colleagues (2018), progressions of learning in engineering can serve as a "form of curriculum research that advances a linked understanding of students learning over time through careful articulation of a curricular framework and progression, instructional sequence, assessments, and levels of sophistication in student learning" (p. 30). Consequently, sample progressions of learning in engineering can be developed by leveraging the taxonomy created through this study. It is important to note that the authors have purposefully used the term *progression of learning* instead of *learning progression*, as they understand that this work can only be used to support "a progression of learning" and not "the learning progression." As discussed by Duncan and Hmelo-Silver (2009), a learning progression in science education includes a combined focus of content and practice, is bound by an

Table 9
Proposed expanded draft of the dimensions of engineering literacy.

Engineering Habits of Mind	Optimism	Engineers, as a general rule, believe that things can always be improved. Just because it hasn't been done yet, doesn't mean it can't be done. Good ideas can come from anywhere and engineering is based on the premise that everyone is capable of designing something new or different.	
	Persistence	Failure is expected, even embraced, as engineers work to optimize the solution to a particular challenge. Engineering—particularly engineering design—is an iterative process. It is not about trial and error. It is trying and learning and trying again.	
	Collaboration	Engineering successes are built through collaboration and communication. Teamwork is essential. he best engineers are willing to work with others. They are skilled at listening to stakeholders, thinking independently, and then sharing ideas.	
	Creativity	Being able to look at the world and identify new patterns or relationships or imagine new ways of doing things is something at which engineers excel. Finding new ways to apply knowledge and experience is essential in engineering design and is a key ingredient of innovation.	
	Conscientiousness	Engineering has a significant ethical dimension. The technologies and methods that engineers develop can have a profound effect on people's lives. That kind of power demands a high level of responsibility to consider others and to consider the moral issues that may arise from the work.	
	System thinking	Our world is a system made up of many other systems. Things are connected in remarkably complex ways. To solve problems, or to truly improve conditions, engineers need to be able to recognize and consider how all those different systems are connected.	
Engineering Practice	Engineering design	• Problem framing • Information gathering • Ideation • Prototyping • Engineering graphics	• Decision making • Project management • Design methods • Design communication
	Material processing	• Measurement and precision • Manufacturing • Fabrication • Material classification • Joining	• Casting/molding/forming • Separating/machining • Conditioning/finishing • Safety
	Quantitative analysis	• Computational thinking • Computational tools • Data collection, analysis, and communication	• System analytics • Modeling and simulation
	Professionalism	• Professional ethics • Workplace ethics • Honoring intellectual property	• Impacts of technology • Role of society in technological development • Engineering-related careers
Engineering Knowledge	Engineering sciences	• Statics • Mechanics of materials • Dynamics • Thermodynamics • Fluid mechanics	• Mass transfer and separation • Chemical reactions and catalysis • Circuit theory • Heat transfer
	Engineering mathematics	• Engineering algebra • Engineering geometry and trigonometry	• Engineering statistics and probability • Engineering calculus
	Engineering technical applications	• Electrical power • Communication technologies • Computer architecture • Process design • Structural analysis • Environmental considerations	• Hydrologic systems • Transportation infrastructure • Geotechnics • Chemical applications • Mechanical design • Electronics

Note. The dimensions of literacy are based on the following works: International Technology Education Association (1996); National Academy of Engineering & National Research Council (2002, 2006); and *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas* (2012). The big ideas are synthesized from the following works: Carr et al. (2009, p. 101); Merrill et al. (2009); National Academy of Engineering (2009, pp. 151–152; 2010, pp. 35–36); Sneider & Rosen (2009, p. 131). The engineering habits of mind definitions are provided by the National Academy of Engineering's (2018) LinkEngineering Educator's Exchange. The concepts for the *Engineering Knowledge* and *Engineering Practice* dimensions emerged from this study. In addition, the results of this study included sub-concepts for each concept, which are not provided in this table, to support the scaffolding of engineering instruction.

upper anchor (expected achievement) and lower anchor (expected prior knowledge and skills), and describes various intermediate steps a student may achieve to reach the upper anchor. These various intermediate steps are expected to be derived from empirical evidence. As empirical research concerning student learning of engineering concepts is still limited (NASEM, 2020), progressions of learning in engineering are presented to serve as a starting point for researchers to determine what intermediate steps are most effective for learners.

To provide an example of how the taxonomy can be leveraged to form progressions of learning, the authors created a Progression of Learning in Engineering (PLiE) template. Learning progressions are typically presented as "visual and conceptual maps that explain how students might move from simpler to more sophisticated understanding within a subject area" (Achieve, 2015, p. 3). Learning progressions are typically models of student learning over an extended amount of time, often several years (Lehrer & Schauble, 2015). However, the PLiE model presented here is intended to provide teachers with a sharper understanding of how sub-concepts may be related and how they may build upon each

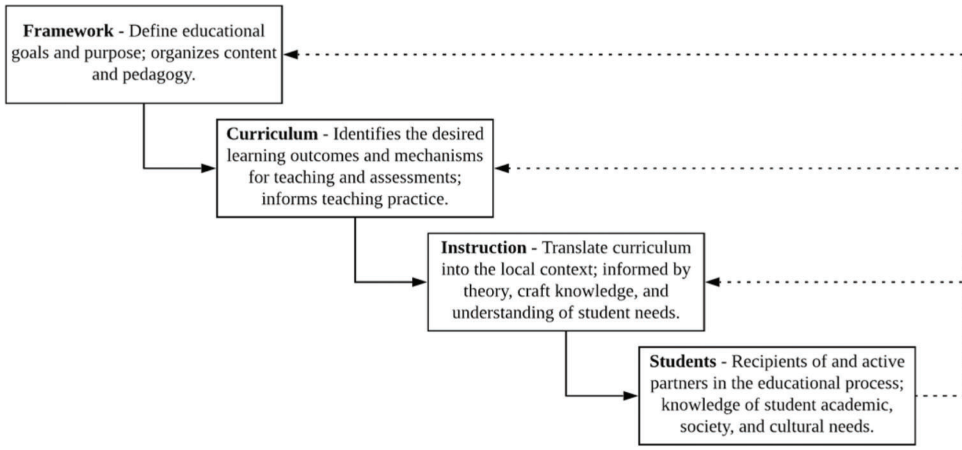

Figure 5. General model to advance quality P-12 engineering education.

other in order to influence more immediate and purposeful instructional practice. The goal is to help teachers think through novel concepts in engineering to improve their instruction from day to day or week to week. Accordingly, the template in Figure 6 was developed based on the five characteristics of learning progression frameworks by Magana (2017). Then, following the consultation with a variety of engineering education experts, including teachers, professors, and industrial practitioners, sample progressions of learning for each of the concepts from the emerging taxonomy were drafted. In Figure 7, a sample draft for the concept of *Problem Framing* is provided. While these sample PLiEs can indicate how to scaffold progress across different depths of student understanding, from basic to advanced, the authors realize that learning can and will be shaped according to the individualities of students and their communities. Similar to science education, PLiEs must be empirically grounded, testable, and hold true for different learners in various instructional settings (Corcoran, Mosher, & Rogat, 2009; Duncan & Hmelo Silver, 2009). Therefore, the hope is that the initial development will spur the refinement and expansion of PLiEs within and possibly beyond the scope presented in this paper.

Research Recommendations

As development continues, on-going research is necessary to validate the efficacy of the taxonomy and of each progression of learning as it relates to varying demographics, grade levels, and cognitive abilities. For example, although the progressions of learning can provide stepping stones among and between concepts and sub-concepts, as they are implemented, focused research will be needed to understand the major and minor changes teachers make between the varying levels. This will ensure that appropriate revisions are made with consideration of pedagogical and learning approaches. Additionally, although participants from a variety of backgrounds and areas of expertise convened to inform the perception of what students should know through developmentally appropriate instruction, next phases of research should be focused on students' cognitive and emotional abilities. Some future areas of inquiry, originally recommended by the National Academy of Engineering (2010, p. 3), include:

- How do children in formal educational settings come to understand (or misunderstand) core concepts and apply (or misapply) skills in engineering?
- What are the most effective ways of introducing and sequencing engineering concepts, skills, and ways of thinking for learners at the high-school level?
- What are the most important synergies in the learning and teaching of engineering along with mathematics, science, technology, and other subjects?
- What are the most important considerations in designing materials, programs, assessments, and educator professional development that engage all learners, including those historically underrepresented in engineering?
- How may a conceptual framework for the study of engineering inform the creation of P-12 engineering education standards?

Engineering Dimension: *(Knowledge or Practice)*

Engineering Practice or Domain: *(Identified in the taxonomy)*

Concept: *(Identified in the taxonomy)*

Overview: *Definition and importance to Engineering Literacy. Why does knowledge of this concept matter for students?*

Level 4	I can successfully (Engineering Habit) (Engineering Context) through application of (Concept). **(Performance Task)** Performance Task: Indicator of mastery understanding by applying core concept knowledge through engineering skillsets and habits of mind.

	Sub-Concept #1	**Sub-Concept #2**	**Sub-Concept #3**	**Sub-Concept #4**
Level 3	I can… **(Advanced)** Advanced Level (3): Demonstrating competency over challenging subject matter, including subject-matter knowledge, application of such knowledge to real-world situations, and analytical skills appropriate to the subject matter.	I can… **(Advanced)** Advanced Level (3): Demonstrating competency over challenging subject matter, including subject-matter knowledge, application of such knowledge to real-world situations, and analytical skills appropriate to the subject matter.	I can… **(Advanced)** Advanced Level (3): Demonstrating competency over challenging subject matter, including subject-matter knowledge, application of such knowledge to real-world situations, and analytical skills appropriate to the subject matter.	I can… **(Advanced)** Advanced Level (3): Demonstrating competency over challenging subject matter, including subject-matter knowledge, application of such knowledge to real-world situations, and analytical skills appropriate to the subject matter.
Level 2	I can… **(Proficient)** Proficient Level (2): Representing solid academic performance.	I can… **(Proficient)** Proficient Level (2): Representing solid academic performance.	I can… **(Proficient)** Proficient Level (2): Representing solid academic performance.	I can… **(Proficient)** Proficient Level (2): Representing solid academic performance.
Level 1	I can… **(Basic)** Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.	I can… **(Basic)** Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.	I can… **(Basic)** Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.	I can… **(Basic)** Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.

Figure 6. Progression of Learning in Engineering (PLiE) template.

Engineering Dimension: Engineering Practices

Engineering Practice: Engineering Design

Core Concept: Problem Framing

Overview: *Problem Framing* is a process, which occurs early in and throughout the practice of *Engineering Design,* that involves outlining one's mental interpretation of a problem situation by identifying the goals and essential issues related to developing a desired solution. This includes identifying design parameters to formulate a problem statement that (a) considers multiple perspectives, (b) removes perceived assumptions that unnecessarily limit the problem-solving process, and (c) frames the design scenario in such a manner that helps guide the problem-solving process. This core concept is important to the practice of *Engineering Design* as design problems are, by nature, ill-structured and open-ended.

Level 4	I can successfully construct justified problem statements that highlight the key elements of a design scenario, including multiple perspectives (incorporating the clients/end-users), to guide the evaluation of trade-offs between multiple, and sometimes conflicting, goals, criteria, and constraints during a design project. (Performance Task)

	Identifying Design Parameters		Problem Statement Development		Considering Alternatives
Level 3	I can evaluate the relationships between design criteria and constraints to prioritize them within a specific context of design in order to effectively balance trade-offs between any conflicting goals. (Advanced)	**Level 3**	I can evaluate a problem statement to determine if a vision for a design team is clearly stated with sufficient information that justifies the execution of a problem-solving process. (Advanced)	**Level 3**	I can evaluate alternative problem frames/statements in an effort to select the ones which have the greatest opportunity to generate innovative solutions. (Advanced)
Level 2	I can infer design criteria and constraints that are not explicitly described in a provided description of a design situation. (Proficient)	**Level 2**	I can summarize the key elements of a design situation to write a concise problem statement that represents a clear description of a justifiable issue along with the main goal(s) to be addressed by the problem-solving team. (Proficient)	**Level 2**	I can rephrase a problem from multiple perspectives to generate alternative problem frames/statements that remove assumptions limiting solution designs. (Proficient)
Level 1	I can analyze a provided description of design situation to identify explicit design criteria and constraints. (Basic)	**Level 1**	I can identify the key elements of a design situation which includes "what the central issue is that requires a resolution", "who the issue affects", "when/where the issue occurs", and "why the issue needs a novel solution". (Basic)	**Level 1**	I can identify the assumptions or perceived rules associated with a problem statement that are limitations for solution opportunities. (Basic)

Figure 7. Sample Progression of Learning in Engineering (PLiE) for the concept of problem framing (Kim, Newman, Lastova, Bosman, & Strimel, 2018).

Conclusion

As multiple reports have concluded, a lack of epistemological foundation for engineering at the P-12 level can be one of the factors hindering students' coherent and consistent study in engineering. Specifically, the ability of teachers to successfully design, align, and assess instructional tasks is dependent upon the creation and validation of a framework of engineering concepts and practices, which have been supported by research and vetted by professionals from a variety of backgrounds. Therefore, the authors of this study reviewed the literature on P-12 engineering education and conducted an investigation to establish a taxonomy of engineering concepts deemed potentially appropriate for secondary learners in an effort to set the epistemic basis for the school subject. To achieve this task, a modified Delphi study was enacted that involved various experts in the process of identifying and agreeing on engineering concepts. The result of this study implies that the defined dimensions of engineering literacy (see Table 9) and content taxonomy can support educators in establishing a clearer vision and roadmap for designing and developing curricula and instruction for P-12 engineering education. This would involve scaffolding instruction that builds from explicitly developing engineering habits at a young age to teaching in-depth concepts to inform engineering practice in high school (see Figure 2). While continued research is necessary, the authors hope that this work can help further define engineering literacy, set a foundation for developing progressions of learning in P-12 engineering, and open more conversations about engineering as a compulsory school subject. Through these conversations, it will be exciting to see what the engineering and education communities can develop to ensure that every child has the opportunity to learn, think, and act like an engineer.

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Appendix A

Concept Discovery Questionnaire

The overall intent of this study is to provide educators with the primary components of a viable engineering taxonomic structure for secondary technology and engineering programs. Specifically, this study will seek to establish (1) core concepts and (2) sub-concepts for the development of learning progressions to support the coherent study of engineering within secondary technology and engineering education classrooms. You have received this invitation because you have been identified or nominated as an expert in secondary/postsecondary engineering education with experience in the engineering or engineering technology professions. The engineering content being sought in this study is intended for use in the future development of a curriculum framework for students at the high school level.

If you agree to participate in this research study, you will be expected to serve as a panel expert for a three-round Delphi study. The Delphi technique attempts to build a consensus of opinion by asking experts a round of questions, developing more refined questions that are fed back to the respondents, and so on. After each round of questions, the research team will synthesize the results and return these results in the subsequent Delphi round to allow each participant to refine the results and indicate their agreement with the information that has been established.

- **Round 1:** focused on *concept discovery* (identifying core concepts and sub-concepts in both the technical and fundamental content areas of engineering)
- **Round 2:** focused on *concept prioritization*
- **Round 3:** focused on *concept rating*
- Member checking of the final results will take place in a symposium setting. Throughout this process, no identifiable information about each expert will be collected in connection with the responses.

Delphi Round #1

Thank you for your participation in the first Delphi round to identify the core concepts and corresponding sub-concepts for the secondary study of engineering. The following diagram depicts the hierarchical structure for the engineering content knowledge. It shows the relative positions of the taxonomy divisions. This visual aid is provided to more clearly convey to panel members the approach to identifying unique knowledge areas of secondary engineering.

A key feature of this taxonomy is the content knowledge elements in addition to the fundamental practices of engineering literacy. Several attempts have been made to identify and define the general and broad set of fundamental elements of engineering or the nature of engineering (e.g., designing solutions to ill-defined problems, considering impacts, balancing trade-offs, modeling, etc.). See Supporting Literature #1. However, this project also seeks to identify the specific technical content to support the analytical and practical skills exclusive to engineering. While some of the core concepts that you will identify in these content areas may be considered science or mathematics, it is the context and application of these concepts in engineering that will differentiate the study of the technical elements from other school subjects.

The term "content area" was purposefully selected for use in this taxonomy. The selected content areas should not be viewed as engineering career disciplines but organizers for concepts that will support the development of engineering literacy at the secondary level and prepare students for success in any engineering major if they decide to do so. The four content areas (Mechanical, Electrical, Civil, and Chemical) were selected as the areas for organizing the technical elements of secondary engineering as these areas can be viewed as the foundations of any engineering career discipline. For example, one can view computer engineering having roots in electrical, aerospace engineering having roots in mechanical, environmental engineering having roots in civil, etc. A key piece of literature supporting these content areas can be found at Supporting Literature #2 on page 27. Now, based on the information provided, use your knowledge and expertise in the field of engineering and technology education to answer the following questions.

Engineering Knowledge

Content Area: Mechanical

1. What are the main core concepts you feel represent the technical content of the mechanical engineering content area? (Support for identifying these core concepts can be found at Fundamentals of Engineering Exam, National Academies Taxonomy, or Engineering Majors) (Be as succinct as possible. Limit to 8)
   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept…
2. Under each of your designated core concepts for the content area of mechanical engineering, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)
   1. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
   2. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2

Content Area: Electrical

1. What are the main core concepts you feel represent the technical content of the electrical engineering content area? (Support for identifying these core concepts can be found at Fundamentals of Engineering Exam, National Academies Taxonomy, or Engineering Majors) (Be as succinct as possible. Limit to 8)
   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept…
2. Under each of your designated core concepts for the content area of electrical engineering, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)
   1. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
   2. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2

Content Area: Civil

1. What are the main core concepts you feel represent the technical content of the civil engineering content area? (Support for identifying these core concepts can be found at Fundamentals of Engineering Exam, National Academies Taxonomy, or Engineering Majors) (Be as succinct as possible. Limit to 8)

1. Core Concept 1
2. Core Concept 2
3. Core Concept…

2. Under each of your designated core concepts for the content area of civil engineering, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)

1. Core Concept 1
   a. Sub Concept 1
   b. Sub Concept 2
2. Core Concept 1
   a. Sub Concept 1
   b. Sub Concept 2

Content Area: Chemical

1. What are the main core concepts you feel represent the technical content of the chemical engineering content area? (Support for identifying these core concepts can be found at Fundamentals of Engineering Exam, National Academies Taxonomy, or Engineering Majors) (Be as succinct as possible. Limit to 8)

1. Core Concept 1
2. Core Concept 2
3. Core Concept…

2. Under each of your designated core concepts for the content area of chemical engineering, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)

1. Core Concept 1
   a. Sub Concept 1
   b. Sub Concept 2
2. Core Concept 1
   a. Sub Concept 1
   b. Sub Concept 2

Engineering Practices

The fundamental elements of engineering education have been divided into four content areas based on the previous literature on the nature of engineering. This literature also supports the identification of the core concepts and sub-concepts for each content area. Please review the following literature as needed:

- *Delivering Engineering Content in Technology Education*
- *Engineering in K-12 Education*
- *Standards for K-12 Engineering Education?* (See pages 35 & 36)
- *Core Engineering Concepts* (Page 37)
- *A Framework for Quality K-12 Engineering Education: Research and Development*
- *The Engineering of Technology Education*

http://dx.doi.org/10.7771/2157-9288.1232

Content Area: Engineering Design

1. What are the main core concepts you feel represent the fundamental content of the engineering design content area? (Be as succinct as possible. Limit to 8)
   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept…
2. Under each of your designated core concepts for the content area of engineering design, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)
   1. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
   2. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2

Content Area: Quantitative Analysis

1. What are the main core concepts you feel represent the fundamental content of the quantitative analysis content area? (Be as succinct as possible. Limit to 8)
   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept…
2. Under each of your designated core concepts for the content area of quantitative analysis, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)
   1. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
   2. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2

Content Area: Society & Ethics

1. What are the main core concepts you feel represent the fundamental content of the society & ethics content area? (Be as succinct as possible. Limit to 8)
   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept…
2. Under each of your designated core concepts for the content area of society & ethics, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)

1. Core Concept 1
    a. Sub Concept 1
    b. Sub Concept 2
2. Core Concept 1
    a. Sub Concept 1
    b. Sub Concept 2

Content Area: Material Processing

1. What are the main core concepts you feel represent the fundamental content of the material processing content area? (Be as succinct as possible. Limit to 8)
    1. Core Concept 1
    2. Core Concept 2
    3. Core Concept…
2. Under each of your designated core concepts for the content area of material processing, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)
    1. Core Concept 1
        a. Sub Concept 1
        b. Sub Concept 2
    2. Core Concept 1
        a. Sub Concept 1
        b. Sub Concept 2

Final Comments

1. Please use the following space to provide any additional feedback on the content areas that have been identified for this taxonomy. Add a justification or clarification for any suggested modifications to the taxonomy. This feedback will be used to make final edits to each item.

Appendix B

Results from Rounds 2 and 3 of the Delphi Study

Mechanical: Rating from Rounds 2 and 3

	Round 2		Round 3	
Core and Sub-Concept	**Mean**	**SD**	**Mean**	**SD**
Mechanics of Materials	4.79	0.77	4.59	0.60
• Stress type (axial, bending, torsion, shear) and transformations	4.74	0.91	4.71	0.75
• Solid mechanics (metals, plastics, woods, composites, alloys, ceramics, natural materials)	4.26	0.91	4.47	0.70
• Stress-strain analysis (stress-strain diagrams; shear and moment diagrams)	4.37	0.74	4.24	0.88
• Static equilibrium	4.32	1.26	4.18	1.10
• Material deformations	3.58	1.04	3.47	0.70
• Combined loading	3.79	0.83	3.29	0.75
• Tribology (principles of friction, lubrication, and wear)	3.47	1.31	3.18	0.92
• Material equations	3.32	1.03	3.18	1.10
• Phase diagrams and transformation	3.11	0.72	3.18	0.92
• Heat treating	3.21	0.95	3.00	0.69
Dynamics and Vibrations	4.16	0.81	4.00	0.84
• Scalars, vectors, resistance, gears	4.37	0.93	4.59	0.97
• Newton's second law for particles and rigid bodies	4.00	1.08	4.12	0.68
• Work-energy of particles and rigid bodies	3.79	0.77	3.94	1.26
• Kinematics of mechanisms	3.74	0.85	3.59	0.77
• Impulse-momentum of particles and rigid bodies	3.63	0.93	3.59	0.91
• Kinematics of particles and rigid bodies	3.63	1.04	3.47	0.85
Mechanical Design	5.00	0.73	5.18	0.62
• Manufacturing processes	4.63	0.74	4.65	0.76
• Machine elements (springs, pressure vessels, beams, piping, cams and gears, threads and fasteners, power transmission, electromechanical components)	4.95	0.83	4.53	0.98
• Machine control	4.37	0.58	4.12	0.90
Electro-mechanical Systems	4.95	0.89	4.47	0.70
• Basic electricity (voltage, current, resistance, power, AC and DC)	5.32	0.92	5.53	0.61
• Circuits (series and parallel, Ohm's law, Kirchhoff's law)	5.11	0.85	5.41	0.60
• Motors and generators (induction)	4.74	0.85	4.82	1.04
• Charge	4.53	0.88	4.65	0.97
• Magnetism	4.68	1.13	4.59	0.91
Emerging Mechanical Engineering	4.16	1.09	4.12	0.90
• Mechatronics (robotics)	4.26	1.02	4.65	1.03
• Bio-mechanical engineering	4.11	1.02	4.24	0.88
• Nanotechnology	3.95	1.10	4.12	0.83
• Ocean engineering	3.42	1.04	3.35	0.90
Fluid Mechanics	4.68	0.80	4.76	0.81
• Fluid properties	4.58	0.75	4.65	0.59
• Lift, drag, and fluid resistance	4.58	0.82	4.47	0.78
• Fluid statics and motion	4.32	0.86	4.24	0.81
• Hydraulics	4.42	1.04	4.18	1.10
• Pneumatics	4.42	1.04	4.12	1.13
• Compressible and incompressible flow	4.05	1.00	4.06	0.73
• Computational fluid mechanics	3.63	0.93	3.47	0.98
Thermodynamics	4.53	0.75	4.24	1.00
• Thermodynamic properties, laws, and processes	4.32	0.86	4.29	1.02
• Energy transfers	4.63	0.93	4.24	0.94
• Equilibrium	4.26	1.16	4.18	0.78
• Thermal resistance	3.95	0.83	3.88	0.83
• Gas properties	4.53	1.23	3.82	0.86
• Power cycles and efficiency	3.79	1.06	3.71	1.07
• Heat exchangers	3.95	0.76	3.65	0.76
• HVAC processes	3.21	1.06	3.18	0.92

Note. The rating scale: 1 through 6.

Electrical: Rating from Rounds 2 and 3

Core and Sub-Concept	Round 2		Round 3	
	Mean	SD	Mean	SD
Electrical Power	4.83	1.07	5.12	0.68
• Force	4.67	1.05	5.00	0.59
• Motors and generators	4.61	0.89	4.71	0.96
• Electrical materials (chemical, mechanical, thermal)	4.28	0.80	4.65	0.76
• Electro-magnetics	4.56	0.83	4.41	1.09
• Transformers	4.28	0.87	4.06	0.73
• Voltage regulation	4.22	1.18	3.94	1.00
• Transmission and distribution	4.06	0.97	3.88	0.96
• Single and three-phase AC power	3.72	0.93	3.76	0.94
• Maxwell equations	3.72	0.93	3.59	0.84
Circuit Analysis	5.00	0.82	5.24	0.55
• Current, voltage, charge, energy, and power	5.11	0.87	5.29	0.57
• Series and parallel equivalent circuits	5.00	0.94	5.12	0.47
• Ohm's law and Kirchhoff's laws	5.11	0.94	5.00	0.69
• Power and energy	5.00	0.88	4.94	0.64
• Impedance, capacitance, and inductance	4.22	1.13	4.59	0.77
• Wave forms	4.06	0.97	4.06	0.64
• Node and loop	4.28	1.19	3.88	0.68
Electronics	4.72	0.87	4.94	0.80
• Instrumentation	4.33	0.82	4.35	0.68
• Semiconductor	4.11	0.87	4.29	0.75
• Amplifiers	4.11	0.81	3.94	0.80
• Solid state fundamentals	3.78	0.85	3.82	0.62
• Discrete devices	3.72	0.87	3.71	0.67
Control Systems	4.67	1.00	4.65	0.68
• Sensors	4.78	0.97	4.94	0.87
• Closed and open loop	4.78	0.97	4.82	0.78
• Feedback systems	4.78	1.08	4.71	0.82
• Block diagramming	4.50	1.17	4.59	1.03
• System response	4.33	1.15	4.35	0.90
• System performance	4.56	1.07	4.29	0.89
• Automated processes	4.28	0.93	4.24	0.64
• State variables and machines	4.17	1.17	3.88	0.83
• Dynamic systems	4.22	1.08	3.88	0.83
• Measurement uncertainty	4.00	1.11	3.88	0.90
Digital Systems	4.89	1.05	5.00	0.69
• Programmable logic devices	4.44	1.26	4.76	0.88
• Logic simplification (Boolean logic, K-mapping)	4.33	1.41	4.53	0.92
• Analog system components and difference with digital systems	4.56	1.07	4.47	0.70
• Number systems	4.33	1.15	4.35	0.90
• Logic states and gate arrays	4.44	1.17	4.29	0.82
• State machine design	3.72	1.24	3.76	0.81
• Data path and controller design	3.89	1.24	3.65	0.68
• Timing	3.83	1.26	3.65	0.90
• MOSFET (metal-oxide-semiconductor field-effect transistor: the most common transistor in digital circuits)	3.11	0.99	3.06	0.80
• VHSIC hardware description languages	3.11	1.05	3.00	0.77
Signal Processing	3.50	1.12	3.53	1.04
• Analog and digital conversions	3.56	1.30	3.35	1.03
• Analog and digital filters	3.28	1.04	3.24	1.06
• Parallel processing	3.28	1.10	3.18	0.92
• Convolution	3.28	1.04	3.12	0.83
Communication Technology	4.72	1.10	4.65	0.84
• Digital communications	4.39	1.11	4.47	0.92
• Telecommunications	4.50	1.17	4.18	0.86
• Fiber optics (photonics)	3.72	1.04	4.00	1.03
• Radio frequency	3.72	0.99	3.82	0.78
• Antenna theory	3.17	1.01	3.35	0.97
Computer Systems	5.11	0.66	5.06	0.80
• Computer architecture	4.44	0.68	4.65	0.76
• Integrated circuits	4.83	0.83	4.59	0.49

(Continued)

Core and Sub-Concept	Round 2		Round 3	
	Mean	SD	Mean	SD
• Processors and microprocessors	4.67	0.82	4.53	0.78
• Interfacing	4.50	0.90	4.53	0.50
• Algorithms	4.72	1.04	4.53	0.85
• Networks	4.83	0.83	4.53	0.61
• Embedded systems	4.44	0.96	4.41	0.77
• Memory	4.56	0.90	4.35	0.59
• Software engineering	4.50	1.12	4.35	0.97
• Data structures	4.67	0.82	4.24	0.64
Emerging Fields in Electrical Engineering	4.33	1.05	4.29	0.75
• Biomedical engineering applications	4.06	1.08	4.24	0.73
• Virtual system	3.72	1.19	3.71	0.67

Note. The rating scale: 1 through 6.

Civil: Rating from Rounds 2 and 3

Core and Sub-Concept	Round 2		Round 3	
	Mean	SD	Mean	SD
Geotechnical Engineering	3.61	0.89	3.71	0.67
• Laboratory and field tests	3.61	1.16	3.59	0.69
• Erosion control	3.61	1.16	3.59	0.77
• Geological properties and classifications	3.61	1.21	3.53	0.61
• Soil characteristics (quality, erosion)	3.61	1.11	3.53	0.61
• Bearing capacity	3.56	1.07	3.47	0.85
• Drainage systems	3.61	1.16	3.47	0.78
• Foundations and retaining walls	3.50	0.96	3.35	0.68
• Slope stability	3.39	1.06	3.35	0.76
Hydrologic Systems	3.78	0.97	3.82	0.71
• Hydrology and hydraulics	3.67	1.05	4.00	0.69
• Water distribution and collection systems	3.50	1.17	3.76	0.88
• Pressurized flow	3.39	1.11	3.65	0.68
• Open channel flow	3.39	1.11	3.53	0.61
• Pumping stains	3.28	0.99	3.35	0.68
• Boundary layer theory	3.17	1.12	3.00	0.59
Structures	5.33	0.82	5.35	0.76
• Work, energy, and power	5.17	0.76	5.35	0.76
• Loads and forces	5.22	0.79	5.29	0.82
• Frames and truss design	5.11	0.74	5.06	0.87
• Stress (tension and compression)	5.22	0.71	5.06	0.87
• Beams and columns	4.78	0.79	4.76	0.88
• Code and design	4.50	1.17	4.53	1.04
Structural Analysis	5.00	1.05	5.12	0.68
• Physical properties of materials	4.78	0.85	5.06	0.73
• Stress and strains of materials	4.78	0.71	4.88	0.68
• Shear and moment diagrams	4.67	0.82	4.82	0.78
• Steel, ceramics, natural materials, composites, and alloys	4.33	0.94	4.65	0.76
• Deflection	4.78	0.97	4.24	0.73
• Deformations	4.33	1.05	4.18	0.78
• Column analysis	3.56	1.17	3.65	0.76
• Mohr's circle (2D graphical representation of the transformation law for the Cauchy stress tensor)	3.72	1.15	3.59	1.09
Applied Statics	4.83	1.07	5.06	0.64
• Force	5.00	1.00	5.29	0.57
• Equilibrium	4.72	1.04	4.76	0.88
• Inertia	4.61	1.06	4.71	0.57
• Friction	4.50	1.12	4.71	0.75
• Centroids and moments	4.22	1.03	4.41	1.09
• Rigid bodies	4.39	0.95	4.41	0.60
• Resultant calculations	-	-	4.35	0.97
• Static and stable structures	4.17	1.07	4.18	0.78
Infrastructure	4.44	1.21	4.35	0.90
• Street, highway, and intersection design	3.94	1.08	4.06	0.87
• Transportation planning and control (safety, capacity, flow)	3.67	1.29	3.88	1.02
• Traffic design	3.61	1.16	3.76	0.81
• Pavement design	3.39	1.16	3.65	0.84
Construction Management	4.11	0.99	3.94	1.00
• Project planning and management	3.83	1.07	4.06	1.21
• Construction safety	4.11	1.20	4.00	1.08
• Construction methods and operations	3.94	0.97	3.88	1.02
• Project delivery	3.61	1.06	3.65	0.97
• Human resource management	3.28	1.15	3.29	1.13
Environmental Engineering	4.39	0.76	4.65	1.08
• Ground and surface water quality	4.39	0.76	4.65	1.03
• Wastewater management (disposal)	4.11	0.87	4.53	1.09
• Environmental impact regulations and tests	3.78	0.97	4.29	1.18
• Natural systems	4.00	0.88	4.24	1.11
Surveying	3.83	0.83	3.29	0.75
• Leveling	3.56	0.83	3.47	0.78
• Coordinate system	3.83	1.07	3.41	0.84

Note. The rating scale: 1 through 6.

Chemical: Rating from Rounds 2 and 3

	Round 2		Round 3	
Core and Sub-Concept	**Mean**	**SD**	**Mean**	**SD**
Chemical Reaction and Catalysis	4.44	1.38	4.00	0.77
• Reaction rate and order	4.22	1.31	3.76	0.64
• Rate constant	4.00	1.15	3.71	0.67
• Conversion, yield, and selectivity	3.83	1.17	3.65	0.76
• Reaction and reactor types	3.83	1.26	3.41	0.69
Fluid Mechanics and Dynamics	4.50	1.12	4.29	0.75
• Bernoulli's principle	4.78	0.97	4.76	0.81
• Flow	4.67	1.11	4.59	0.77
• Hydraulics	4.39	1.11	4.35	0.76
• Pumps, turbines, and compressors	4.28	1.19	4.24	0.73
• Pneumatics	4.33	1.11	4.24	0.81
• Fluid properties	4.50	1.01	4.18	0.71
Heat Transfer	4.28	0.99	4.12	0.83
• Conductive, convective, and radiated heat transfer	4.39	1.01	4.18	0.86
• Heat transfer coefficients	3.67	0.94	3.71	1.02
• Heat transfer equipment design and operation	3.56	1.01	3.65	0.90
• Chemical equilibrium	3.83	1.01	3.53	0.78
• Phase equilibrium diagram	3.56	0.96	3.29	0.89
Energy	5.11	0.99	5.06	1.11
• Work, energy, and power	5.06	0.91	5.00	1.03
• Electricity laws	4.83	0.90	4.94	1.00
• Energy balance	4.72	0.99	4.71	1.07
• Fuels	4.50	0.96	4.47	0.92
• Combustion	4.33	0.88	4.35	1.03
• Recycle and bypass processes	4.00	0.82	3.76	0.73
Applied Chemistry	3.72	1.15	3.82	0.78
• Inorganic chemistry	3.44	0.96	3.35	0.48
• Organic chemistry	3.11	1.10	3.18	0.71
Biological	3.78	1.13	3.59	0.84
• Bio-molecular engineering	3.67	1.00	3.59	0.84
• Biochemical	3.67	1.11	3.53	0.78
Material Properties	4.61	1.25	4.71	1.02
• Material types and compatibility	4.56	1.17	4.65	0.90
• Chemical, electrical, mechanical, and physical properties	4.61	1.25	4.47	0.98
• Material selection	4.56	1.17	4.47	0.85
• Metal, naturals, plastics, liquids, papers, fibers, and polymer	4.17	1.34	4.24	0.94
• Corrosion	3.89	1.20	3.82	0.98
• Recycling processes	4.17	1.17	3.76	0.94
• Petroleum engineering	3.72	1.15	3.35	0.90
• Membrane science	3.33	1.05	3.24	0.81
• Pharmaceuticals	3.56	1.12	3.12	0.58
Mass Transfer and Separation	3.56	1.12	3.47	0.98
• Molecular diffusions	3.28	0.93	3.24	1.11
• Separation systems	3.33	0.94	3.24	0.81
• Equilibrium state methods	3.33	1.05	3.24	0.64
• Humidification and drying	3.11	0.99	3.24	0.88
• Continuous contact methods	3.17	0.96	3.18	0.86
• Convective mass transfer	3.11	0.99	3.12	0.68
Process Design	4.39	1.30	4.47	0.98
• Process optimization	4.28	1.48	4.00	0.97
• Time value of money	3.83	1.34	3.88	1.13
• Process controls and systems	3.94	1.27	3.82	0.86
• Process flow, piping, and instrumentation diagrams	3.78	1.23	3.76	0.81
• Comparison of economic alternatives	3.83	1.26	3.76	0.81
• Cost estimation and analysis	3.89	1.24	3.71	0.67
• Equipment selection	3.94	1.22	3.65	0.68
• Industrial chemical operations	3.50	1.30	3.18	0.51
Safety, Health, and Environment	4.83	1.26	4.71	1.18
• Hazardous properties of materials	4.61	1.25	4.76	0.88
• Industrial hygiene	4.17	1.12	4.06	0.94
• Waste minimization, treatment, and regulation	4.00	1.11	4.06	0.80
• Process safety and hazard analysis	4.33	1.11	4.00	0.77
• Pressurization protection	3.89	1.10	3.71	0.82

Note. The rating scale: 1 through 6.

Engineering Design: Rating from Rounds 2 and 3

	Round 2		Round 3	
Core and Sub-Concept	**Mean**	**SD**	**Mean**	**SD**
Design Processes	5.50	1.12	5.65	0.97
• Iterative cycles	5.17	1.17	5.29	1.02
• User-centered design	4.89	1.24	5.24	0.94
• Closed-loop design process	4.56	1.17	4.82	0.98
• Linear and concurrent engineering design	4.17	1.30	4.41	0.97
Engineering Design Practices	5.56	0.83	5.76	0.55
• Design procedures (defining user needs, creating a decision support matrix [DSM], building prototypes, testing/evaluating/redesign)	5.56	0.83	5.65	0.59
• Ideation techniques	5.22	0.79	5.47	0.70
• Creativity for engineering design	-	-	5.41	0.77
• Design analysis	5.22	0.85	5.29	0.96
• Troubleshooting	5.44	0.83	5.29	1.02
• Reverse engineering	5.00	1.05	5.00	0.97
Defining Problems	5.67	0.82	5.65	0.84
• Identifying design parameters	5.61	0.68	5.59	0.84
• Problem scoping	5.17	1.12	5.29	0.82
• Problem statement development	5.33	0.82	5.24	0.94
Research	5.44	0.90	5.35	0.97
• Information gathering	5.22	0.92	5.53	0.78
• Identifying key content areas	5.22	0.85	5.41	0.84
• Data collection methods	5.33	0.94	5.41	0.60
• Data analysis	5.39	0.89	5.41	0.60
• Information quality assessment	5.33	0.88	5.35	1.03
• Research design	5.22	0.97	5.29	0.89
Design Communication	5.50	0.76	5.47	0.61
• Graphical communication to professionals	5.28	0.87	5.53	0.61
• General communication	5.22	0.92	5.47	0.61
• Technical writing	4.94	0.97	5.47	0.78
• Presentation tools	5.00	1.00	5.06	1.11
Engineering Graphics	5.67	0.67	5.53	0.70
• Sketching	5.39	0.89	5.53	0.78
• 3D parametric modeling	5.11	1.05	5.29	0.82
• Projection theory (orthographic projections)	5.06	0.97	5.24	0.88
• Isometrics	4.94	1.08	5.06	1.06
• Geometric dimensioning and tolerances	4.78	1.08	5.06	0.73
• Section view	4.61	1.25	4.88	1.08
• Drawing for manufacturing	5.11	0.94	4.88	0.90
• 2D CAD	4.56	1.38	4.82	1.20
• CAM and CNC	4.56	1.34	4.76	1.00
• Auxiliary view	4.44	1.26	4.71	1.13
• Pattern development	4.17	1.30	4.59	0.97
Prototyping	5.22	0.92	5.59	0.49
• Testing and modification	5.39	0.95	5.59	0.77
• Material selection	5.00	1.00	5.29	0.57
• Scientific testing methods	5.28	0.87	5.29	0.96
• Physical model testing	5.22	0.71	5.18	0.78
• Rapid prototyping	5.11	1.10	5.12	0.83
• Virtual model testing	5.11	0.94	5.00	0.97
• Manufacturing processes	4.89	1.05	4.94	0.80
• Efficiency and economics	4.94	1.13	4.82	0.98
• Theoretical model testing	5.06	0.91	4.76	1.00
Decision Making	5.33	0.94	5.47	0.98
• Data-driven decisions	5.33	0.82	5.24	0.88
• Applying STEM principles for decision making	5.06	0.97	5.24	1.16
• Decision-making tools (matrix, etc.)	4.89	1.10	5.18	0.92
• Balance trade-offs	5.33	0.82	5.12	1.02
Project Management and Teamwork	5.33	0.75	5.47	0.61
• Team communication	5.67	0.47	5.59	0.49
• Cooperation	5.67	0.58	5.47	0.70
• Time management	5.50	0.69	5.29	0.89
• Peer evaluation	5.11	0.94	5.29	0.67
• Coordination	5.33	0.82	5.06	0.80

Note. The rating scale: 1 through 6.

Quantitative Analysis: Rating from Rounds 2 and 3

Core and Sub-Concept	Round 2 Mean	Round 2 SD	Round 3 Mean	Round 3 SD
Applied Mathematics	5.56	0.68	5.59	0.49
• Creating and writing equations	4.67	0.88	4.94	0.80
• Trigonometry	4.94	1.18	4.88	0.68
• Basic statistics	4.94	0.97	4.82	0.78
• Probability	4.83	0.96	4.71	0.67
• Analytic geometry	4.89	1.20	4.65	0.68
• Vector analysis	4.72	1.15	4.65	0.84
• Linear algebra	4.78	1.27	4.53	0.61
• Numerical methods	4.61	1.21	4.47	0.70
• Curve fitting	4.17	1.26	4.24	0.94
• Statistical process control	4.28	1.15	4.18	0.98
• Calculus	4.17	1.54	4.06	1.11
• Regression	4.22	1.27	4.06	1.06
• Differential and integral equations	3.78	1.44	3.88	1.18
Computational Thinking	5.11	1.15	5.29	0.67
• Programming and algorithms	4.78	1.31	4.88	0.58
• Programming (script programming languages)	4.56	1.17	4.59	0.69
• Software design, implementation, and testing	4.56	1.30	4.24	1.16
Computational Tools	5.33	0.88	5.24	0.64
• Spreadsheet computations	5.22	0.79	5.59	0.49
• Flow charts	5.06	0.91	4.94	0.80
• Data visualization	5.17	0.83	4.94	0.80
Data Analysis and Communication	5.11	0.87	5.18	0.71
• Data collection	5.17	0.90	5.24	0.64
• Data-driven decisions	5.17	0.76	5.12	0.76
• Creating graphs and documents	5.06	0.97	5.06	0.73
• Reporting data	4.94	1.13	5.00	0.84
• Experimental methods	4.83	1.01	4.76	0.64
• Classification	4.67	1.20	4.65	0.68
• Refinement	4.56	1.17	4.41	0.60
System Analysis	5.28	0.99	4.94	0.73
• Inputs and outputs	5.00	1.11	4.88	0.90
• Feedback loops	5.00	1.15	4.88	1.02
• Optimization	5.17	1.07	4.82	1.04
• Product life cycle	4.94	1.03	4.59	0.91
Modeling and Simulation	5.33	0.75	5.24	0.88
• Physical models	5.00	0.94	5.12	0.83
• Computational models	4.83	1.07	4.88	0.83
• Mathematical models	4.67	1.05	4.82	0.78
• Design validation through calculations	4.94	0.85	4.82	0.71

Note. The rating scale: 1 through 6.

Society and Ethics: Rating from Rounds 2 and 3

Core and Sub-Concept	Round 2		Round 3	
	Mean	SD	Mean	SD
Engineering Economics	4.33	0.94	4.18	0.86
• Cost estimation and analysis	4.33	1.05	4.35	0.90
• Time value of money	4.28	0.99	4.24	1.06
• Cost–benefit analysis (breakeven points)	4.17	1.07	4.24	0.64
• Economic feasibility	4.11	1.15	4.12	0.76
• Expected value and risk	4.22	1.40	4.00	0.84
• Life-cycle analysis	4.33	1.05	3.82	0.86
• Depreciation	3.33	1.25	3.18	0.71
Ethics	5.33	0.88	5.18	0.86
• Code of ethics	5.11	0.81	5.06	0.87
• Legal and ethical considerations	5.00	0.88	4.76	1.00
• Application of ethics	4.83	0.96	4.76	0.88
• National and international code	4.61	0.95	4.47	0.85
• Purpose and intent	4.78	0.92	4.24	0.94
• Public protection issues (licensing boards)	4.44	1.07	4.24	0.88
• Trade organizations	4.22	1.13	4.12	0.90
Professional Practice	4.00	1.15	4.41	0.97
• Public health, safety, and welfare	4.50	1.12	4.53	1.04
• Responsible conduct of research	4.06	1.31	4.35	1.03
• Workplace ethical culture	4.39	1.06	4.35	1.13
• Ethical business operation	4.17	1.26	4.24	0.94
• Agreements and contracts	3.67	1.11	3.82	0.78
• Public regulation	3.56	1.12	3.82	0.78
• Professional skills (public policy, administration, and contracts)	3.72	0.99	3.82	0.92
• Professional liability	3.72	1.10	3.53	0.85
Intellectual Property	4.78	1.18	4.65	1.08
• Patent	4.44	1.30	4.47	0.98
• Licensure	4.39	1.30	4.41	0.84
• Copyright	4.44	1.30	4.35	1.08
• Entrepreneurship	4.50	1.12	4.29	0.75
• Open source	-	-	4.00	0.84
Impacts of Technology	5.22	0.97	4.88	1.23
• Environmental impacts	4.67	1.05	4.76	1.16
• Global impacts	5.06	0.85	4.76	1.21
• Social impacts	5.00	0.94	4.65	1.08
• Culture impacts	4.78	0.92	4.65	0.97
• Economic impacts	4.67	1.05	4.59	1.09
• Individual impacts	4.83	1.07	4.53	1.04
• Political impacts	4.61	1.11	4.29	0.89
Role of Society in Technology Development	5.17	1.01	4.76	1.00
• Societal needs and desires	5.22	0.85	4.76	0.94
• Design sustainability	5.11	0.66	4.71	1.02
• Technology design in cultures	4.78	1.03	4.65	0.84
• Scaling of technology	4.78	1.08	4.59	1.03
• Development and availability in countries and regions	4.78	0.92	4.47	0.92

Note. The rating scale: 1 through 6.

Material Processing: Rating from Rounds 2 and 3

Core and Sub-Concept	Round 2		Round 3	
	Mean	SD	Mean	SD
Measurement and Precision	5.39	0.59	5.35	0.84
• Measurement instrumentations	5.17	0.69	5.18	0.92
• Layout and measurement	5.33	0.58	5.12	0.76
• Units and significant figures	5.00	0.82	5.00	1.03
Fabrication	4.94	0.52	5.06	0.64
• Tool selection	4.94	0.78	5.18	0.71
• Product assembly	4.67	0.58	4.94	0.80
• Machines	4.78	0.71	4.82	0.98
• Hand tools	4.72	0.73	4.76	1.00
• Quality and reliability	4.78	0.53	4.71	0.89
Finishing	4.00	1.25	4.29	0.89
• Adhesion	3.89	1.15	4.12	0.76
• Grind	3.56	1.21	3.82	0.78
• Polish	3.56	1.21	3.76	0.88
• Burnish	3.44	1.21	3.71	0.89
Forming	3.89	1.10	3.94	0.80
• Forging	3.33	1.25	3.65	0.84
• Extrusion	3.44	1.21	3.65	0.84
• Rolling	3.39	1.21	3.65	0.84
Joining	4.11	1.15	4.12	0.68
• Fastening	4.44	0.96	4.24	0.88
• Soldering	4.22	1.08	4.00	0.91
• Adhesion	4.11	1.05	3.94	0.80
• Welding	3.61	1.11	3.65	0.84
• Brazing	3.28	1.28	3.41	0.97
Machining	4.33	1.20	4.00	0.77
• Drilling	4.17	1.07	4.00	0.84
• Cutting	4.28	0.99	3.88	0.83
• Milling	3.72	1.24	3.71	0.96
• Turning	3.50	1.17	3.65	0.97
• Grinding	3.83	1.17	3.41	0.97
• Reaming	3.39	1.16	3.29	0.82
Material Classification	4.50	0.96	4.76	0.73
• Metals and alloys	4.28	0.93	4.59	0.69
• Composites	4.28	0.93	4.47	0.78
• Polymers	4.28	0.93	4.41	0.84
• Ceramics	4.28	0.93	4.29	0.75
Manufacturing	4.78	0.85	4.76	0.94
• Safety for material processing	-	-	4.82	0.98
• Computer-aided manufacturing	4.56	0.90	4.65	0.84
• Automated manufacturing	4.33	0.82	4.47	0.98
• Additive manufacturing	4.39	0.83	4.35	0.97
• Traditional manufacturing	4.39	0.83	4.35	0.97

Note. The rating scale: 1 through 6.