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Engineering Design and Children: A Systematic Literature Review

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Abstract

Over the last two decades, a remarkable number of studies have examined the role of engineering education in supporting knowledge and skill building among children. In this paper, we present a synthesis of this literature to evaluate the added value of pre-college engineering design experiences at the elementary level, and ways researchers have gathered evidence of children's development of this knowledge and skills. We have conducted a systematic literature review. The initial search across four different databases with relevant keywords resulted in over 3000 journal articles and conference papers. In a two-rounds screening, by applying the inclusion criteria first to titles and abstracts, and then to the full text, 78 peer-reviewed publications were included in this systematic literature review. We summarized and synthesized empirical evidence of student learning and engagement in engineering design activities, and approaches they were assessed and elicited. The thematic analysis revealed five categories of knowledge and skills: (1) disciplinary content knowledge; (2) engineering design practices, (3) engineering thinking skills; (4) professional skills; and (5) career awareness. Additionally, the assessment and evaluation approaches that were used for each of these categories were identified and discussed. The findings provide collective evidence of variety in student learning opportunities but also suggest the need to carefully define these knowledge and skills. Since a wide range of evaluation approaches were used to capture similar outcomes, we conclude that it is imperative to develop a shared research agenda by carefully defining the knowledge and skills we expect children to learn.

Introduction

The integration of engineering in pre-college education is an area of growing interest (Murphy et al., 2019; NAE, 2009; NASEM, 2020; NRC, 2012). In 2013, the *Next Generation Science Standards* (NGSS Lead States, 2013) became the impetus for expansion in the United States with an increased number of states that added engineering to their standards throughout kindergarten to twelfth grade (K-12). In parallel to these developments in public education, research in pre-college engineering education has grown significantly over the last few decades, along with systematic analyses of this body of research.

One of the earliest synthesis studies of the engineering education literature was conducted by Diaz and Cox (2012). They examined research papers published between 2000-2011 with a focus on pre-college engineering education in the United States. Diaz and Cox concluded their analysis with a recommendation for the need for designing better quality research studies and the need to develop research-informed curricular interventions designed based on an understanding of engineering. Building on and expanding Diaz and Cox's study, Hynes and colleagues (2017) provided a global perspective of the literature by synthesizing over two-hundred peer-reviewed articles published between 2000 and 2015. Their analysis highlights three focus areas of education: students, teachers, and curriculum. They argued that the body of research they have examined addressed aspects of student learning and teacher preparation, but with a heavier focus on perceptions of and dispositions towards engineering. In contrast, Murphy and colleagues (2018)'s analysis of STEM education in Australia points out the solid emphasis on building student learning but calls for more research in building positive dispositions about STEM careers. Another notable discrepancy within the synthesized literature is evident when researchers specifically looked at literature on design education. Clark and colleagues (2020) conducted a content analysis of articles published in seventeen research journals to identify assessments with a focus on design processes and outcomes. Their analysis, covering across early childhood to tertiary education, found that the majority of the work was on assessing the performance of students' design artifacts, followed by assessments of communication, problem scoping, and creativity. Their synthesis resulted in little evidence in the applications of science and mathematics during design.

The disagreements in the synthesized literature can perhaps be explained by the make-up of the literature body based on the educational levels (elementary, secondary, tertiary), where the motivations in teaching engineering varies. Hence, focusing the literature synthesis efforts to a specific student population can provide a nuanced understanding of ways students develop knowledge and skills as they engage in engineering design activities. Even among the studies that concentrate on student learning within a specified group, we expect variety in regard to their research foci and design (Brown, 2012; Hynes et al., 2017; Macalalag et al., 2010). However, such an examination would provide us better insights into the body of empirical evidence.

Thus, in this systematic literature review, we identified and synthesized studies pertaining to children's engineering learning to explore the knowledge children learn, skills they develop, and practices they engage in when participating in engineering design activities. Through this review, we also explored how researchers evaluated and captured the knowledge and skills during children's engagement in engineering. We focus on synthesizing the literature to explain what content knowledge and skills children develop as they engage in engineering design as well as the ways researchers have gathered evidence of children's development in these knowledge and skills through the examination of research methods and assessment practices.

Methods

A systematic literature review approach was used (Grant & Booth, 2009) to address the aforementioned research questions. In particular, we followed Borrego et al. (2014)'s recommendation for conducting a systematic literature review. As Borrego et al., 2014 suggests, conducting a systematic literature review can benefit the field of engineering education since it helps to reveal patterns and relationships extracted from the collected body of studies which can be used to better inform teaching and future research (Borrego et al., 2014).

Search Procedure

The corpus of data was made up of studies published in peer-reviewed journal articles as well as peer-reviewed proceedings of two engineering education conferences. The addition of the proceeding of the American Society for Engineering Education (ASEE) and IEEE Frontier in Education (FIE) conferences to the data corpus is justified as following: (1) these conferences are the main and biggest conferences of the field of engineering education and include emergent studies in childhood engineering education, (2) both conferences have rigorous multi-stage, double-blinded peer-review processes, and (3) both provide archival publications with DOI. Four databases are used to identify journal articles: Scopus, ERIC, PsycInfo, and Education Resources. All FIE and ASEE proceedings are indexed in Scopus; hence, we conducted a separate search in only Scopus to locate the conference proceedings. In addition to the database search, we examined the references of the seminal literature reviews on pre-college engineering education research (i.e., Cox et al., 2014 & Hynes et al. 2017) to assure the inclusion of relevant papers we may have missed in database search.

Table 1 presents two examples for Boolean Phrases used for journal papers and conferences. Within the keyword field, in each database, we entered the term engineering with a combination of words representing the focused age level. We limited our search to papers published in English (or those available in English translation), between January 2000 to December 2020.

Table 1**.** Boolean Phrase used to Search Journal Articles and Conference Proceedings

Paper type	Databases	Boolean phrase used to search
Journal articles	Scopus, ERIC, PsycInfo, and Education Resources.	Engineering AND ("elementary school" or "primary school" or child* or 0-5 or kindergarten or "Elementary student*" OR "Fifth Grade*" OR "Fourth grade*" OR "Third grade*" OR "Second Grade*" OR "first grade*)
Conference proceedings	Scopus	(TITLE-ABS-KEY ("Elementary school" OR "primary school" OR k-5 OR child* OR kindergarten "Elementary student*" OR "Fifth Grade*" OR "Fourth grade*" OR "Third grade*" OR "Second Grade*" OR "first grade*") AND CONF (asee OR "American Society of Engineering Education" OR fie OR frontiers in education))

Inclusion and Exclusion Criteria

Six criteria are used when making inclusion and exclusion decisions based on our research questions and focus. First, to be included in the systematic review, journal articles and conference papers must be peer-reviewed. We included this criterion to ensure the quality of the papers examined. Yet, we recognize and acknowledge the peer-review process is not bias-free. Second, the study must focus on elementary aged children (5-10 years old). Third, the studies must report on hands-on engineering design either exclusively or in integration of engineering with other subjects. Studies that engaged children in other engineering activities such as coding and programming were not included. However, studies in which programming and coding were integrated in engineering design were included. Fourth, the studies focused on students/children and those that focused on educators were excluded. Fifth, all the studies were empirical, meaning that they measured or explored student learning and knowledge building. Sixth, we excluded studies that evaluated programs in terms of students' participation and interest in the program, as well as studies that focused on personal aspects such as self-confidence, identity, and interest.

Screening Process

Screening happened in two rounds, by applying the inclusion criteria first to titles and abstracts, and then to the full text. In total, the initial search, after removing duplications (n=250), resulted in 2519 journal articles and 682 conference papers for screening. In the first round, 2417 journal articles and 618 conference papers did not meet the inclusion criteria and were excluded. The remaining 102 journal articles and 64 conferences underwent full-text screening. Finally, this systematic review process resulted in 78 peer-reviewed publications (40 journal articles and 38 conference proceedings) that were examined in detail.

Data Analysis

After reading each paper carefully, we noted the knowledge and/or skills the studies focused on and/or discussed in their results. Using inductive thematic analysis, we synthesized the knowledge and skills, and organized them into five overarching categories. For example, a study that captured and discussed children's problem scoping behaviors was categorized as problem scoping. The study was later labeled as "engineering design practices" and was grouped with other studies that had similar focus. We then further extracted information about the skills and knowledge with details, the age group and the assessment and evaluation approach that was used in the paper. Tables 2 through 6 present summaries of findings, for each category, while Table 7 summarizes findings on the assessment/evaluation approaches.

Results

The Knowledge and Skills Gained when Elementary Students Engaged in Engineering Design

In this systematic literature review, we examined a total of 78 papers. The thematic analysis of these papers resulted in five categories of skills and knowledge that were targeted by engineering design practiced by elementary-aged children: (1) content knowledge, (2) engineering design practices, (3) engineering thinking, (4) professional skills and (5) STEM career understanding. As shown in Figure 1, content knowledge included four STEM subjects as well as literacy. The studies used different approaches to measure children's learning or present their practices during engineering design experiences, including different qualitative approaches, pre- and post-assessments, and only post-tests. Below, we present the skill and knowledge categories by sharing the studies and describe the evaluation approaches used in the studies. One important note is that some papers focused and measured several variables which fall into multiple categories. Therefore, the sum of the papers does not add up to the number papers included in this review.

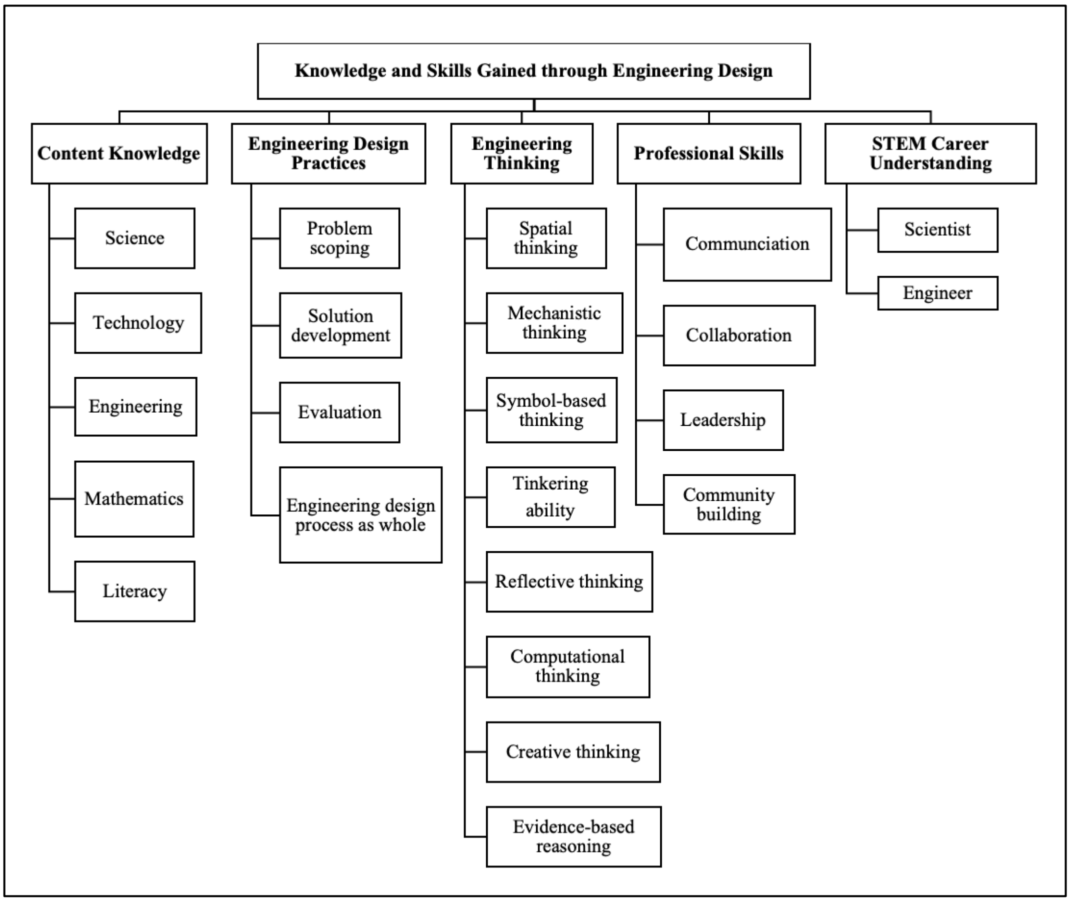

Figure 1. Themes of the Thematic Analysis

Content Knowledge

Of the studies explored, 42 empirical studies integrated engineering design process to engage students in content specific learning to develop their core disciplinary understanding across STEM disciplines as well as in literacy. These studies argue that by practicing engineering design, students gained content knowledge in STEM subjects and literacy and applied their understanding of this disciplinary content knowledge into their design projects. Some of the papers focused on multiple outcomes and are included in multiple categories. Therefore, the sum of the number of the papers across all the categories does not add up to the number of papers included in this review.

Science

Twenty-one papers centered on science content knowledge. Eight papers brought evidence of students' engagement in learning science during design activities. Most of the studies argued that through design, students gained knowledge of different science concepts and domains (Cunnigham et al., 2020; Dailey et al., 2018; Dankenbring & Capobianco, 2016; Levy, 2013; Li et al., 2020; Macalalag et al., 2010; Parekh & Gee, 2018; Pantoya & Aguirre-Munoz, 2017; Strawhacker et al., 2020; Wendell & Lee, 2010; Wendell & Roger, 2013). For example, Wendell and Roger's (2013) study showed significant increase in children's knowledge of sound, simple machine, animals, and material properties. Some studies focused on specific concepts students learned in the science domains such as earth science concepts, such as, solar trackers and water filtrations (Capobianco et al., 2016; Cunningham & Lachapelle, 2007; Dankenbring & Capobianco, 2016; Moore et al., 2014; Suescun-Florez et al., 2013;), physical rules (Levy, 2013; Shrestha et al., 2008) or energy, force and weight (Foster et al., 2013; Karahan et al. 2019) concepts by designing musical instruments with LEGO materials (Wendell et al., 2010) and some studies discussed the science content knowledge more broadly (Dailey et al., 2018, Cunningham et al., 2020). Additionally, one study (English & King, 2015) stated that students applied their existing scientific knowledge and understanding in their design. Another focused on using science concepts to apply design throughout scientific argumentation (Rynearson et al., 2017). Dankernbring and Capobianco (2016), used designed based task in two fifth-grade classrooms to examine students' conceptions of sun-Earth relationships. Capobianco and colleagues (2016) conducted their study in two classrooms in which one engaged in traditional science lesson and the other in design-based science task. Similarly, Suescun-Florez and colleagues (2013) taught students the basic concepts of physics and mechanics to be applied into soil mechanics activities using the engineering design process.

Pre-and post-assessments as well as qualitative approaches were used to assess children's science learning. Twelve studies used only pre-and post-assessments to measure students' conceptual understanding and learning of science. These pre-and post-tests were either multiple choice (Cunningham & Lachapelle, 2007; Dailey et al., 2018; Pantoya, & Aguirre-Munoz, 2017; Wendell et al., 2010), in open-ended written format (Cunningham et al., 2020; Levy, 2013; Wendell & Rogers, 2013;), verbal and one-on-one intervention (Strawhacker et al., 2020) and finally, assessments were used to measure students' conceptual knowledge (Macalalag, et al., 2010; Shrestha, et al., 2008; Suescun-Florez et al., 2013). Six studies (English & King, 2015; Foster et al. 2013; Moore et al., 2014; Parekh & Gee, 2018; Rynearson, et al., 2017; Wendell & Lee, 2010) used qualitative approaches such as grounded theory approaches with constant comparative strategies, case studies. In these qualitative studies, the data resources included observations while students worked on their tasks, field notes, and interviews where students responded to science questions, students design notebooks and models they worked on. Other studies used both quantitative and qualitative approaches, such as Li et al. (2020), Capobianco et al., (2016) and Dankenbring & Capobianco, 2016.

Technology

Four papers explored knowledge in technology. The papers discussed students' knowledge about technology from different conversations such as building materials and function technology performs (Marcus et al., 2017; Marcus et al., 2018; Pantoya & Aguirre-Munoz, 2017) and reflection on the integration of technology and using of technology (Li et al., 2020). Cunningham and Lachapelle's work (2007) investigated students' understandings of what technology is and compared it with students' understanding of what engineering is.

Marcus et al. (2017; 2018) used a qualitative approach and analyzed video recordings of children to capture children's understanding about technology. Li et al. (2020) used a pre- and post- written assessment track and measured students' knowledge and reflection of using and integrating technology. The assessment included single choice questions and scenario-based questions. Finally, Cunningham and Lachapelle's (2007) used pre- and post-assessments that consisted of a set of multiple-choice, fill-in-the-blank, and choose-all-that-apply questions.

Engineering

Twenty-two studies stated that as students engaged in engineering design, they gained engineering knowledge and understanding. These studies showed evidence that students gained knowledge of robotic and programming (Cuellar et al., 2015; Fidai et al., 2019; Kahn & Bers, 2005; Sullivan & Bers, 2016) engineering principles (Pantoya & Aguirre-Munoz, 2017), structures (Brady & Guthrie, 2014), mechanical systems (Bolger et al., 2009) disciplinary knowledge (Cunningham & Lachapelle, 2007; Cunningham et al., 2020; Macalalag, et al., 2010; Marcus et al., 2017, 2018; Strawhacker et al., 2020; Tank et al., 2018), and the knowledge of engineering design process (Dailey et al., 2018; Hsu et al., 2012; Foster et al., 2013; Li et al., 2020; Moore et al., 2014; Pantoya & Aguirre-Munoz, 2017; Siverling et al., 2018; Yang et al., 2015).

Both written assessments and qualitative approaches were used to capture children's understanding and learning of engineering knowledge and practices. Sullivan and Bers (2016) used two written post assessments to measure children's robotic and programming knowledge. Li et al., (2020) used multiple choice and scenario-based pre- and post- measure and captured students' improvement in understanding of engineering process. Marcus and colleagues (2017, 2018) used video recordings of children and photographs of their designs, to measure the extent in which children used and applied engineering principle of diagonal bracing in their design. Daily et al., 2018 were given a design scenario and asked children to select an appropriate engineering design process. Pre and post text were used to examine engineering design process and modeling (Cunningham, 2007; Brady & Gutherie, 2014; Macalalag, et al., 2010; Faisal, Kapila, & Iskander, 2012; Hsu, et. al., 2012; Pantoya, & Aguirre-Munoz, 2017; Strawahacker 2020; Bolger et al., 2009) used flexible interviews. Other studies used video record data, observations, and questionnaires (Kahn and Bers, 2005; Yang et al., 2015; Cuellar et al., 2015; Moore, et. al., 2015; Kahn & Bers, 2005; Marcus et al., 2018; Silverling et al., 2018; Tank et al., 2018) and students' notebooks (Foster et al., 2013).

Mathematics

Eleven papers argued that students learned and used mathematical knowledge during engineering design. Except for Burte et al. (2017) that broadly mentioned mathematics, all other papers examined specific mathematical conceptions students used/learned which include fractions (Coxon et al., 2018), numeracy (McDonald & Howell, 2012), numbers and geometric shapes (Marcus et al., 2017; Burghardt & Christine, 2006) volume (Park et al., 2018), measurements (Karahan et al., 2019), and mathematical modeling and calculations (Li et al., 2020). English and King (2015) mentioned that in certain design processes (i.e., design solution and improving) students incorporated calculations. Faisal et al. (2012) used robotic activities, in the context of engineering design, to encourage students to apply unit conversion concepts to learn in previous mathematics' classes. Finally, one paper focused on helping students to problem-solving math problem related to engineering activities (Tillman, 2013).

Five studies used pre- and post-assessments (Burghardt, & Christine, 2006; Burte et al., 2017; Coxon et al., 2018; Faisal et al., 2012; Li et la., 2020) and one used post-assessment to measure children's mathematics learning (McDonald & Howell, 2011). Another study used survey at the end of the math unit (Tillman, 2013). Four studies used qualitative approaches to capture children's learning and/or using of mathematics concepts and skills (English & King, 2015; Karahan et al. 2019; Marcus et al., 2017; Park et al., 2016). English and King (2015) conducted a rigorous qualitative coding (adopted aspects of the grounded theory), reviewed children's sketches, and observed what mathematical concepts children applied in their design. Marcus et al. (2017) and Karahan et al. (2020) analyzed video recordings and interviews of families and found conversations on mathematics concepts during building. Park et al. (2016) used different sources of data (interviews, photocopies of their design, and fieldnotes) to capture children's understanding and applying of a mathematic concept during the design activity.

Literacy

Four papers stated that students developed literacy knowledge during their engineering design experiences. Students used spatial language including spatial dimensions, features, and properties (Gentner et al., 2016) and specialized vocabulary associated with construction, color, prepositions, and placement (McDonald & Howell, 2012) during the design process. Studies also discussed children's use of engineering vocabulary in the design process (McDonald & Howell, 2012; Cardella et al., 2013), and Strawhacker and Bers, (2018) stated that students engaged in creating content during the design activity.

All studies used qualitative approaches to measure and capture the use of language arts (McDonald & Howell, 2012; Gentner et al., 2016; Strawhacker & Bers, 2018; Cardella et al., 2013). For example, Cardella et al., (2013) used video-and audio-recordings of child-adult interactions during an engineering design task to review the engineering-related terminology used by children.

Table 2. Content Knowledge in STEM and Literacy

Authors	**Type**	**Age / Grade**	**Content Knowledge**				
			Science	**Technology**	**Engineering**	**Math**	**Literacy**
Bolger et al., 2009	Conference Proceeding	2nd & 5th grades			☑		
Brady & Gutherie, 2014	Conference Proceeding	4th & 6th grades			☑		
Burte et al., 2017	Journal article	1st to 5th grades				☑	
Burghardt & Christine, 2006	Conference Proceeding	5th grade				☑	
Capobianco, et al., 2016	Conference Proceeding	5th & 6th grades	☑				
Cardella et al., 2013	Conference Proceeding	Pre-school program					☑

Coxon et al., 2018	Journal Article	4^{th} & 5^{th} grades				☑	
Cuellar et al., 2015	Conference Proceeding	5^{th} & 4^{th} grade			☑		
Cunningham, & Lachapelle, 2007	Conference Proceeding	2^{nd} to 6^{th} grades	☑	☑	☑		
Cunningham et al., 2020	Journal article	Elementary grades	☑		☑		
Dailey et al., 2018	Journal article	3^{rd} to 5^{th} grades	☑		☑		
Dankenbring & Capobianco, 2016	Journal article	5^{th} grade	☑				
English & King, 2015	Journal article	4^{th} grade	☑			☑	
Fidai et al., 2019	Conference Proceeding	4^{th} grade			☑		
Faisal, et al., 2012	Conference Proceeding	4^{th} grade				☑	
Gentner et al., 2016	Journal Article	6-to 8-year-olds					☑
Foster et al., 2013	Conference Proceeding	4^{th} grade	☑		☑		
Hsu et al., 2012	Conference Proceeding	Elementary grades			☑		
Karahan et al., 2019	Journal Article	4^{th} grade	☑			☑	
Kahn & Bers, 2005	Conference Proceeding	5-to 7-year-olds			☑		
Levy, 2013	Journal Article	5-to 6-year-olds	☑				
Li et al., 2020	Journal Article	5^{th}-6^{th} grades	☑	☑	☑	☑	
Park et al., 2018	Journal Article	6-to 7-year-olds				☑	
Pantoya & Aguirre-Munoz, 2017	Conference Proceeding	Kindergarten to 2^{nd} grade	☑	☑	☑		
Parekh & Gee, 2018	Journal Article	4-to 12-year-olds	☑				

Macalalag, et al., 2010	Conference Proceeding	3^{rd} to 5^{th} grade	☑		☑		
Marcus et al., 2017	Journal Article	5- to 7-year-olds		☑	☑	☑	
Marcus et al., 2018	Journal Article	8-year-olds			☑		
McDonald & Howell, 2012	Journal Article	5-to 7-year-olds				☑	☑
Moore, et al., 2014	Conference Proceeding	5^{th} grade	☑		☑		
Rynearson et al., 2017	Conference Proceeding	Kindergarten	☑				
Shrestha et al., 2008	Conference Proceeding	4 to 6 grades	☑				
Strawhacker & Bers, 2018	Journal Article	Kindergarten					☑
Strawhacker et al., 2020	Journal Article	4-to 7-years old	☑		☑		
Suescun-Florez, et al, 2013	Conference Proceeding	2^{nd}, $3^{rd,}$ & 4^{th} grades	☑				
Sullivan & Bers, 2016	Journal Article	Prekindergarten, Kindergarten, 1^{st} & 2^{nd}			☑		
Siverling, et al, 2018	Conference Proceeding	5^{th} grade			☑		
Tank et al., 2018	Journal Article	Kindergarten			☑		
Tillman, 2013	Conference Proceeding	Elementary				☑	
Wendell & Lee, 2010	Journal Article	3^{rd} grade	☑				
Wendell, et al, 2010	Conference Proceeding	3^{rd} and 4^{th} grade	☑				
Wendell & Rogers, 2013	Journal Article	3^{rd} and 4^{th} grade	☑				
Yang et al., 2015	Conference Proceeding	4^{th} grade			☑		
Total	**43 papers**		**21**	**4**	**22**	**11**	**4**

Engineering Design Practices

A total of 28 papers reported on students' engagement in engineering design practices. We observed a clear inconsistency in ways the engineering design practices were named and/or defined across all papers. Thus, to organize the papers, we divided engineering design process to three distinct practices of problem scoping, solution development and evaluation. As seen in Table 3, papers are organized based on their focus on engineering design as a whole process or on single practices of the engineering design. Problem scoping includes problem definition and information gathering. Solution development includes idea generation and representation. Evaluation includes testing, troubleshooting, revising, redesigning. Moreover, it is important to note that the engineering learning in Content Knowledge Category is different than the second category, "Engineering Design Practice". We categorized papers as engineering content knowledge and understanding where engineering design engagement resulted in children learning of engineering knowledge and principles, and their knowledge of the practices that engineers engage in and engineering as a discipline. Whereas the papers that are categorized in engineering design practices provided evidence of children's ability in engaging in engineering design practices.

Fifteen papers focused on single/multiple practices of engineering design, including problem scoping (Cherniak et al., 2019; Chiang et al., 2020; Ehsan & Cardella, 2019, 2020; Park et al., 2018; Watkins et al., 2014), solution development (Chiang et al., 2020; Karahan et al., 2019; Wendell et al., 2017) and evaluation (Andrew, 2016; Ehsan et al., 2018; Karahan et al., 2019; Lottero-Perdue 2017; Lottero-Perdue & Tomayko, 2020; Wendell et al., 2017). The practice of problem scoping was named and defined differently across the papers. For example, Watkins et al. (2014) and Ehsan and Cardella (2020) presented detailed evidence of children's engagement in problem scoping where they named the criteria, balanced between criteria, and reflected on their decisions. Park et al. (2018) reported on students' engagement in problem definition by defining the problem and considering the criteria of success. Cherniak et al. (2019) discussed children's experiences in problem identification and material inspiration during design. Children's engagement in troubleshooting and identifying the problematic area and learning from failure was discussed by Ehsan et al. (2018), Lottero-Perdue (2017), Lottero-Perdue and Tomayko (2020), and Andrews (2016).

Seventeen papers focused on the entire engineering design process and multiple practices (Batrouny et al., 2020; Cardella et al., 2013; Dorie et al., 2014; Ehsan et al., 2020; English & King, 2015, 2017; Francis et al., 2017; Glancy et al., 2015; Kendall, 2015; Moore et al., 2014; Kelly et al., 2015; Tank et al. 2018; Wang et al., 2013). English and King (2015) observed that students completed rounds of design and redesign. In each round, they observed evidence of students engaging in engineering design process including problem scoping, idea generation, design and construct, and design evaluation. Engagement in design solution was very evident in students' sketches and drawings. When problem scoping, they added context by considering constraint and criteria of the problem. Kelly et al (2014) observed that students engaged in the design process including defining the design problem, identifying constraints and criteria, generating design ideas, brainstorming, and analysis. Tank et al. (2018) provided evidence that children practiced all aspects of engineering design process including define, learn, plan, try, test, and decide. The educators in Francis et al (2017) observed many instances of children's aspects of design thinking including test, assess, debugging, troubleshooting, revising, and retesting. Similarly, Ehsan and colleagues (2020) observed evidence of children's engaging in problem scoping, idea generation, idea representation, design evaluation and revisions.

Karahan et al. (2019) focused on the engineering design process as a whole. However, they shared evidence of children's engagement in only aspects of engineering design that could be categorized as solution development and evaluation. They discussed ways children engaged in design decision making, sketching, developing material, learning from errors, determining best solution, and doing trial and error.

Four studies aimed to examine certain skills that children used during different aspects of engineering design process, while also provided evidence of children's engagement in engineering design practices. McCormick and Hammer (2016) focused on children's abilities to reason about the problem which they provided evidence of inferring design criteria and constraints, making informed assumptions and estimates, co-constructing scaled representations, and defining evaluation criteria. Wendell et al. (2017) examined children's reflective decision-making during multiple aspects of planning and redesigning phases of design. Tõugu et al., (2017) reported on children's engagement in defining a problem, considering different solutions, testing hypothesis, and generalizing across examples, while they referred to their abilities as STEM-related problem-solving skill. One paper explored how students share understanding of their designed artifact (Batrouny et al., 2020).

Table 3. Engineering Design Practices

			Engineering Design Practices			
Authors	**Type**	**Age/grade**	**Engineering Design Process as a Whole**	**Problem Scoping**	**Solution Development**	**Evaluation**
Andrew, 2016	Conference Proceeding	4th to 6th grades				☑
Batrouny et al., 2020	Conference Proceeding		☑			
Cardella et al., 2013	Conference Proceeding	4-to 6-year-olds	☑			
Cherniak et al., 2019	Journal Article	7-year-olds		☑		
Chiang et al., 2020	Journal Article	2nd, 4th & 6th grades		☑	☑	
Dorie et al., 2014	Conference Proceeding	4- to 11-year-olds	☑			
Ehsan et al., 2018	Conference Proceeding	8-11 years old				☑
Ehsan &	Conference	8 to 10 years		☑		

Cardella, 2019	Proceeding	old				
Ehsan & Cardella, 2020	Journal Article	9-year-old		☑		
Ehsan et al., 2020	Journal Article	5-to-7-year-old	☑			
English & King, 2015	Journal Article	4th grade	☑			
English & King, 2017	Journal Article	4th grade	☑			
Francis et al., 2017	Journal Article	9-to 10-year-olds	☑			
Glancy, et al, 2015	Conference Proceeding	5th grade	☑			
Karahan, et al., 2019	Journal Article	4th grade	☑		☑	☑
Kelley et al., 2015	Journal Article	5th & 6th grades	☑			
Kendall, 2015	Conference Proceeding	Kindergarten & 3rd grade	☑			
Lottero-Perdue, 2017	Conference Proceeding	Elementary				☑
Lottero-Perdue & Tomayko, 2020	Conference Proceeding	Kindergarten				☑
McCormick & Hammer, 2016	Journal Article	4th grade	☑			
Moore et al., 2014	Conference Proceeding	5th grade	☑			
Park et al., 2018	Journal Article	1st grade		☑		
Siverling et al., 2018	Conference Proceeding	5th grade	☑			
Tank et al., 2018	Journal Article	Kindergarten	☑			
Tõugu et al., 2017	Journal Article	4- to 9-year-olds	☑			

Wang et al., 2013	Journal Article	7- to 11-year-olds	☑			
Watkins et al., 2014	Journal Article	4^{th} grade		☑		
Wendell et al., 2017	Journal Article	2^{nd}, 3^{rd}, $4^{th,}$ & 5^{th} grades			☑	☑
Total	**28 papers**		**17**	**6**	**3**	**6**

All 28 studies used one or multiple qualitative approaches to capture children's engagement in engineering design practices. In all of these studies, researchers evaluated children's engagement by analyzing different qualitative data sources. The most common approach was analyzing children's interactions and discourse using live observations, field notes and/or via video-audio recordings (Andrew, 2016; Cardella et al., 2013; Cherniak et al., 2019; Ehsan & Cardella, 2020; Ehsan et al., 2018, 2019, 2020; English & King, 2015; Dorie et al., 2014; Francis et al., 2017, Glancy et al., 2015; Karahan et al., 2019; McCormick & Hammer 2016; Moore et al., 2014; Park et al., 2018; Siverling et al., 2018; Tank et al., 2018; Watkins et al., 2014; Wang et al, 2013; Wendell et al., 2017;). Studies also used interviews and think-aloud protocols (Cherniak et al., 2019; Kelley et al., 2015; Kendall, 2015; Park et al., 2018; Wang et al., 2013), and evaluating their journals, artifacts, and sketches (Kelley et al., 2015; Moore et al., 2014; Park et al., 2018; Tõugu et al., 2017). Three studies used pre-and post-test instrument to capture children's understanding of engineering design process and modeling (Foster et al., 2013; Hsu et al., 2012; Macalalag et al., 2010). Except for Francis et al. (2017), all other studies provided thick description or excerpts as their evidence. Francis et al. (2017) asked professionals to analyze the video of children engaging in design, and professional responses were provided as evidence for children's design engagement. Lottero-Perdue & Tomayko, (2017) used both survey and video recorded instruments to explore students' reflections and ethnography (Lottero-Perdu & Tomayko, 2020) for engineering design failures.

Engineering Thinking Skills

Table 4 presents papers that examined students' engagement in different ways of thinking. These various forms of thinking included, Mechanistic Reasoning (MR), Visual Spatial Thinking (VST), Symbol-based Thinking (SBT), Creative Thinking (CritT), Tinkering Ability (TAb), Reflecting Thinking (RT), Computational Thinking/Coding/Algorithmic Thinking (CompT/Cd/AT), and Evidence Based Reasoning (EBR).

A total of 23 papers reported that students engaged in different ways of thinking, including spatial thinking (Burte et al, 2017; Francis et al., 2017; Smith, 2018; Taylor & Hutton, 2013), mechanistic reasoning examined by Bolger and colleagues (2009, 2012), symbol-based thinking (Francis et al., 2017) Tinkering (Pagano et al., 2019), cognitive patterns (Sung, & Kelley, 2017) and decision-making and reflective thinking (Batrouny et al., 2019; Johnston et al., 2019; Pagano et al., 2019; Wendell et al., 2014; Wendell et al., 2015, 2017). Computational thinking and algorithmic thinking, and Coding were also observed occurring as a result of engaging in engineering design in four studies (Ehsan & Cardella, 2017; Ehsan et al., 2020: Rehmat et al., 2020; Francis et al., 2017; Fidai et al., 2019). Moreover, creative thinking was mentioned happening by students in three studies (Karahan et al., 2019; Strawhacker & Bers, 2018; Nemiro et al., 2015). Children’s decision-making ability was observed happening during engineering design activities by Mathis et al. (2016), Siverling et al. (2018), and McCormic and Hammer (2016).

Different thinking skills were assessed or captured using various approaches. In two studies, spatial thinking skill was assessed using pre-and post-spatial assessments (Burte et al., 2017; Taylor & Hutton, 2013) and captured through video analysis (Francis et al., 2017; Smith, 2018). Pre and posttest were also used to examine algorithmic thinking (Fidai et al., 2019). Flexible interview was used during the design activity to examine children mechanistic reasoning (Bolger et al., 2009, 2012). Observational approaches, such as checklist instrument, reviewing fieldnotes and journals, were used to examined and captured creativity (Nemiro et al., 2015; Strawhacker & Bers, 2018; Karahan et al., 2019).

Reflective decision making was assessed through analyzing videos (Johnston, 2019; Pagano et al., 2019; Wendell et al., 2017), field notes, transcribed classroom conversations, design notebooks (Wendell et al., 2014, 2015). Videos of children’s interactions and discourse were also used to capture symbol-based thinking (Francis et al., 2017), computational thinking (Ehsan & Cardella, 2017; Ehsan et al., 2020), reasoning (Mathis et al., 2016; McCormick & Hammer, 2016; Siverling et al., 2018,), team share understandings of a design problem (Batrouny et al., 2019) and tinkering (Pagano et al., 2019).

Table 4. Engineering Thinking Skills

Authors	**Type**	**Age/ Grade**	**Engineering Thinking Skills**							
			MR	**VST**	**SBT**	**CritT**	**TAb**	**RT**	**CompT/ Cd/AT**	**EBR**
Batrouny et al., 2019	Conference Proceeding							☑		
Bolger et al., 2012	Journal Article	2nd & 5th grades	☑							
Bolger, et al, 2009	Conference Proceeding	2nd & 5th grades	☑							
Burte et al., 2017	Journal Article	3rd, 4th, 5th, & 6th		☑						
Ehsan & Cardella, 2017	Conference Proceeding	Kindergarten & 2nd grade							☑	
Ehsan, et al, 2020	Journal Article	Kindergarten & 2nd grades							☑	
Karahan et al., 2019	Journal Article	4th grade				☑				

Authors	**Type**	**Age/ Grade**	**Engineering Thinking Skills**							
			MR	**VST**	**SBT**	**CritT**	**TAb**	**RT**	**CompT/ Cd/AT**	**EBR**
Fidai et al., 2019	Conference Proceeding	4th grade							☑	
Francis et al., 2017	Journal Article	9-to 10-year-olds		☑	☑				☑	
Johnston, et. al, 2019	Conference Proceeding	1st grade						☑		
Mathis, et al, 2016	Conference Proceeding	7th grade								☑
McCormick & Hammer, 2016	Journal Article	4th grade								☑
Nemiro et al., 2017	Journal Article	4th, 5th & 6th grade				☑				
Rehmat et al., 2020	Journal Article	Kindergarten, 1st, & 2nd grades							☑	
Pagano et al., 2019	Journal Article	6- to -11-year-olds					☑	☑		
Siverling et al., 2018	Conference Proceeding									☑
Smith, 2018	Journal Article	6- to -12-year-old		☑						
Strawhacker & Bers, 2018	Journal Article	Kindergarten				☑				
Sung & Kelley, 2017	Conference Proceeding	4th grade					☑			
Taylor & Hutton, 2013	Journal Article	3rd, 4th, 5th, & 6th grades		☑						
Wendell, et al, 2014	Conference Proceeding	4th grade						☑		
Wendell, et al, 2015	Conference Proceeding	2nd, 3rd ,4th & 5th grades						☑		
Wendell et al., 2017	Journal Article	2nd, 3rd, 4th & 5th grades						☑		
Total	**23**		**2**	**4**	**1**	**3**	**1**	**6**	**4**	**3**

Professional Skills

Nine papers focused on professional skills as an outcome of students' practicing engineering design (See Table 5). Communication was identified as a learning objective in six studies (Francis et al., 2017; Karahran et al., 2019; Streawhacker & Bers, 2018; Svarovsky et al., 2018; Rahman et al. 2019; Wang et al., 2013). Other observed skills included collaboration and teamwork (Batrouny et al., 2020; Cherniak et al., 2019; Francis et al., 2017; Jordan, 2014; Karahan et al., 2019; Rahman, et al., 2019; Streawhacker & Bers, 2018), leading, directing, agency (Karahan et al., 2019; Svarovsky et al., 2018;), and community building (Streawhacker & Bers, 2018).

All nine papers which reported children's engagement in professional skills used qualitative data and in particular video data (Cherniak et al., 2019; Karahan et al., 2019; Francis et al., 2017; Svarovsky et al., 2018; Strawhacker & Bers, 2018). In Svarovsky et al. (2018)'s study, children's agency and leading abilities were demonstrated by examining their conversation. They conducted content analysis on videos of children's engagement in engineering activities and presented thick excerpts as evidence in their paper. Similarly, Francis et al. (2017) conducted video analysis and presented examples from the video where children communicated and collaborated during engineering design activity. Strawhacker and Bers (2018) used observational instrument checklist and collected data from participants in classrooms. They also collected video data as a backup source. They provided children's average number of engagements in communication, collaboration, and community building, as well as, provided descriptions of context this engagement occurred in. Wang et al. (2013) further quantified their findings which emerged form video data analysis and conducted quantitative analysis. Wang et al. (2013), quantitatively showed that communication about engineering design practice.

Table 5. Professional Skills

Authors	Type	Age/grade	Professional Skills			
			Communication	Collaboration, teamwork	Community Building	Leadership
Batrouny et. al., 2020	Conference Proceeding	4th grade		☑		
Cherniak et al., 2019	Journal Article	7-year-olds		☑		
Francis et al., 2017	Journal Article		☑	☑		
Karahan, et al., 2019	Journal Article					☑
Jordan, 2014	Conference Proceeding	5th grade		☑		
Rahman et al. 2019	Conference Proceeding	Elementary		☑		

Strawhacker & Bers, 2018	Journal Article	Kindergarten	☑	☑	☑	
Svarovsky et al., 2018	Journal Article	4- to -11-year-olds				☑
Wang et al., 2013	Journal Article	7- to 11-year-olds	☑			
Total	**9 papers**		**3**	**5**	**1**	**2**

STEM Career Understanding

Three studies showed that through engineering design activities children showed an understanding of what scientists and engineers do as a profession (See Table 6). Through a robotic activity, children in Coxon et al. (2018) study demonstrated understanding of the career of scientists. Dailey et al. (2018) and Tank et al. (2018) showed that students built an understanding of engineering and engineers as they engaged in integrated STEM curriculums. In Tank et al.'s study (2018), children showed evidence of seeing some similarities between what they did and what scientists do.

Among the three studies that focused on children's STEM career understanding, two used pre-and post-assessments including Draw-a-Scientist (Coxon et al., 2018) and What is Engineering (Dailey et al., 2018). Tank et al. (2018), on the other hand, used a naturalistic inquiry approach and examined children's talk and captured their understanding of what engineers and/or scientists do.

Table 6**.** Understanding of Careers of Scientists and Engineers

Authors	**Type**	**Age/grade**	**Gained understanding of STEM Careers**	
			Scientist	**Engineer**
Coxon et al., 2018	Journal Article	4^{th}-5^{th} grades	☑	
Dailey et al., 2018	Journal Article	3^{rd}, 4^{th}, 5^{th} grades		☑
Tank et al., 2018	Journal Article	Kindergarten, $1^{st,}$ and 2^{nd} grades		☑
Total	**3 papers**		**1**	**2**

Summary of Evaluation Approaches

The body of literature on engineering design in elementary education examined a variety of knowledge of skills engineering education aims to develop. Overall, most studies used qualitative methods as shown in Table 7.

However, as described in previous sections, when the learning outcomes in content areas are examined quantitative methods were more common.

Table 7. Assessment and Evaluation Approaches

Categories		**Qualitative Approaches**	**Quantitative Approaches**	**Mix-Methods**
Content knowledge	Science	6	13	3
	Technology	2	2	
	Engineering	6	16	
	Mathematics	4	7	
	Literacy	4		
	Total	22	38	3
Engineering practices		27		
Engineering thinking		18	2	
Professional skills		9		
STEM career understanding		1	2	
Total		**77**	**42**	**3**

Discussion

This systematized literature review, identified, summarized, and synthesized existing literature regarding student learning and engagement when elementary students engaged in engineering design projects and activities. The body of literature argues, with research evidence, that by engaging in engineering design projects elementary-aged children develop:

(1) disciplinary content knowledge in science, technology, engineering, mathematics, and literacy,
(2) understanding of and abilities in the engineering design process,
(3) engineering thinking skills such as spatial reasoning and decision-making,
(4) professional skills such as communication and leadership, and
(5) understanding of STEM careers and the work of scientists and engineers.

Purzer and Quintana-Cifuentes (2019) describe the underlying reasons of this abundance of learning outcomes as a result of three different arguments these studies emerge from: pedagogical, epistemological, and methodological.

The pedagogical arguments center on the premise of design as a pedagogy and has produced design-based learning models (Kolodner et al, 2003; Moore et al, 2014a). As evident in the findings, the use of engineering design activities as context for instruction has produced promising results (Cunnigham et al., 2020; Dailey et al., 2018; Dankenbring & Capobianco, 2016; Levy, 2013; Li et al., 2020; Macalalag et al., 2010; Parekh & Gee, 2018; Pantoya & Aguirre-Munoz, 2017; Strawhacker et al., 2020; Wendell & Lee, 2010; Wendell & Roger, 2013). The findings demonstrate that researchers intentionally used engineering design for students to learn disciplinary core ideas (e.g., science, math, language arts). These studies argued that students content knowledge across the various disciplines improved as a result of their engagement in design-based activities (Cunnigham et al., 2020;

Strawhacker et al., 2020). The use of enginnering design allows students to be more involved in their learning, and engineering design places the student in the role of scientist/engineer. The student *is* the scientist/engineer. Metz (2014) argues for the use of engineering design based on its ability to foster learning at a deeper level, increasing scientific literacy and empowering portions of the population that are historically underrepresented in science and engineering fields. The integration of enginneirng design also supports students application and understanding of disciplinary content knowledge into their design projects. Through engaging in the design process, which involves asking questions, making observations, and collecting evidence similar to the scientific inquiry, students gained knowledge of various domains (Cunnigham et al., 2020; Dailey et al., 2018; Dankenbring & Capobianco, 2016; Levy, 2013; Li et al., 2020).

Moreover, engineering design can serve as conceptual framework for various content areas, such as math and science and can easily intertwined into engineering design activities (Strawhacker et al., 2020). The enginering design process offers a structure that supports devlopement of skills encouraged in the Next Genneration Science Standards (National Academies Press. NGSS Lead States, 2013), such as problem solving, utilizing reasoning and evidence, modeling, and use of communication. The intellectual richness that engineering offers with engineering design-based activities support disciplinary learning (Wendell & Rogers, 2013). While engagement in the engineering design helps to make abstract science ideas more concrete. As Purzer and Quintana-Cifuentes (2019), stated, “Engineering is the application of science” (p. 4). Thus, the pedagogical approach fosters deeper understanding of disciplinary core ideas in science, which is likely a reflection of the use of engineering design as pedagogy.

The epistemological arguments that inform education are based on engineering philosophy as well as design research and practices. In many of the studies we reviewed, researchers provided children with opportunities to practice engineering and engage in engineering design practices. The engineering ways of being and thinking as well as the interdisciplinary nature of engineering were highlighted as students scope design problems, generate ideas, and analyze and troubleshoot (Brophy et al., 2008). The learning outcomes associated with the engineering design process, engineering thinking, and awareness of the work of scientists and engineers also reflect an epistemological outlook. This supports the idea that engineering is interdisciplinary and “requires literacies in a range of disciplines” (Purzer & Quintana-Cifuentes, 2019, p. 5). For instance, some of the studies presented in the epistemological framing, discussed opportunities where students engaged in engineering design that aligns with the ways knowledge is constructed and evaluated in a given discipline. Karahan et al. (2019), shared evidence of children’s engagement in only aspects of engineering design that could be categorized as solution development and evaluation. They discussed ways children engaged in design decision making, sketching, developing material, learning from errors, determining best solution, and doing trial and error. McCormick and Hammer (2016) focused on children’s abilities to reason about the problem and provided evidence of which they provided evidence of inferring design criteria and constraint. Tõugu et al., (2017) reported on children’s engagement in defining a problem, considering different solutions, testing hypothesis, and generalizing across examples, while they referred to their abilities as STEM-related problem-solving skill.

The learning and engagement presented in these studies demostrated the *doing of engineering* to help students understand that their role is to actively construct knowledge through a process of sense making (Schellinger et al., 2021). In this way, students engaged in the "*doing of engineering"* to find workable solutions to problems that fit within the scope of constraints imposed on the particular context (Schellinger et al., 2021). Moreover, this engagement motivated students' need to understand how underlying disciplinary concepts influence engineering solutions (Brophy et al., 2008).

Finally, Purzer and Quintana (2019) present the methodological arguments with a focus on building 21st century skills such as creativity and critical thinking. The methodological argument supports the notion that "students need to develop abilities to solve problems, and engineering design provides strategies to do so" (Purzer & Quintana, 2019). Our findings related to the development of professional skills align with claims that engaging in engineering design can improve students' communication, critical thinking, creativity, and problem-solving skills (Stohlmann et al., 2012). For instance, Svarovsky et al. (2018)'s study, the authors examined moments of agency for children during an engineering design activity. They found that a connection between the ways that parents engage with their children during engineering design activities and the ways that children exhibit elements of persistence through demonstrating agency in STEM activities. In Strawhacker and Bers's (2018) study provided the average number of times children engaged communication, collaboration, and community building, as well as, provided descriptions of context this engagement occurred in. Whereas Wang et al. (2013), showed that communication about design ideas and decisions was correlated with children's engagement in engineering design practices.

Across these studies, it is important to note that despite variations in the adult's motivations, in all arguments children are presented with opportunities to engage in authentic design experiences (Foster et al., 2013, Wendell et al., 2010). While the knowledge and skills we identified here are promising outcomes of engineering design engagement, we believe the types of engineering design activities need to be further explored to be able to associate the outcomes to the different arguments presented in the studies that document the methodological approach. This exploration can better guide the engineering education community as they continue to engage young students in engineering design in various learning settings.

The synthesis of the studies revealed that researchers employed a broad range of tools and methods to elicit, assess, and explain children's development of these knowledge and skills as they engage in engineering design. To assess students' content knowledge of a subject, studies used pre- and post- assessments, post-only assessments or different qualitative approaches. For example, Li et al., (2020) used multiple choice and scenario-based pre-post assessments to assess students' understanding of the engineering design process.

Similarly, Daily et al., (2018) provided children with a design scenario and asked them to select an appropriate engineering design process in a pre-and then a post-test. Studies that aimed to capture children's engineering design practices, engineering thinking skills, and professional skills employed a wide range of qualitative approaches. These approaches included think aloud protocols, observations, video analysis, discourse analysis and artifact analysis. Through these different approaches, researchers provided evidence of what children did, said and/or created during the engineering design activity. For example, in Francis et al (2017)'s study, researchers analyzed videos of children designing by examining children's actions and conversations and provided evidence of children's engagement in engineering design practices, engineering thinking skills and professional skills. Similarly, Wendell et al (2017) analyzed children's conversations during their design activity to examine their reflective decision-making skills during planning and redesigning phases of engineering design. Analysis of children's sketching in the assessment of children's understanding of the work of scientists and engineers. In addition, English and King (2015)'s study, examining children's sketches, provided evidence of children applying science and math in their design.

The results of this literature review also revealed opportunities for future research. The scope of this paper was elementary grades, and we did not fully zoom in at the data in regard to children diversity (e.g., age/grade level, race and ethnicity, nationality, and disability) and the learning settings (formal vs. informal). For example, among all the studies, only two focused on children with disabilities. With the increase in the need for research regarding children with disabilities and the urge to diversify engineering education, we call for more research on children with disabilities. Given the possible differences in the outcomes of research and approaches used in implementation at various settings with diverse children, we believe that future reviews should report on findings in more narrowed focused. The research gap on the issues of diversity, which Hynes and colleagues pointed out in 2017, still persists.

Additionally, many of the studies highlighted the importance of teamwork and collaboration in engineering, including learning and engagement in engineering design occurring in groups. The studies lacked to identify and discuss if through this social interaction children developed these teamwork and collaborative skills. Perhaps, further studies could explore if the social interaction as a result of the engagement in the engineering design process can develop such skills which are critical for engineering professional. An additional component of efforts related to social interaction is ethical conduct. Clark and colleagues (2020) point out this gap calling for the need for explicit integration of ethical reasoning within design education. Future research needs to address ethics in relationship to design and add ethical reasoning under the category of engineering thinking.

Conclusion

The goal of this paper was to characterize engineering design in elementary-aged children through a systematic literature review that synthesizes empirical evidence of child learning and engagement during engineering design experiences. This study is unique in its focus on elementary aged children's knowledge and skills as demonstrated by engaging in the engineering. The body of literature published between 2000 and 2020 provide empirical evidence on student learning outcomes in disciplinary content knowledge, design process skills, engineering thinking, professional skills, and career knowledge. Thus, it is important to reflect on the various ways engineering design is positioned, integrated, assessed, and implemented in K-12, since this can impact student learning. Most importantly, it is imperative to develop a shared research agenda by carefully defining the knowledge and skills we expect children to learn and detailing ways the research methods elicit and assess the acclaimed learning outcomes with an effort to produce a collection of evidence on student learning as they engage in engineering design.

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