Journal of Pre-College Engineering Education Research (J-PEER)

Volume 8 | Issue 2 Article 5

2018

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Lammi, Matthew; Denson, Cameron; and Asunda, Paul (2018) "Search and Review of the Literature on Engineering Design Challenges in Secondary School Settings," *Journal of Pre-College Engineering Education Research (J-PEER)*: Vol. 8: Iss. 2, Article 5.
https://doi.org/10.7771/2157-9288.1172

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Journal of Pre-College Engineering Education Research 8:2 (2018) 49–66

Search and Review of the Literature on Engineering Design Challenges in Secondary School Settings

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Abstract

Engineering design activities offer the promise of enhanced learning and teaching in pre-college science, technology, engineering, and mathematics (STEM) settings. The wide variation and lack of coherence in research and practice concerning pre-college engineering design challenges necessitates an investigation of the literature. The overarching research question guiding this search and review of literature was, "How are engineering design challenges conceptualized in pre-college environments?" A search and review coupled with iterative thematic analysis was employed to understand and conceptualize the current body of literature on pre-college engineering design challenges. It is anticipated that this review will provide a general picture of the salient features surrounding engineering design challenges, including: authenticity to the learner and to engineering practices, open-ended problems, modeling, optimization to continuously improve, and the promotion of engineering habits of mind such as balancing trade-offs and satisficing. It is also expected that the results will contribute toward ongoing discussions of the role of design challenges in STEM educational settings, future research directions, and implications for practice.

Keywords: engineering design, K–12, problem solving, technology education

Introduction

Engineering is becoming a significant constituent of pre-college learning environments across the US and is finding its way into international discussions as well (Blackley & Sheffield, 2015; King & English, 2016; Kőycű & de Vries, 2016). This change is evidenced in US K–12 education standards for both technology education and science education, educational research, classroom curricula, pedagogical practice, and education departmental name changes (Katehi, Pearson, & Feder, 2009; NGSS Lead States, 2013). In pre-college engineering curricula, engineering design is paramount (Brophy, Klein, Portsmore, & Rogers, 2008). Engineering design activities offer the promise of enhanced critical thinking, problem solving, creativity, and authentic context to problems that can integrate science, technology, engineering, and mathematics (STEM) subjects (Hynes et al., 2011; Katehi et al., 2009; NGSS Lead States, 2013; Schunn, 2011). A common strategy employed to teach the engineering design process is a problem solving activity in the form of a design challenge (Eisenkraft, 2011; Mentzer, Becker, & Sutton, 2015; Sadler, Coyle, & Schwartz, 2000).

Even though engineering holds a prominent focus in STEM education, the dearth of research on engineering design challenges in pre-college environments has resulted in pedagogical practices independent of the literature base (Carr & Strobel, 2011; Katehi et al., 2009). The wide variation and lack of coherence in pre-college engineering design necessitates an investigation of the research literature (Householder & Hailey, 2012; Hynes et al., 2011). To this end, the overarching

http://dx.doi.org/10.7771/2157-9288.1172

research question guiding this search and review of literature was, "How are engineering design challenges conceptualized in pre-college environments?" Therefore, it is anticipated that this review will provide a general picture of the salient features surrounding engineering design challenges, contribute toward ongoing discussions of their role in STEM educational settings, and provide fodder to spawn new lines of inquiry.

Methods

We employed a search and review coupled with iterative thematic analysis to conceptualize the current body of literature on pre-college engineering design challenges. A search and review is a far-reaching, comprehensive literature review that aims to broadly explain what is known, provide recommendations for practice, and delineate limitations (Grant & Booth, 2009). A search and review is similar to a systematic review in that terms and databases are searched and collected with a fixed approach. A search and review differs from a systematic review in that the search and review is more fluid, allowing literature that might not fit delimitative inclusion criteria, such as study type. In other words, literature is pursued and included even though it may not have appeared in the initial search results. A search and review can be done in many ways such as reviewing reference and citation lists, examining gray literature, hand searching targeted journals, and including authors' own databases (Fazel, Reed, Panter-Black, & Stein, 2012). Nevertheless, the search and review may lack a clearly defined process, potentially yielding an overly subjective selection process (Grant & Booth, 2009).

The search and review supported our efforts to examine primary or original scholarship on various engineering design challenges for the purpose of describing, integrating, and synthesizing the contents of this review. We believed that this approach would yield "a general overall picture of the evidence [in engineering design challenges, in order] to direct future research efforts" (Petticrew & Roberts, 2008, p. 21). Literature was gathered from numerous sources and various sampling techniques including database queries, cross-referencing citations, and hand searches. Subsequently, patterns were sought and the results were coded, synthesized, and categorically tabulated (see Figure 1).

Engineering is a transdisciplinary endeavor that reaches deep into and even beyond other STEM disciplines. Therefore, the literature search was intentionally drawn with a wide swath. This resulted in literature that might not have included the term engineering, but spoke to topics and characteristics germane to engineering design. Nonetheless, the data sources were taken primarily from journals related to engineering education (*Journal of Engineering Education, International Journal of Engineering Education, Advances in Engineering Education, Journal of Pre-college Engineering Education, International Journal of Science Education,* and the *Journal of Technology Education*), conference proceedings (the annual conferences of the International Technology and Engineering Education Association (ITEEA), the American Society for Engineering Education (ASEE), and the Frontiers in Engineering Education (FIE)), books, and online database searches using Science Direct, IEEE Explore, and the Association for Computing Machinery digital library (ACM Portal). There are numerous others journals, conference proceedings, and databases that could have been hand searched, but those selected were chosen as they specifically address the engineering design process in pre-college settings or serve as databases where these could be found. The terms used in the database searches included "engineering design challenge," "engineering design" + "engineering education" + "K–12," and "engineering design education." The initial database searches yielded 128 papers. These papers were then placed against the inclusion criteria for further examination.

The article database searches were strengthened with a review of secondary sources and gray literature—conference proceedings, reports, and working papers—including the National Research Council reports (Katehi et al., 2009; National Academy of Engineering, 2004) and literature reviews on engineering design (Brophy et al., 2008; Dym, Agogino, Eris, Frey, & Leifer, 2005). In addition to giving an overall landscape of the field, these sources were analyzed through hand searching techniques. Hand searching is the process of examining and analyzing tables of content of journals (or other sources) and their reference lists (Dyba & Dingsoyr, 2008). This technique helps overcome search-term bias. This is particularly helpful when working with transdisciplinary fields where different terms are used for similar constructs. Hand searching was used with the primary source reference lists as well.

Literature Selection Process

Literature was included if it related to research on engineering design challenges. This broad topic not only includes the engineering disciplines and their accompanying content, but also the teaching and learning of engineering design. The primary focus of this work was on engineering design and not engineering content. As a result, supporting subjects such as drawing, mathematics, and the learning sciences literature were included in the review. The findings from this literature review come from over 50 journal articles, books, and conference proceedings.

Engineering design challenges are not limited to one specific population, thus the selection of literature encompassed articles on K–12 students, post-secondary engineering students, and practicing engineers from industry. Although engineering design is found in K–12 classroom settings and has recently been included in national standards (NGSS Lead States, 2013), engineering design in pre-college is also accomplished outside the structure of formal classrooms: in summer camps, museums, design

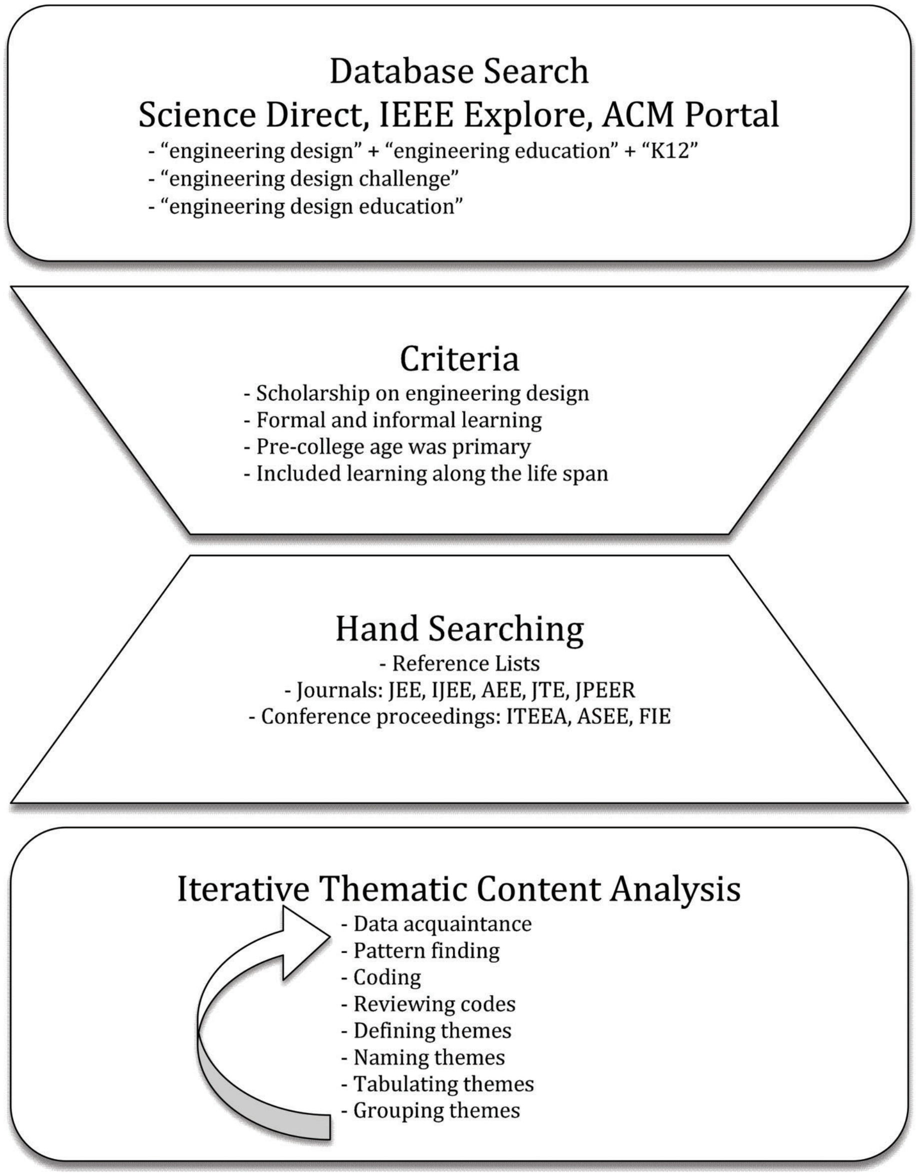

Figure 1. Search and review with thematic content analysis.

competitions, and maker spaces (Schnittka, Brandt, Jones, & Evans, 2012). Therefore, the review spanned formal and informal learning settings.

Iterative Thematic Content Mapping

Thematic analysis typically commences with immersing oneself in the data; searching for salient patterns across the data, coding the findings, reviewing the codes, and defining, naming, tabulating, and grouping themes (Clarke & Braun, 2013). This process is repeated until the researcher can make inferences based on existing literature or interpret the findings within the context of her or his own experiences (Chism, Douglas, & Hilson, 2008).

As the articles were compiled and reviewed, salient themes and patterns were discovered using content analysis (Borrego, Douglas, & Amelink, 2009). After the initial articles were chosen from the database searches, the researchers read through the articles highlighting passages, annotating findings, and hand reviewing the reference lists. The results were coded and tabulated into a spreadsheet (see Appendix). The process of tabulation was to classify and catalogue the themes. Once tabulated, the themes were analyzed and synthesized, resulting in categorical arrangements.

Although frequencies were recorded, the results, analysis, and synthesis were interpretive, aiming for latent content and a broader meaning (Borrego, Foster, & Froyd, 2014). The researchers also engaged in peer-debriefing to discuss the findings and emergent themes (Chism et al., 2008). Additionally, three individuals who have expertise in engineering design with high school students were invited to provide feedback to refine the data themes that were emerging from the synthesis. Each of these three individuals coded the literature with a pseudo-random overlapping assignment. The resulting percent agreement (71%) was not high, but satisfactory for exploratory research (Lombard, Snyder-Duch, & Campanella Bracken, 2006).

This process iteratively continued as the number of articles and themes increased. Each theme was given a column allowing for additional themes as they emerged. For example, the theme or code of *assessment* quickly became salient in many of the readings. Questions related to assessment practices in engineering design-related activities surfaced, including what should be assessed, how it should be assessed, and who should be responsible for assessment. In pursuing these questions, distinct assessment subthemes became apparent: formative and summative assessment, rubrics, documentation, reflective exercises, and modeling artifacts. The research team readily conceded that assessment in engineering design merited its own review.

As a theme was recognized in an article, an "X" was marked in the corresponding theme in the article's row (see Appendix). As a process for discovering themes emerged, the researchers recognized a need to record the specific pages where an article mentions or discusses a theme. For better analysis and more efficient bookkeeping, at least one page number was recorded when an author implied or explicitly referenced a theme. In cases where a theme was not explicitly mentioned, an "X" sufficed. Themes were not selected based solely on being discussed or mentioned by an author, but emerged from purposeful analysis of patterns across multiple sources.

Although many themes emerged, they began to conglomerate around specific categories. The naming and grouping of the themes and categories became a highly synthetic exercise requiring great reflection and deliberation. As new themes were discovered, they were placed into a new or existing category. The purpose of the categories was to help understand and communicate the study findings. Nonetheless, the act of categorizing must be taken with caution since engineering design is boundless. Hence, although a theme may be listed in one category, it does not imply that the theme is mutually exclusive from other themes and categories. This is similar to a system that may have many interconnected subsystems. For example, the theme of *modeling* is related to *applied math* and *assessment,* both of which reside in distinct categories.

In this paper the emergent themes were sorted into three categories: *attributes*, *habits of mind and practice*, and *pedagogy*. The categories were not formed a priori; they emerged and morphed throughout the analysis. The purpose of categorizing the themes was to discriminatingly encompass and summarize the findings from the data. Although not mutually exclusive, the categories further understanding toward a conceptualization of engineering design challenges in K–12 settings by addressing, not answering, the following questions: What makes a design challenge an engineering design challenge? What should students learn from these challenges? How should instruction be framed?

The thematic analysis continued until theoretical saturation was met (Glaser & Strauss, 1967). This saturation means that a continued review of the sources yielded repeated, satisfactory findings. Although there are many other articles and sources that could have been used for this review, the coding and comparison of the themes and categories became well developed, reaching a point of sufficient maturation.

Research Themes Findings

The results are not only a summary of the literature, but moreover include a diligent discovery and synthesis of the findings, which yields constructs or themes and their interrelations. These themes and constructs are detailed in the discussion at the end paper, but the authors have also taken the liberty to interweave them in the findings for greater readability.

Attributes of Engineering Design Challenges

This review identified four principal attributes of engineering design challenges: *relevance*, *open-endedness, systems perspective,* and *transdisciplinarity*. Although these attributes do not cover all aspects of engineering design challenges, they offer a varied and helpful perspective.

Relevance

The first attribute of engineering design challenges proffered is relevance. Relevance may refer to the professional perspective or context, as well as a student's perceived experience (Dinsmore, Alexander, & Loughlin, 2008). The idea of relevance is also expressed throughout the literature as real-world, realistic, or authentic.

Brophy, Klein, Portsmore, and Rogers (2008) maintain that instructors and curriculum developers should provide engineering design challenges in an authentic context. A design challenge can be more effective if it is authentic to the field of engineering. Although supporting subjects such as science and math may be taught, the primary purpose of an engineering design challenge is to afford students the opportunity to experience, develop, and learn engineering habits of mind and practice. Design challenges can be authentic to engineering and to the student. Brophy and colleagues (2008, p. 370) stated that teachers can provide "educational opportunities and resources that make learning about engineering and technology relevant to young learners. Typically, this is done through engaging, hands-on, authentic activities." Sadler, Coyle, and Schwartz (2000) concluded that students should buy into the design challenge if they are to succeed.

Authenticity or relevance is not unique to engineering design challenges. Relevance is a central component to Keller's instructional model (Keller, 1987). Design can also anchor and provide context for theories and concepts (Carlson & Sullivan, 2003), while authenticity can help motivate students to explore new learning. Open-ended challenges allow the students to discover a problem and a solution that they can own through their efforts (Hynes et al., 2011). Students will more readily find an authentic educational activity if they are allowed to "own" the problem.

Carlson and Sullivan (2003) reported that the attrition at their college of engineering was 45%, and even greater for underrepresented populations. After employing an authentic, hands-on first-year engineering design course the general retention over a five-year study increased by 19% with higher retention rates noted for women and Latino populations (27% and 54%, respectively). Schunn (2008) also found that relevant activities increased student learning in middle schools on multiple choice assessments, particularly with underrepresented populations.

All educational design activities have some element of contrivance. In other words, the design experience has a learning purpose and scheme that may conflict with authenticity. Contrivance can be manifested in competition and arbitrary benchmarks. Sadler and colleagues (2000) claimed that competition can be engaging but also can imply failure. Competitions can provide motivation, particularly when competing against oneself, natural laws, or perceived technological limitations. Sadler and colleagues (2000, p. 313) coined these competitions as "Tests Against Nature" and claimed that "students are quite often satisfied with determining how well their new design works compared to its predecessor, with the test itself the sole arbiter." Contrivance does not preclude a successful design challenge, but it should be taken into account and limited if authenticity is to be maintained.

Sadler and colleagues (2000) viewed design challenges as a means to help show the connection between engineering science and real world problems. Too often, students do not know the application of a concept or its contextualization and resort to memorizing what is needed to pass a test. Everyday activities can provide a context that extends beyond technical knowledge. Apedoe, Reynolds, Ellefson, and Schunn (2008) discussed how design relates to students' lives:

> Focusing on needs from their own lives creates a personal motivation for the design work, makes the topic relevant across ethnicity, gender, and other student micro-cultures, and makes salient how science and technology is a part of students' everyday lives. Students find many creative needs that connect clearly to their own lives. (p. 456)

Through authentic design challenges students can gain a perspective of the impact and relevance of their design solutions (McKenna & Hirsch, 2005).

Students may be encouraged to search out engineering examples and products already around them. Schulz (1991) used everyday items such as blow dryers and curling irons to increase student interest in electrical engineering. Carlson and Sullivan (1999) have used assistive technologies, art exhibits, and green designs to appeal to students. Service learning is another activity that facilitates authenticity.

Service-based engineering design challenges provide a broad learning context for students. The benefits of service-based challenges are multi-dimensional. Students engage philanthropically, learn 21st century skills, are provided an authentic context, and take part in systems design (Coyle, Jamieson, & Oakes, 2005). Furthermore, the students are afforded the opportunity to engage in selfless endeavors. For example, Carlson and Sullivan (2003, p. 3) stated, "The satisfaction a recent team gained by building a complete cosmetic prosthetic arm for an Afghan refugee child could not come from a textbook." Service learning can be successfully effected through many venues including playground design or the development of an environmental monitoring system for a museum (Coyle et al., 2005; Dally & Zhang, 1993).

Authenticity is no guarantee of success in design challenges. What is authentic or relevant to one student may not be relevant to another. Relevance can vary on a number of factors, such as demographics, personal interest, age, life experiences, and cultural implications. Additionally, should educational design challenges include the realistic factors included in industrial settings such as office politics, continuing budget reductions, and the possibility of employment termination to name a few?

Open-Endedness

Jonassen (2000) described "design" as a form of problem solving that is open-ended and complex. Engineering design is open-ended with respect to the solution as well as the process. Engineering designs generally have multiple solutions and varying solution paths (Brophy et al., 2008; Eide, Jenison, Mashaw, & Northrup, 2002; Foster, Kay, & Roe, 2001). This variability often leads to engineering design problems having complex interactions that may be emergent and synergistic. Ottino (2004) suggested that the process of design is non-linear, involving multiple decision points that shape and mold over time. Katehi and colleagues (2009) found that in engineering design the solution paths are influenced by various personal and technical considerations. Crismond (2001, p. 793) stated that good design challenges should "allow for multiple solution pathways" that "do not necessarily converge on a single 'right' design solution."

Bucciarelli (1994, p. 196) posited that "There are always significantly different design alternatives given the same initial conditions—performance specifications, resources, infrastructure, and the like." In other words, there is too much complexity to have a best solution in design. In their program, Carlson and Sullivan (1999) successfully employed design courses with open-ended design problems that had no right answer. Although a solution is desired at the conclusion of an engineering design challenge, the process the students take is also important. It is possible that the students by chance could produce a satisfactory solution and miss the process of designing.

Open-ended problems may extend well beyond the scope of a typical course or semester. Open-ended activities require the instructor to not have a single right answer. The students may also take the activity in a completely different direction than what is stated in the objectives. Then there is the challenge of assessing authentic and open-ended problems (Dym et al., 2005). These are a few of many questions regarding open-endedness that need to be addressed further by those in research and practice.

Systems Perspective

The concept of systems is significant to engineering design (Apedoe et al., 2008; Brophy et al., 2008; Dym, 2004; Hmelo-Silver, 2004; Sheppard et al., 2004; Sneider, 2011). As Dym and Little (2009, p. 13) stated, "All design is systems design because devices, systems, and processes must operate within and interact with their surrounding environments." Systems is represented by several different terms: systems thinking, systems view, systems perspective, thinking in terms of systems, and systems approach.

A system in engineering design has multiple interconnected variables, is loosely bound, involves human factors, and often requires a global or holistic view. Multiple interconnected variables yield emerging interactions that cannot be viewed in isolation in order to understand the aggregate system (Hmelo-Silver & Azavedo, 2006). In addition to technical variables, such as temperature, load, or electrical current, there are non-technical variables at play in design as well. Wulf and Fisher (2002) offered a few possible non-technical variables encountered in engineering: concerns for safety, environmental impact, ergonomics, nature, cost, reliability, manufacturability, and maintainability. The human factor is essential in engineering design (Brophy et al., 2008; NAE, 2004, 2005). As an example, motivation for task completion will be different for students engaged in engineering design in comparison to engineers in the profession. Jones, Paretti, Hein, and Knott (2010) speak to the role of identification with academics, which concerns how students define self through performance in academics, as a particularly motivating factor for students completing tasks in an engineering design setting. Furthermore, in an engineering problem, the designer has to decide which variables are germane and which are not. Some of these factors can be integrated into K–12 engineering design challenges as constraints upon discussion with students.

In addition to containing several variables, the variables often vary non-linearly along unique scales. The behaviors resulting from the interaction of components in a system are often termed emergent in engineering design (Katehi et al., 2009). Katehi and colleagues (2009, p. 125) further stated, "Aggregate behavior is qualitatively distinct from the sum of behaviors of individual components and indicates a complex engineered system, such as highways, the Internet, the power grid, and many others, which are all around us."

Transdisciplinarity

Engineering design transcends other fields of study. Dym and Little (2009) claimed that many engineering problems are transdisciplinary and demand the understanding of the clients and end user requirements. Design is not unique to any one discipline and engineering is no exception. Even within engineering, Householder (2011) asserted that design has non-engineering constraints, standards, and unanticipated problems that require distributed knowledge and collaborative activity. There is a wealth of information and perspective that can be learned outside the realm of any singular discourse.

While engineering design is broad and allows for myriad approaches and solutions, there are certain mathematical and scientific principles that must be followed. Ignoring context-specific principles such as gravity or Ohm's Law would be hapless to an engineering designer. Cross (2002, p. 4) studied three expert designers from different fields and found that all of the designers "explicitly or implicitly rely upon 'first principles' in both the origination of their concepts and in the detailed development of those concepts." The "first principles" used in engineering are numerous and are often unique to a specific discipline.

An engineering design challenge is a fertile seedbed for teaching non-engineering principles. Various studies have used engineering design to teach core concepts from their discipline (Apedoe et al., 2008; Crismond, 2001; Eisenkraft, 2011; Kolodner, 2002; Mehalik, Doppelt, & Schunn, 2008). Additionally, a design will cause the designer to reach into a specific knowledge domain (Mehalik & Schunn, 2006).

Many of the principles of engineering include mathematical representation and analysis (Mentzer, Huffman, & Thayer, 2014). Engineering modeling is often performed by applying mathematics. Carlson and Sullivan (2003, p. 26) claimed that "analysis characterizes engineering design, allowing numerical models to accurately predict the behavior of a complex design before it is built." Engineering is not just applied math. Rather, mathematical reasoning and skill is a way of thinking and doing; as mathematics is used in modeling, predictive analysis, and evaluation it serves as a foundation to engineering design.

Attributes Summary

These attributes suggest that we believe engineering design should be relevant, open-ended, and modeled through challenges that promote scientific and mathematical thinking as a process, rather than a step-by-step activity. Due to its open-ended nature and obstacles pertaining to relevance, engineering design embodies an iterative process. Such a process, when repeatedly performed and practiced, captures the attributes shared in this section. Individuals can then begin to develop habits of mind, as described in the next section of this paper.

Habits of Mind and Practice

This section describes habits of mind and practice associated with engineering design. This section does not describe all of the ways of thinking and doing germane to engineering design, but represents a portion of the design experience. The themes include *modeling*, *graphical visualizations, decision making, problem formulation, questioning, reflection, continuous improvement*, *optimization,* and *material resources*. Worth mentioning further is the constraint of *costs*, as it plays a prominent part in material resources.

Modeling

Engineering design is performed in order to produce an artifact: a device, system, or a process (ABET, 2016). Often, this end product is modeled before final production for testing and evaluation. A model can be a tangible prototype, simulation, or procedure. Students most often encounter modeling in engineering design challenges through hands-on experiences. Roth (1996, p. 163) stated,

> The construction of artifacts is far more important to learning than simply to motivate students. Materials, tools, and artifacts serve in important ways as structuring resources to design and make sense of the learning environment and as backdrop against and with which students can construct individual understandings and negotiate shared meanings.

The learning that occurs from hands-on activities is more than procedural knowledge; the students may also engage in experiential learning (Halverson & Sheridan, 2014; Kolb, 1984). Crismond (2001, p. 193) further states, "Hands-on activities can help students build or reconnect with substance schemas that may be important to doing design and can activate device knowledge and mechanism schemas that naïve designers understand only poorly."

Graphical Visualizations

Graphical visualization is an important theme in engineering design. Graphical visualizations may include sketches, notes, digital forms of drawings, renderings in more than one dimension, simulations, and any other type of visual representation of the design. Mehalik and Schunn (2006, p. 522) stated, "A designer often attempts to visualize details for a design in order to explore the design's overall configuration, the design's relationship to its context, or to explore some feature of the design in great details."

Drawing is pervasive in engineering practice (Bucciarelli, 1994). Drawings are often expressions or manifestations of the designer's intentions, expectations, and creativity. MacDonald, Gufstason, and Gentilini (2007) asserted that drawing is a core skill for students. Graphical visualization is not just limited to offloading cognitive effort; it may also be used to generate, develop, and communicate designs. Table 1 provides a list of uses for graphical visualization that may be applied to engineering design.

Table 1
Graphical visualization in design.

Author	Item
Plimmer (2002)	Reduce cognitive load Create a visual dialogue
Anning (1997)	Envision artifacts or structures Formulate or record plans Communicate intentions
Fraser & Henmi (1994)	Draw existing phenomena or ideas Provide repository for future inspiration Generate ideas Develop ideas Discover and develop emerging projects Test and verify solutions Optimize designs

Decision Making

Marston and Mistree (1997, p. 1) suggested that "the principal role of a designer, in decision-based design, is to make decisions. Decisions help bridge the gap between an idea and reality." In engineering design, decision making is a continuous activity, involving trade-offs, requiring satisficing, and potentially incorporating various processes. Another activity involved with decision making in engineering design challenges is decision justification.

As a continuous activity. Making decisions is not just a final step in engineering design; rather, decisions are made continuously throughout the design process. Jonassen posited that engineering design could be perceived as a series of decisions (Jonassen, 2011b). For example, while exploring and framing a problem, the designer has to decide what the problem(s) is, what constraints will be considered, and what the criteria for success will be. The decisions made in the front end of the design process greatly influence the designer's approach as well as the final artifact (Mehalik & Schunn, 2006).

Trade-offs. Engineering involves trade-offs. Trade-offs require the designer to make an often difficult decision between opposing variables and solutions. Trade-offs entail compromise (Eide et al., 2002). Each decision has a consequence, whether positive, negative, or, as is usually the case, a combination of both. The designer, often along with other team members, decides which net sum of consequences is best at the time of making a decision. The decision may not necessarily have a clear best choice, and typically cannot be reduced to an algorithm. The constraints or variables influencing a design decision are not always well known and may require bold action to move forward. Many engineering designers grapple with this concept as they strive for excellence and continual improvement. The idea of "faster, better, cheaper" is rarely sustainable, if even obtainable.

Satisficing. Bucciarelli (1994) asserted that a designer must decide when a problem has been adequately solved. At some point in the engineering design process, a decision regarding the final design will be made. As there is always more than one design solution and any solution can perpetually be improved, a stopping point should be chosen. The process of coming to a point when the design is deemed good enough has been coined "satisficing" (Simon, 1996).

Decision making processes. How, then, are decisions made in engineering design? Even if the designer does not make the final decision on the design implementation, the designer decides what is to be considered for the final decision. Decision making can be done with varying strategies, such as decision matrices, cost-benefit analysis, and decision trees (Eide et al., 2002; Jonassen, 2011b). It is not certain how high school students currently use decision making processes in design, nor is it well known how it should be used. This is a fertile area for further research.

Decision justification. When students are given the opportunity to justify their decisions in design, it sheds light on their cognition and learning. In their study of 6th grade students designing an artificial lung for a science unit, Hmelo-Silver and colleagues (2000) found that when students justified their decisions, the justification process afforded them an opportunity to evaluate and synthesize their designs. Jonassen (2011b, p. 372) stated, "If students can argue effectively about their solutions to problems, how they solved the problem, or why they did what they did, they provide confirmatory evidence about their problem-solving ability." In addition, students' ability to effectively argue for their problem solutions provides keen insight into their understanding of concepts covered.

Schunn (2011) suggested that students give reflective presentations at natural design points, arguing that students can become lost in the process if the only deliverable is a final artifact. Justifying their decisions at natural points, such as during prototyping and the final delivery of the artifact, can help students reflect on their design strategies and lessons learned, and can inform the peers who are listening to their successes and failures. Eisenkraft (2010) incorporated reflection activities in his *Active Physics* curriculum to help students stay focused on the physics content and design, not on the procedures and artifact. After working with high school students from Massachusetts on engineering design, Hynes and colleagues (2011) suggested that students need to be able to justify and reason through their decisions. In justifying their decisions, students can reflect on their learning, pass along their learning to fellow students, and help the instructor assess their learning.

Problem Formulation

Problem formulation is a central concept to engineering design. Too often, students are given the problem with most of the accompanying constraints and resources. Dym and colleagues (2003, p. 106) suggested that "we spend more time thinking about how we *define* the problem, rather than on the solution to the problem." Problem formulation is the process of exploring, identifying, and discovering a problem within a given context determined by constraints and personal beliefs. Problem formulation is not performed in isolation from the design solution. Carr and Strobel (2011) claimed that the first step in any design project includes posing questions to understand the problem. Although problem formulation may take place before moving onto a solution, they are both activities that influence the other and often take place iteratively. Mehalik and Schunn (2006, p. 521) stated that "the way in which designers construe their task can have an impact on what aspects of a design a designer emphasizes, on what solution paths designers choose, and on which goals and constraints designers meet."

Adams, Turns, and Atman (2003) claimed that problem setting was as important as problem solving and proffered a working definition. This definition included: the designer's broadness of design factors, information gathered, and the time spent in problem setting activities. The results of their study suggest that more advanced designers consider broader factors, gather more varied information, and transition between problem settings frequently.

Questioning

Being able to ask questions is a skill that transcends any discipline. Question posing is integral across the design process. Dym and colleagues (2005) posited that various types of questions occur at varying places in the design. Oftentimes, questioning is associated with deep levels of reflection and learning (Katehi et al., 2009; Prince & Felder, 2006). Carr and Strobel (2011, p. 16) stated that "engineering design promotes questioning and inquiry, which develop the ability to reason, particularly with math and science content."

Reflection

Atman, Kilgore, and McKenna (2008) define reflection as a metacognitive activity that gives meaning and learning to an experience. Schön (1983) asserted that reflection is critical to practice. Asunda and Hill (2007) claimed that reflection is a key component of K–12 engineering design as it offers learners the opportunity to make meaning of their previous experiences and design.

Beckman and Barry (2012) had students regularly maintain journals reflecting on their classroom activities. Another practice that encourages reflection is keeping a running portfolio. It is asserted that experience without the complement of reflection diminishes the learning experience (Kolb, 1984; Mehalik & Schunn, 2006). Reflection can take place individually as well as in a group (Hmelo-Silver et al., 2000). Kolodner (2002, p. 16) advanced at least three goals of reflection,

> (a) connecting up one's goals, intentions, plans, procedures, results, and explanations of results; (b) explaining results that are different than what was expected, and from those explanations developing new conceptions; and (c) reflection across experiences to extract commonalities (and differences).

Kolodner (2002) also asserted that for reflection to become a habit of mind it must deliberately and consistently take place over a long period of time.

Continuous Improvement

As engineering designs have multiple potential solutions, they may also have multiple potential improvements. Furthermore, engineering design is an iterative process, allowing the designer to make continual improvements and changes. Crismond (2001) suggested that the design process should entail multiple iterations for students to grapple and discover the underlying problem in the design challenge.

The culture of continuous improvement is not only evident in design, but in all aspects of engineering. Satisficing is a concept that helps limit the engineering designer's desire to always improve. The idea of continual improvement in engineering can be seen in the next year's model of a car, the next generation of cell phones, and perpetual software updates.

Optimization

Designers frequently encounter conflicting requirements or constraints in engineering. Balancing these constraints is often termed optimization (Brophy et al., 2008; Cross, 2002; Silk & Schunn, 2008). Katehi and colleagues (2009, p. 128) stated, "Real-world designs must always meet multiple, conflicting requirements and are always subject to constraints. Thus optimization necessarily involves trade-offs among different aspects of a design to improve one quality at the expense of another." Hence, optimization is generally an iterative process of balancing trade-offs. Trade-offs may include the competition of performance versus cost, robustness versus social constraints, and time versus environmental impacts. Although the components in trade-offs may be considered individually to help understand the system, they often interact with each other and are therefore not evaluated in isolation.

Material Resources

Wulf and Fischer (2002, p. 36) stated, "Our own favorite description of what engineers do is 'design under constraint.'" Constraints include the laws of nature, mathematics, and resources such as materials, costs, and time. An engineering design artifact is often determined by what resources are available. Apedoe and colleagues (2008) concluded that engineering design is a hands-on endeavor that requires materials for modeling. The same holds true for educational engineering design challenges. The resources the students are given will influence their designs, but the material resources should not take away from the learning objectives (Crismond, 2001).

Hands-on projects are beneficial in various aspects: "Designing and constructing artifacts produces a good deal of problem solving in ill-structured settings, allows students to construct an experience-based design-related discourse, and facilitates interactions and sharing of knowledge in the classroom" (Roth, 1996, p. 163). The selection and use of material resources is an important factor in engineering design challenges. As such, design challenges can be preceded by discussions to help students realize the importance of material examination by conduct of simulation exercises, review of tangible materials, and how these may inform use and selection of real materials to complete a given challenge.

Costs. Although there are many different constraints in engineering design, cost is noteworthy. Most, if not all, engineering designs are financially influenced or limited. Carlson and Sullivan (1999) stated that cost was a key component of their students' projects in engineering design. Albeit, students are not given an endless budget, but they typically are not responsible for the financial obligations in a design challenge. Therefore, the students should be taught to be cognizant that a design budget is not limitless (Asunda & Hill, 2007; Brophy et al., 2008). Furthermore, students' cognitive development is fostered through budgetary constraints, which have implications for the type of materials that can be used and the abundance available.

Habits of Mind and Practice Summary

To summarize this theme, habits of mind and practice represent a way of thinking and doing, which emanates from everyday encounters with societal problems that are understood through the engineering design process. Hands-on tasks are a common tool for forming these habits, as they require students to engage with a given design problem. We believe that as students negotiate and build insights into understanding and eventually solving a problem, they employ several ways of thinking that are ingrained in their funds of knowledge. For example, the Next Generation Science Standards [NGSS] (NGSS Lead States, 2013) accentuate the integration of engineering design into K–12, which can help students develop habits synonymous to the habits of practicing engineers in the field. We acknowledge that there is need to further explore how teams formulate problems, optimize within constraints, and negotiate and make decisions that lead to innovative solutions in the realm of habits of mind and practice.

Pedagogy

The scope of this review did not cover all of the pedagogical characteristics and implications of engineering design challenges. There were a few salient points worth mentioning as they related to engineering design challenge pedagogy, including: *initial student reaction, scaffolding, instructional preparation,* and *assessment.*

Initial Student Reaction

Too often students are accustomed to assignments or problems with one solution. The engineering design challenges fly in the face of most students' previous experiences. Students may see the use of open-ended problems as disorganized and tangential to their learning. Through a series of interviews following an introduction to design challenges, Eisenkraft (2011, p. 33) found "that the students were in shock." This may be due to the openness of what they conceive and design for a solution upon being asked to explore and define the problem. Such experiences are antithetical to traditional learning experiences for students and may initially produce adverse feelings toward the design challenge. Prince and Felder (2006) claimed that there is an initial resistance by some students, who may even become hostile.

Students are generally taught to find convergent answers to a problem and to seek out items relevant to a test. Asking students to explore a problem is a new exercise for most. Prince and Felder (2006) shared that most students eventually favor open-ended problems. Jonassen (2011a, p. 5) stated that "although frustrating, it appears that the productive failure approach engaged deeper level learning and problem solving in students." Introducing engineering design challenges into K–12 curriculum is a cultural change, and most change does not come without resistance.

Scaffolding

Pre-college students can benefit from the assistance given by an instructor while working an engineering design challenge. The extent to which students need assistance has not been established (Carr & Strobel, 2011). The assistance provided to students is termed instructional scaffolding. Scaffolding implies that the framework is only temporary and acts as an aid to the student's learning, not a replacement.

Teaching engineering design entails not only factual knowledge, but familiarity with the processes inherent in design as well. There are a multiplicity of engineering science and mathematical principles that can be explored (Hernandez et al., 2014). Additionally, the pedagogical approach with open-ended problems and solutions is quite novel for most students. Jonassen (2011a) suggested that scaffolding would be needed to help most students succeed in a new learning environment. Further research could help ascertain what level of scaffolding students need through the different grade levels.

Instructor Preparation

Whether in the classroom or in a less formal setting, teaching engineering design is a relatively novel experience for the majority of pre-college instructors. Therefore, most instructors are not familiar with engineering culture and its accompanying ways of thinking, speaking, and doing. Instructors need time, resources, and patience to become comfortable with new practices (Kolodner, 2002). For students designing solutions to engineering problems, failure is an accepted practice and the first step toward a viable solution; teachers, then, should also be afforded the opportunity to fail and reflect on their teaching practices, taking a metacognitive approach to improving their instruction.

Failure to discuss their shortcomings with other practitioners and mentors, as well as reflect on their teaching and ways they may alter their practices, may hinder development in teacher's instructional practices. Nevertheless, engineering encompasses a broad set of content and practices spanning nuclear fusion research to human interaction with controversial technologies. Teaching pre-college engineering design has the potential to be a co-learning experience for both the student and the teacher.

As engineering design is an open-ended process, a successful engineering design instructor should help students embrace ambiguity. Crismond and Adams (2012, p. 771) stated, "A critical and perhaps threshold concept is developing an awareness of and tolerance for ambiguity in design." In so doing, an instructor must overcome the tendency to fall back to what is pedagogically comfortable. Often, engineering design teaching entails a paradigmatic change in pedagogy and learning environment.

Repeated deliberate experiences help students gain a deeper understanding of engineering. Affording students the opportunity to design and redesign takes time. Kolodner (2002) asserted that learning takes place over long periods of time with numerous interactions. Not only do iterations in design allow for reflection, but they also encourage persistence through failure (Crismond & Adams, 2012). If students are afforded multiple designs iterations, then they are also allowed to make failures, leading to potential design improvements. Beckman and Barry (2009, p. 371) asserted that students need multiple opportunities to iterate—and fail—to learn divergent thinking:

> At the core of being able to iterate is the ability to 'make it and break it . . . There is a tendency on the part of the teams composed primarily of convergers to attach themselves to the first solutions they identify, to be unwilling

to then generate alternative solutions, and to have great difficulty giving up the solutions they have developed.

As asserted earlier in the paper, modeling is an essential engineering design skill. Instructors "who have little or no experience with formal modeling may not have a deep understanding of the process and thus may not be able to formulate questions to guide students" (Katehi, p. 124). Furthermore, modeling takes time, especially when numerous iterations are afforded. Crismond and Adams (2012) suggested that instructors help their students enhance their sketching skills, work with simple models early on, and make explicit connections with the design from their models.

Assessment

Engineering design assessment, particularly at the pre-college level, is an area of research that warrants multiple studies and a separate literature review. Assessment can be used for evaluation, but more importantly offers opportunities for feedback and reflection. In the case of peer assessment it also affords giving and receiving critique. Although there is no definitive assessment for engineering design, the literature does point to potential methods and philosophies of assessment appropriate for engineering design challenges (Rose, Shumway, Carter, & Brown, 2015). The most prominent themes that emerged from this review were what to assess, how to assess, and common tools for assessing.

Without a standard definition for engineering design there is the challenge of knowing what to assess and what form success may take. Custer and colleagues (2009, p. 1) stated, "The development of meaningful learning, teaching, and assessment is exceptionally problematic in the absence of a clear understanding of the conceptual base appropriate for K–12 engineering." This is further exacerbated by the point that engineering design has multiple goals and does not yield identical outputs (Eisenkraft, 2011; Sadler et al., 2000).

If engineering design is a process, then engineering design involves more than declarative and conceptual knowledge alone. Hence, procedural knowledge is paramount to engineering design; however, infusing procedural knowledge into curriculum comes with pedagogical challenges. Assessing a student's process can be elusive (Dym et al., 2005). Furthermore, processes tend to be situated and may not lend well to knowledge transfer (McCormick, 1997).

Rubrics. The prominent form of assessment found in this review was rubrics (Asunda & Hill, 2007; Diefes-Dux, Moore, Zawojewski, Imbrie, & Follman, 2004; Eisenkraft, 2011; Mendoza & Cox, 2012; Sadler et al., 2000). A rubric is typically a set of scoring criteria and expectations derived from learning objectives. These criteria should be observable, as they will be assigned a quantitative or qualitative measure. Rubrics tend to be used summatively for evaluation; however, they may also be used as a guide or standard throughout the design process. Additionally, for student buy-in and for setting clear expectations, Eisenkraft (2011) suggested that the students help generate the rubrics.

Design artifacts. The artifacts produced by students in engineering design challenges are often in the form of models. These artifacts provide solid evidence of student learning (Kolodner, 2002). Kolodner (2002, p. 36) went on to state that some teachers who employ design in their classroom give tests, but "some of them find that they collect enough evidence of learning from work the students are doing from day to day that there is no need to give tests." Roth (1996) further found that the students demonstrated their learning through drawings and text. Furthermore, Tucker-Raymond, Gravel, Wagh, and Wilson (2011) provided compelling evidence that online posts and other digital literacies represent an opportunity for students to demonstrate what they are learning during their projects, while simultaneously promoting a relationship between the digital, electronic, and physical world.

As students continually generate design artifacts—sketches, mind maps, journals, etc.—these artifacts lend to formative assessments. The assessment does not have to be evaluative, but should be specific and relevant (Diefes-Dux et al., 2004). The use of modeling artifacts can also help address the tension of process versus product, especially when used with documentation in summative assessments (Asunda & Hill, 2007).

Documentation and reflection. Students may be asked to document what they are doing and why they are doing it. There is not only one way to document the design process. Students can provide presentations (Kolodner, 2002), keep an engineering log book to tell a narrative (Asunda & Hill, 2007), or capture their process using a number of different media such as blogs, websites, or how-to posts on Maker websites. Another promising approach is keeping a portfolio, electronic or paper-based, of their design projects and experiences (Asunda & Hill, 2007). If documentation is only left to the written word, an instructor might find themselves primarily assessing the student's writing rather than the design process itself (Diefes-Dux et al., 2004). Documentation also provides a glimpse into students' design discourse and vocabulary (Atman et al., 2008; Roth, 1996). Roth found that understanding was evidenced by an enhanced engineering design vocabulary, the integrating of ideas within the design and without to prior units, and meaningful connections and associations.

Another challenge in engineering design assessment is differentiating between individual skills and learning and those performed by the group (Dym et al., 2005). Group work can shed light on what students learned, as well as their analytical abilities and decision making processes. In order to assess individual learning, Kolodner (2002) suggested separate write-ups for the individual. She also stated that teachers should give supplemental performance tasks that targeted specific skills, abilities, and knowledge. Roth (1996) noted six competencies for engineering design that could be assessed: coping with complexity, interpretive flexibility (as opposed to functional fixedness), evolving design strategies, negotiating differences, using tools and materials, and design discourse.

Assessing engineering design challenges is not a simple or straightforward task. There are many methods being used that would benefit from further and deeper research. These topics are varied, but primarily include rubrics, modeling artifacts, and reflexive documentation.

Pedagogy Summary

In summary, pedagogy practices evolve and are dependent on numerous factors and contexts. The complexity of engineering design as an open-ended process calls for creativity in teaching to help students comprehend that there is no singular, best solution to everyday encounters. Multiple studies have documented strategies that instructors may utilize in teaching engineering design. This review suggests that there is not only one prescribed method for teaching engineering design. We assert that students' habits of mind and practice can be enhanced by implementing engineering design challenges with various scaffolds, assessment, and periodic feedback. Nevertheless, this theme calls for continued research on how to better teach and assess engineering design tasks.

Conclusion

The purpose of this review was to understand and synthesize the literature on engineering design challenges in pre-college settings. Multiple themes that conceptualize an engineering design challenge have been presented. Not all design activities must include all of these themes to infuse engineering practices in STEM-related curricula. Engineering design challenges that purposefully include these themes can offer a rich learning experience to students of all ages. Although this landscape is not completely exhaustive, it has the potential to not only inform the researcher, but the practitioner as well.

It has been noted that engineering design is complex and without bounds. Although this review was thoroughly in-depth and extensive, the primary focus was to better understand how engineering design challenges are conceptualized in pre-college settings—not to offer a complete and exhaustive definition of the topic. This literature review suggests that design challenges should: be authentic to the learner and to the field of engineering, be open-ended, include modeling, encourage optimization to continuously improve, and promote engineering habits of mind such as balancing trade-offs and satisficing.

Although the literature provides characteristics that exemplify what an engineering design challenge includes, the review also suggests that there are many areas that need further research. For example: How do subject area standards impact the design of engineering design challenges within courses that have STEM foci? How do teachers plan for and scaffold these concepts? What kind of pedagogical challenges do teachers experience, and how do they overcome them? In addition, research that documents students' experiences and perception of engineering design challenges would lend to insights about the authenticity and relevance of the activity from students' perspectives.

In conclusion, this review offers and describes three key themes of what an engineering design challenge might entail from the perspective of scholars in the field, namely: *challenge attributes, habits of the mind and practice,* and *pedagogy*. We expect that these themes will provide a basis for the fundamentals of design, instruction, and assessment of engineering design challenges, and, most importantly, open a discussion that may realize consensus as to what constitutes an engineering design challenge.

Further Implications

Practitioners and researchers alike continue to struggle with identifying and effectively teaching engineering design in pre-college settings (Carr & Strobel, 2011). This paper attempts to provide a meticulous search and review that equips the learning community with a thematic view of engineering design in pre-college settings. By adding to the growing lexicon of literature dedicated to engineering design in pre-college settings, this paper helps move engineering design forward as a discipline. With this said, the discipline of engineering design will struggle to move forward without more research to identify best practices for introducing and teaching design; please see Table 2 for a list of potential future research vectors. In addition, a more nuanced investigation into the differences of teaching this subject to students of various ages would provide needed insight. Moreover, there is much to be gained by examining how students are able to formulate problems and frame engineering tasks and their implications for guiding an engineering design activity.

As more research is produced and the practice of teaching engineering design becomes more refined there will be a need to amend certain themes within this literature review. This is encouraged and does not detract from the importance of this paper. It is the goal of this paper to move forward the conversation on how engineering design challenges are conceptualized in K–12 settings, and the authors believe that this paper accomplishes this goal. Further work still needs to be done, by practitioners and researchers alike, to break down the specious and contrived disciplinary silos. Collaborative work between researchers and

Table 2
Potential future research.

Category	Question
Attributes	What is "real-world" to students from varying backgrounds? What makes an engineering design challenge unique from other types of design? How much contrivance is appropriate in design challenges? What are the cognitive gains from service learning? What is systems thinking in engineering design? How is it assessed? What level of engineering science should be expected for engineering design at the novice level? What are the mathematics prerequisites for engineering design at the novice level?
Habits of Mind & Practice	What is modeling in engineering design and how should it be taught? What role does drawing/sketching play in K–12 settings? What is the role of documentation for decision making and justification? How do students learn how to identify and formulate design problems? What is the role of question posing in engineering design? How much scaffolding (support) is ideal for teaching novices engineering design habits of mind and practice? How do students frame engineering tasks and how does this alter the direction of an activity?
Pedagogy	What teaching and assessment is appropriate for open-ended problems? How can authentic engineering design challenges work with fixed educational time frames such as semesters and modules? How are open-ended problems assessed in a timely manner? What role do portfolios play in engineering design documentation, reflection, and assessment? How are persistence and growth mindsets taught in engineering design? What does professional development in engineering design teaching look like? What are valid and feasible forms of engineering design assessment?

practitioners will move the field of engineering design forward, particularly as it pertains to pre-college settings.

Acknowledgments

We would like to thank all those from National Center for Engineering & Technology Education Grant #0426421 who assisted in developing and critiquing this research effort.

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Appendix
Engineering Design Challenge Literature Review Matrix.

	Attributes				Habits of Mind & Practice										Pedagogy			
Author	Relevance	Open-endedness	Systems Perspective	Transdisciplinary	Model	Graphical Visualizations	Decision Making	Problem Formulation	Questioning	Reflection	Continuous Improvement	Optimization	Material resources	Costs	Initial reaction	Scaffolding	Instructor preparation	Assessment
Adams et al.		x						281		275								
Anning			456		237	237												
Apedoe et al.	460	x	459		455			456	458		x		460					
Asunda & Hill		26	32	40	32	35		32		45	32	35		35				27
Atman et al.		x								309								
Beckman & Barry		364	364					364	365	368	371							
Bergin et al.	44				47													
Berland et al.					62		56	56										
Brophy et al.	370	371	383	374	383	376	375		376		376			381	383		381	
Bucciarelli		178	46	110	67	90	162	148			x			180				
Burghardt & Hacker		6			6		7	7		6	6				6			
Carlson & Sullivan	22	25		24	24	24								24				
Carlson & Sullivan	1	8	x	1	3,8				16									
Carr et al.	15	14		14		17	17	16							15	17		
Coyle et al.	1			1				2										
Crismond	793				793	816	803	803	816	803	794	794	793					
Crismond & Adams		770	760	774	748	759	745	748	745	749	749	749	744	745	747	777	x	741
Cross			5					5				4						
Cross		429	429				430	439		432	432				432			
Custer et al.			9		8			11			8						14	1

Appendix
(Continued)

	Attributes				Habits of Mind & Practice										Pedagogy			
Author	Relevance	Open-endedness	Systems Perspective	Transdisciplinary	Model	Graphical Visualizations	Decision Making	Problem Formulation	Questioning	Reflection	Continuous Improvement	Optimization	Material resources	Costs	Initial reaction	Scaffolding	Instructor preparation	Assessment
Daly et al.						x		613										
Dally & Zhang	83	x			83	84						84	x	84				
deGrazia et al.	x				18												x	
Diaz & Cox					10													11
Diefes-Dux et al.		181			181		190											184
Dinsmore et al.		379																
Dym et al.			107	106				106										
Dym et al.	110	x	104	112		108	104	x	108	113		107				x	112	112
Dym & Little		10	13	5	10	112	25	46	19		28	20		276				
Eide et al.		42			42		82	42			44	23		42				
Eisenkraft		27			25			25			28	25			24	24		27
Hirsch et al.	x				2	5		2										
Hmelo et al	261	266	291		252	278				254	252	290	266			253	293	
Hmelo & Pfeffer			129			132												
Hynes et al.		9			11	11		10				12						
Jonassen		3		3	6	6	5	5			6	6			4	5		
Jonassen	248									356								354
Katehi et al.			121		124	x				99	39	128		39		124	124	
Kolodner	10	9			10	14	9	14	12	16	10	9			x	15	35	36
Lehrer et al.			514		514				513		514					516		

Appendix
(Continued)

Author	Attributes				Habits of Mind & Practice										Pedagogy			
	Relevance	Open-endedness	Systems Perspective	Transdisciplinary	Model	Graphical Visualizations	Decision Making	Problem Formulation	Questioning	Reflection	Continuous Improvement	Optimization	Material resources	Costs	Initial reaction	Scaffolding	Instructor preparation	Assessment
MacDonald et al.						60				61	60							
McKenna & Hirsch	2	x				2				x								
McKenna & Carberry					263		263	267										
Mehalik & Schuun			524			522	521	521		524	520	520						
Moore et al.		5	5		5		5	5		5	5							
NAE			34	27														
Prince & Felder									6	11					14			
Roth	163	163			157	149	160	132		133	133	140	163			144		151
Sadler et al	323				319	321				304	323	325	x					301
Schön								x										
Schunn	35		36		35			35				36						
Schunn	22		21							23	21					22		
Sheppard et al		91	79					101										
Sneider		32	35		35	35		32			35	31	33	33	32	32		
Svensson & Ingerman	265		255															
Sweeney & Sterman		x	249		252	x		x										
Watkins et al		44	46				46	44		46				44				
Wulf & Fisher			36	38	38						36							

Note: Each column represents a unique theme. The themes are then grouped into one of three categories. The far left column represents an article and the corresponding author(s). The numbers are the corresponding page numbers where the data may be found. An "X" represents that a theme was present but not specifically described.