Building a Framework for Engineering Design Experiences in High School

Not all students will become engineers or pursue engineering careers after completing high school but all students can benefit from having engineering design experiences in high school (Wicklein, 2006; Apedoe, Reynolds, Ellefson, & Schunn, 2008; National Academy of Engineering and National Research Council, 2009). The teaching of engineering design at the secondary level can help students develop critical-thinking and teambuilding skills and provides a platform for the integration of science, technology, engineering, and mathematics (STEM) subjects (Wicklein, 2006). Furthermore, the teaching of design in high school settings has several cognitive advantages including developing engineering habits of mind, problem-solving skills, and the development of system thinking skills (Householder & Hailey, 2012). Although researchers and curriculum developers agree on the benefits of introducing engineering design into high school settings, there is a lack of literature proffering a framework or structure for the successful infusion of engineering design experiences in high school settings.

In response to this void in the literature, the National Center for Engineering and Technology Education (NCETE) solicited positions papers from prominent educators in the field outlining a framework for engineering design experiences in high school. NCETE is a National Science Foundation (NSF) funded collaborative network of scholars whose mission is to build capacity in technology education to introduce engineering design and other related concepts to high school students (Hailey, 2005). The inception of NCETE coincided with a paradigm shift in technology education to develop a more engineering-focused curriculum (Wicklein, 2006; Gattie & Wicklein, 2007). This call for a new focus was not without its problems, including addressing professional development needs for in-service and preservice teachers, lack of alignment with state standards, determining authentic engineering design experiences, and assessing the engineering design experience (Householder, 2011). In an effort to address these needs, NCETE invited six positions papers whose results would provide fodder for future conversations regarding engineering design in high school settings. Collectively, their responses provided us with emergent themes that begin to outline a structure to support the infusing of engineering design experiences in high school settings.

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In putting forth a conceptual framework for engineering design experiences in high school, this article builds upon a synthesis derived from the six position papers referenced above, expanding on their findings through an analysis of the relevant literature. Conclusions drawn from our expanded synthesis build towards a framework for engineering design experiences in high school settings. For our purposes, a framework is defined as a structure that is used to solve complex issues. It is not the goal of this article to attempt the grandiose task of answering all of the pedagogical and curricular questions associated with the infusion of engineering design activities into high school settings. Instead, we endeavor to provide a scaffold that will provide structure and support the introduction and investigation of successful engineering experiences in high school settings. To achieve our goal, we addressed the following areas of argument: (a) situating engineering design in the curriculum, (b) sequencing the engineering design experience, (c) selecting appropriate engineering design challenges, and (d) assessing the engineering design experience. We contend that only after addressing these areas of development that the educational community can begin to provide proper curricula and pedagogical practices needed for the infusion of successful engineering experiences into high school settings.

Situating Engineering Design in the Curriculum

Engineering Design in Science Curricula

Recently, there has been a push in the education community for the integration of an engineering design framework into science settings (Sneider, 2011). In 2011, the National Research Council (NRC) disseminated a report suggesting that the updated science standards include "scientific and engineering practices" as one of the featured domains (Quinn, 2012,). Hynes et al. (2011) suggest that infusing engineering design into the high school science curriculum would satisfy the need to provide engineering design with a set of standards to serve as guiding principles for competencies, skills, and knowledge that all students should develop. This is supported by the newly minted *Next Generation Science Standards*, which include engineering and engineering design as major focal points (National Research Council, 2013). Pedagogically, there is merit to a push for engineering design experiences within high school science classrooms. According to Apedoe, Reynolds, Ellefson, and Schunn (2008), inquiry-based instruction—a staple of science education—provides an ideal milieu to introduce engineering concepts and design-based instruction. Research has provided evidence that inquiry-based instruction not only improves scientific content knowledge but helps develop problem-solving skills as well (Apedoe et al., 2008; Kolodner, 2002; Hmelo, Holton, & Kolodner, 2000).

Including an engineering design framework into high school science settings may provide engineering design with a set of standards; however, it still leaves many pedagogical questions unanswered. There is still a question about *who* is better prepared to introduce engineering design at the secondary level. It is presumptuous to assume that science teachers are prepared to teach engineering design in their classrooms. By nature, engineering education is an interdisciplinary subject that goes beyond the nuances of inquiry-based learning. Consequently, many science educators are not comfortable with introducing engineering design and engineering concepts in their classrooms. To be successful, the infusing of engineering design experiences in high school settings will have to transcend traditional disciplinary boundaries.

Case for Technology Education

Although the science community has moved forward with addressing state standard requirements for engineering design, some may argue that pedagogically, technology educators are better suited to actually teach the engineering design process. Technology educators have vied for the opportunity to introduce engineering design into their classrooms for years, resulting in a refocus of their curriculum, standards, and classroom practices (Daugherty & Custer, 2012; Kelley & Wicklein, 2009; Lewis, 2004). Technology education has, in recent times, shifted its pedagogical focus to feature a more engineering design based approached to instruction (Denson, Kelley, & Wicklein, 2009; Gattie & Wicklein, 2007). In addition, technology educators seem better equipped to handle the hands-on process of engineering design, which often necessitates the use of materials for prototypes and working models (Apedoe et al., 2008). There is still a question of technology educators' preparedness to teach content that so heavily relies on applied math and science. Though eager to introduce this subject into high school settings (Gattie & Wicklein, 2007), technology educators indicated several barriers to teaching engineering design, including "difficulty in locating and integrating appropriate levels of mathematics and science for engineering design" (Kelley & Wicklein, 2009, p. 45).

There have been suggestions of using an interdisciplinary approach to teach engineering design that would include developing teacher teams that would encompass mathematics, science, and technology educators. This suggestion comes with many logistical challenges that educators and administrators have to this point not adequately addressed. Nonetheless, developing a set of standards that educators can utilize as a guideline for teaching engineering design is a good starting point. Addressing the pedagogical and logistical challenges of introducing engineering design into high school should be the next step. These revelations have direct implications on the need for further professional development for instructors and preservice teachers as well.

Sequencing the Engineering Design Experience

Whether discussing the learner who evolves from novice to expert problem solver, or the structure of an engineering design problem that can exist in a well-structured or ill-structured design space, it is clear that the teaching and learning of engineering design problems comprises points on a continuum (Carr & Strobel, 2011). This observation emphasizes the importance of sequencing and correctly identifying the necessary skills and abilities needed to solve ill-structured and well-structured problems. To date, how to properly sequence the engineering design experience is a question that has yet to be adequately addressed in the literature. In contrast to science and mathematics courses, developmental sequences have not been identified in high school engineering education courses (Householder & Hailey, 2012). This is partly due to the nascent state of engineering design in high schools, but it also speaks to the challenge of teaching engineering design to students with varying competencies.

Although some states have established standards that follow a sequential implementation of engineering knowledge and skills across K–12, the learning community still lacks a consensus on the effective sequencing of engineering design based content. Many learning progressions developed by educators for engineering design are based on the assumption that students are exposed to the engineering design process prior to high school (Hynes et al., 2011). This is not a safe assumption. Though most agree with the importance of teaching engineering prior to reaching college (Carr & Strobel, 2011), there is currently a lack of literature documenting what this experience should look like.

Sneider (2011) lays out an intriguing plan for sequencing age-appropriate engineering design challenges starting in the fourth grade. By using the science framework, he addresses the sequencing quandary by using standards-based instruction as guiding principles for an engineering design framework. However, he correctly notes that the specified sequence is not based on research. As we look to develop and select age-appropriate engineering design challenges, researchers and engineering educators will need to work hand-in-hand to develop standards that are age-appropriate for all skill levels of learners. In the interim, researchers and educators can look toward the National Research Council and the National Assessment of Educational Progress (NAEP) for guiding principles to help in identifying age-appropriate knowledge and skill benchmarks. As instructors consider the type of engineering challenges to introduce (open-ended or well-structured), identifying student competencies at certain points on the continuum from novice to expert designer will be key in sequencing the engineering design experience (Jonassen, 2011).

Selecting Engineering Design Challenges

When strictly speaking of engineering design as a *process* and not the content that accompanies this subject, problem (or project) based learning (PBL) is the most widely accepted pedagogical approach to teaching design

(Householder & Hailey, 2012; Dym, Agogino, Eris, Frey, & Leifer, 2005). According to Householder and Hailey (2012), "Engineering design challenges are ill-structured problems that may be approached and resolved using strategies and approaches commonly considered to be engineering practices" (p. 2). With this definition considered, there is still little agreement about what constitutes an appropriate engineering design challenge for high school students. There is some agreement among researchers and instructors about the importance of introducing real-world challenges that appeal to the humane sensibilities of students (Carr & Strobel, 2011; Schunn, 2011; Apedoe et al., 2008). In order to increase motivation and interest in solving engineering challenges, it is recommended that teachers provide students with an opportunity to choose their own challenges and set their own goals (Schunn, 2011). Eisenkraft (2011) even suggests providing opportunities for students to promote their culture or other cultures of interest within the design challenge. Allowing students to pick their own challenges and set their own goals enables them to set standards of excellence and take ownership of their problem.

When developing engineering design challenges, Carr and Strobel (2011) argue that instructors should focus on the intertwinement of real-world problems for high school students. Ideally, engineering design challenges for high school students should be open-ended problems with a plethora of different solutions whereby the students identify the necessary constraints, conduct a needs analysis, and identify their own goals (Hynes et al., 2011). Such an approach would allow students to develop critical-thinking skills, acquire engineering habits of mind, and engage in deeper learning. Unfortunately, studies have shown that, as a result of traditional pedagogy and standards-based curricula, most high school students are ill prepared to solve ill-structured problems (Jonassen, 2011). This finding does not necessarily mean that high school students should not engage in open-ended problems. In fact, high school students should experience *both* open-ended and well-structured problems throughout their learning progression. Carr and Strobel (2011) make the case that ill-structured and well-structured problems both have a place in engineering education but should be represented by different points on a continuum. So the question is not a dichotomous one of *either/or* but one of *when* a particular design problem is appropriate.

When considering the type of engineering design problem to introduce to students, it may behoove instructors to let students identify their own problems. Problem formulation is a central concept in engineering design. Too often, students are given the problem with all of the accompanying constraints and resources. When speaking of designing, Dym, Wesner, and Winner (2003) suggested that "we need to spend more time thinking about how we *define* the problem, rather than on the solution to a problem" (p. 106). Problem formulation determines the framing of the problem and the solution. Mehalik and Schuun (2006) stated, "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" (p. 521). Adams, Turns, and Atman (2003) also assert that problem setting is as important as problem solving and proffered a working definition. This definition included: the designers' 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. Students can gain a more authentic engineering design experience if they are allowed to formulate the problem themselves (Schön, 1983).

Assessing the Engineering Design Experience

One of the most contentious areas of concern when discussing the infusion of engineering design into high school settings is the issue of assessment. Davis, Gentili, Trevisan, and Calkins (2002) proffer that assessment methods for engineering design have not matriculated to a well-understood and accepted level. There have been many suggestions but no consensus about what the most effective approaches for evaluating student performance are, whether it includes student portfolios, verbal protocol analysis, essay responses, or even asking students closed-ended questions (Dym, 2005). What researchers can agree on is the difficult problem that assessing the engineering design process presents. This difficulty is exacerbated by instructors' struggle to provide timely and effectual feedback to students on their performance in engineering design challenges (Schunn, 2011). To address this issue, some educators have reasoned that students must take more ownership of their learning experiences, including developing experimental tests and criteria for their designs (Eisenkraft, 2011; Hynes et al., 2011; Jonassen, 2011). Schunn (2011) even suggests that high school students engaged in a design challenge should be able to identify their own constraints, conduct a needs analysis, and identify their goals in an engineering design experience.

In addition to the inordinate amount of time it may take to assess engineering design outcomes, it also remains a very subjective and difficult subject to assess (Bailey & Szabo, 2005). To combat this, Davis et al. (2002) and Trevisan, Davis, Calkins, and Gentili (1999) suggest creating a set of criteria and developing a scoring rubric for students. This can be done in conjunction with the students themselves. In fact, Eisenkraft (2011) argues that students should not only take ownership of their learning experience by choosing their own challenges and goals but also create their own assessment rubric. This will allow students to set their criteria for excellence, with teachers scaffolding their experiences along the way. Hynes et al. (2011) strengthens this argument by suggesting that students are capable of developing their own experimental tests to evaluate solutions.

Though it is clear that high school students will have to take on more responsibility in assessing their experience, the current literature fails to provide a clear path toward addressing this problem of balancing the responsibilities of assessment between instructor and student; it also fails to provide any suggestions for dealing with the issue of timely feedback. There is some agreement on the following educational objectives as a way to determine student performance: (a) design process, (b) teamwork, and (c) design communication (Davis, Gentili, Trevisan, & Calkins, 2002; Trevisan, Davis, Calkins, & Gentili, 1999). According to the literature, assessment should focus on the design process and the student teams' application of this problem-solving method (Bailey & Szabo; Davis et al., 2002; Trevisan et al., 1999). Teamwork serves as a primary tenet of assessment as this approaches authentic real-world experiences of engineers. Finally, students should be assessed on how well they document and justify their design process and on how well they are able to communicate their design and accompanying decisions to their peers or clients.

Teachers considering introducing engineering design into their classrooms may use modeling artifacts as a way to offer tangible deliverables for students. Students encounter modeling during the engineering design process as a by-product of their design experiences (Roth, 1996). For those teaching engineering design and struggling with assessment, modeling artifacts may provide some inroads as an adequate assessment technique (Lammi & Denson, 2013). Throughout the engineering design process, there are artifacts that students create to document their decision making. These artifacts can come in the form of a device, a system, or even a process. To address the issue of timely feedback, instructors can have students deliver a conceptual, graphical, mathematical, and working model before turning in their final design (Lammi & Denson, 2013). As a form of formative and summative assessment, modeling artifacts may help alleviate much of the ambiguity inherent in engineering design problems. In addition to their use as a pedagogical tool, modeling artifacts also help develop students' higher order thinking skills (National Academy of Engineering and National Research Council, 2009).

Conclusion

In this article, we put forth a conceptual framework that will help promote the successful infusion of engineering design experiences into high school settings. When considering a conceptual framework of engineering design in high school settings, it is important to consider the complex issue at hand. For the purposes of this article, the issue at hand centered on identifying necessary components to support the infusion of engineering design experiences in high school settings. The essential components of this framework include: (a) situating engineering design in the curriculum, (b) sequencing the engineering design experience, (c) selecting appropriate engineering design challenges, and (d) assessing the engineering design experience. Attention to these components will support the teaching of subject matter content and the teaching and learning of critical-thinking skills, engineering habits of mind, problem-solving skills, and systems thinking. Without adequate attention to each of these areas, the infusing of engineering design experiences in high school will be without the necessary structure and curricular support.

Acknowledging the dearth of research focused on engineering design in high school settings, a framework should also support the investigation of engineering design experiences. It must be noted that though this article puts forth a framework for engineering design experiences in high school settings, much of the literature on this matter comes from tertiary settings. More empirical research is needed in high school settings in order to provide empirical evidence to support this or any framework. As research focused on engineering design in high school setting continues to grow, it will serve as the foundation of how engineering design experiences are designed for high school settings. A graphical representation (Figure 1) of our conceptual framework is provided below. As you can see, the four themes presented in this article build upon the foundation of research supporting engineering design experiences in high school. The framework helps supports the teaching of subject matter content while developing engineering habits of mind, problem-solving skills, and critical-thinking skills. Additionally, this framework supports the investigation of engineering design experiences in high school settings.

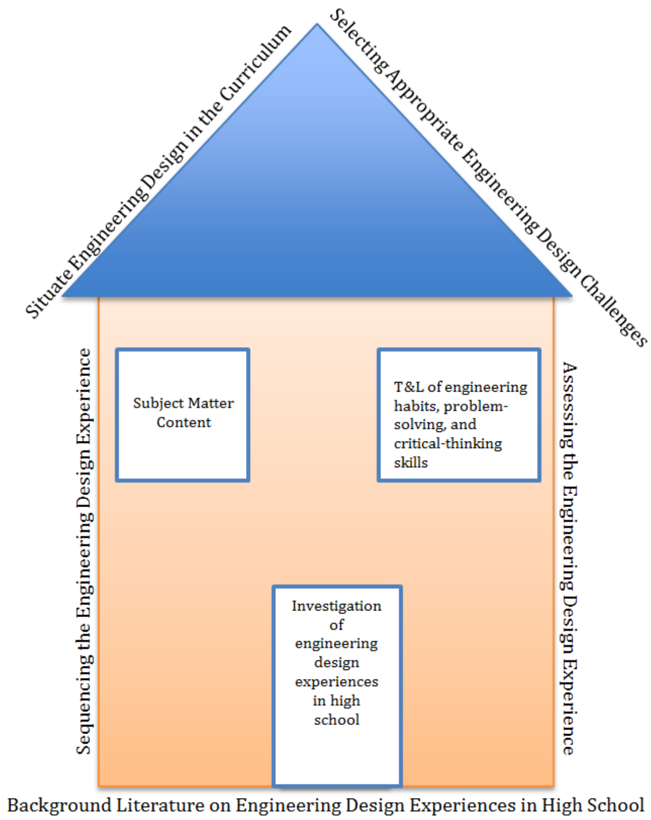

Figure 1. Conceptual framework for infusing engineering design into high school classrooms.

Discussion

For future discussion, it is our assertion that answering the question of age-appropriate sequencing will serve as a key component to the proper development of engineering design challenges and the successful infusion of engineering design experiences in high school. Proper attention to the sequencing of engineering design coursework and astute understanding of the design space will lay the groundwork for investigating successful design experiences. Consequently, more empirical research is needed to identify age-appropriate skills and abilities needed at each grade level in order to properly sequence engineering design experiences.

There are other issues that surround this paradigm shift, and it will take input from the whole learning community to effectively address these questions. If students should have engineering design experiences before high school (Carr

& Strobel, 2011) there is a need for collaboration and consensus across the board on the skills and abilities to be taught in experiences prior to high school. If a theory of a spiral curriculum for engineering education is widely accepted for the teaching of engineering design, then it should be considered in the design of curriculum and teaching strategies (DiBiasio, Clark, & Dixon, 1999). Although some states have established standards that follow a sequential implementation of engineering knowledge and skills across K–12, the learning community still lacks the research needed to trumpet effective sequencing of engineering design based content.

There are also procedural questions that still need to be answered before any consensus can be achieved about the proper instruction of engineering design in high school. As an example, Jonassen (2011) asserts that the goal of design is not optimizing but satisficing. This runs contrary to Hynes et al. (2011), who argue that redesign and optimization is an essential guiding principle for engineering design in high school. This dissonance may be the result of incongruence when it comes to defining optimization. Answering this question will go a long way toward the development of appropriate assessment strategies. There is also the growing expectation for students to develop their own experimental tests and grading rubrics (Hynes et al., 2011; Schunn, 2011). Though the literature makes a compelling case for students taking more responsibility for assessing their engineering experiences, it does not account for the time and skills needed for students to be able develop their own rubrics and other assessment tools.

Implications

Words like *little* and *more* dominate the conversation about research as it relates to engineering design experiences in high school. This is a testament to the nascent status of engineering design in high school classrooms. As researchers go forward with their investigations of engineering design experiences in high school settings, they should pay special attention to decision making. Decision making and improved decision making seems to be an overarching theme in the design process (Hazelrigg, 1998). According to Jonassen (2011), design problem solving can be represented by a series of decisions made by students. The study of students engaged in the engineering design experience should focus upon how students make decisions during the design process. As we consider how students approach problems and narrow the problem space, it would benefit us to investigate the reasons students make specific decisions.

Because it is still a burgeoning subject area, proper professional development for engineering education must accompany the field's shift to focus more on engineering design. As the body of literature on engineering design continues to grow, it is important that the creation of professional development for engineering design in high schools reflects findings based on empirical research. The efforts of this framework will be incomplete until more research on engineering design is reflected in the creation and implementation of professional development. For now, educators vying to introduce engineering design can turn to the Next Generation Science Standards for their standards. Curriculum developers and other stakeholders will have to consider the implementation of team teaching to teach engineering design, particularly if professional development efforts continue to fall short of addressing teacher concerns.

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