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A Conceptual Framework for Engineering Design Experiences in High School

Dr. Cameron Denson, North Carolina State University

Cameron Denson is an assistant professor of Technology and Engineering Design Education (TDE) in the Dept. of Science, Technology, Engineering and Mathematics (STEM) Education at N.C. State University.

Dr. Matthew D. Lammi, North Carolina State University

Assistant Professor of STEM Education

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Abstract

The infusion of engineering design into high school settings can help develop students' critical thinking skills and expose them to engineering careers at an early age. However, since the advent of engineering design in pre-college milieus, researchers, educators, and curriculum developers alike have been brooding over ways to introduce this equivocal subject into the k-12 realm. Due to its interdisciplinary nature engineering design has also struggled to find a home in classroom settings moving between technology education, to science classrooms and even informal learning environments. These factors considered it is our belief that the science, technology, engineering, and mathematics (STEM) field as a whole has failed to provide educators with an adequate literature-based framework for the infusion of engineering design experiences into the classroom. This includes determining proper sequencing of engineering design activities and establishing what types of engineering design problems high school students are able to work or solve. This paper will attempt to ameliorate some of these issues by promulgating a conceptual framework for introducing engineering design experiences to high school students. We will address the following areas in regards to engineering design in high school settings: *situating engineering design in the curriculum, sequencing the engineering design experience, selecting appropriate engineering design challenges and assessing the engineering design experience*. It is our contention that proper attention to these four areas will support the infusion and investigation of proper curricula and pedagogy needed to provide successful engineering design experiences for high school students.

Keywords: framework, engineering design, and high school

Introduction

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 [1-3]. The teaching of engineering design at the secondary level can help students develop critical thinking skills, teambuilding skills and provides a platform for the integration of science, technology, engineering, and mathematics (STEM) subjects [3]. 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 [4]. 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 literature void, 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 [5]. The inception of NCETE coincided with a paradigm shift in technology education to develop a more engineering focused curriculum [3, 6]. This call for a new focus was not without its problems including addressing professional development needs for in-service and pre-service teachers, lack of alignment with state standards, determining authentic engineering design experiences and assessing the engineering design experience [7]. 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.

In putting forth a conceptual framework for engineering design experiences in high school, this paper builds upon a synthesis derived from the six position papers referenced above, expanding on their findings through an analysis of relevant literature. Conclusions drawn from our expanded synthesis builds towards a framework for engineering design experiences in high school settings. For the purposes of this paper, a framework is defined as a structure that is used to solve complex issues. It is not the goal of this paper 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: *situating engineering design in the curriculum, sequencing the engineering design experience, selecting appropriate engineering design challenges and assessing the engineering design experience*. We contend that only after addressing these areas of development can the educational community begin to provide proper curricula and pedagogical practices needed for the infusion of successful engineering experiences for high school students.

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 [8]. 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 [9]. Hynes et al. [10] 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 (NGSS), which include engineering and engineering design as major focal points [11]. Pedagogically there is merit to a push for engineering design experiences within high school science classrooms. According to Apedoe et al. [2], 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 [2, 12, 13].

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 as to *who* is better prepared to introduce engineering design at the secondary level. It is presumptuous to assume 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

While the science community has moved forward with addressing state standard requirements for engineering design, some may argue that pedagogically it is better suited for technology educators 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 [14-16]. Technology education has in recent times shifted its pedagogical focus to feature a more engineering design based approached to instruction [6, 17]. 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 [2]. 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 [6], technology educators indicated several barriers to teaching engineering design including "difficulty in locating and integrating appropriate levels of mathematics and science for engineering design." [14]

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 pre-service 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 [18]. This observation emphasizes the importance of sequencing and correctly identifying the necessary skills and abilities needed to solve ill-structured and/or 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 [4]. 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 from 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 [10]. This is not a safe assumption. Though most agree with the importance of teaching engineering prior to reaching college [18], there is currently a lack of literature documenting what this experience should look like.

Sneider [8] 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 sequence specified 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 [19].

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 [4, 20]. According to Householder and Hailey [4] “Engineering design challenges are ill-structured problems that may be approached and resolved using strategies commonly considered to be engineering practices.” With this definition considered, there is still little agreement as to what constitutes an appropriate engineering design challenge for high school students. There is some agreement among researchers and instructors as to the importance of introducing real-world challenges that appeal to the humane sensibilities of students [2, 18, 21]. 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 [21]. Eisenkraft [22] 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 [18] 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 [10]. 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 traditional pedagogy and standards-based curricula, most high school students are ill prepared to solve ill-structured problems [19]. 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 [18] 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 to engineering design. Too often, students are given the problem with all of the accompanying constraints and resources. When speaking of designing, Dym et al.[23] suggested "we spend more time thinking about how we define the problem, rather than on the solution to the problem." Problem formulation determines the framing of the problem and the solution. Mehalik and Schuun [24] 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, an on which goals and constraints designers meet." Adams, Turns, and Atman [25] 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 setting frequently. Students can gain a more authentic engineering design experience if they are allowed to formulate the problem themselves [26].

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 et al. [27] proffers that assessment methods for engineering design have not matriculated to a well-understood and accepted level. There have been many suggestions but no consensus as to what are the most effective approaches for evaluating student performance whether it includes student portfolios, verbal protocol analysis, essay responses, or even asking students closed-ended questions [20]. 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 [21]. 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 [10, 19, 22]. Schunn [21] 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 determine [28]. To combat this, Davis et al.[27] and Trevisan et al. [29] 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 [22] argues that students should not only take ownership of their learning experience by choosing their own challenges and goals, he also proposes that students should be able to create their own assessment rubric. This will allow students to set their criteria of excellence, with teachers scaffolding their experiences along the way. Hynes et al. [10] 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, current literature fails to provide a clear path toward addressing this problem of balancing the responsibilities of assessment between instructor and student, nor does it have 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 [27, 29]. According to the literature, assessment should focus on the design process and the student teams' application of this problem solving method [27-29]. 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 and/or clients.

Conclusion

In this paper 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 paper our 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: *situating engineering design in the curriculum, sequencing the engineering design experience, selecting appropriate engineering design challenges and 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 needed structure and curricular support.

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