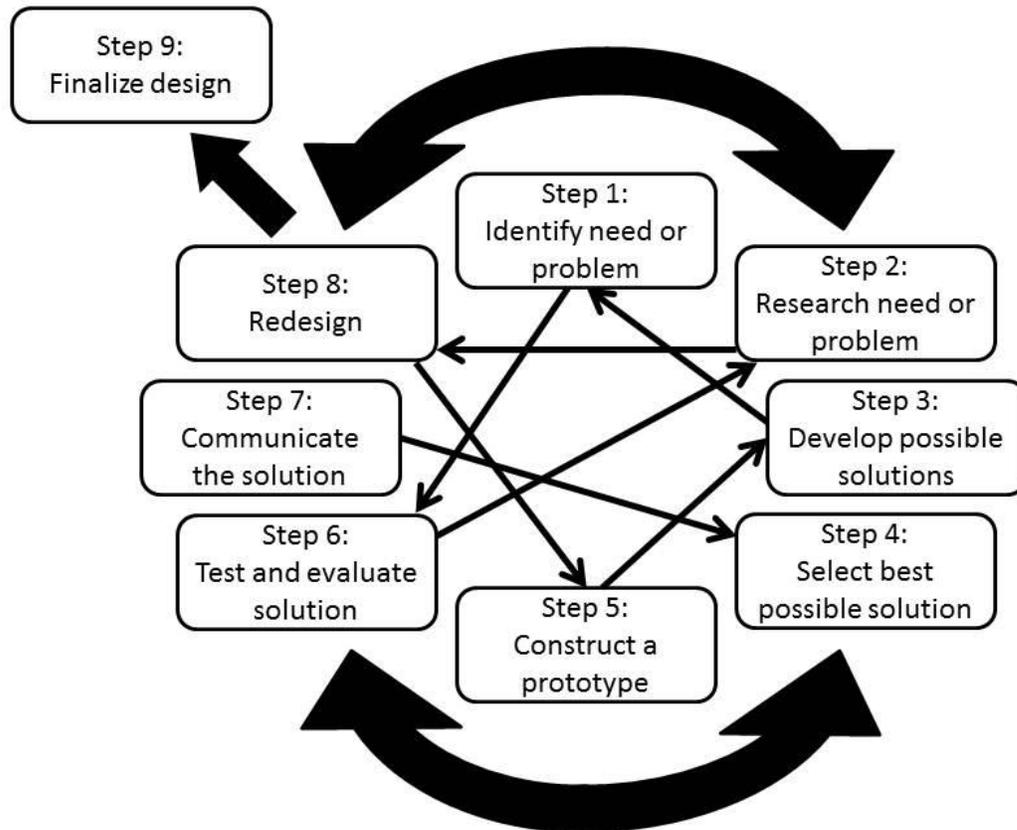


Incorporating Engineering Design Challenges into STEM Courses



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National Center for Engineering and Technology Education

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Preface

The National Center for Engineering and Technology Education (NCETE) invited a small group of experienced engineering educators, curriculum developers, cognitive scientists, and professional development providers to engage in the discussion of guidelines for the selection and development of engineering design challenges suitable for all students in grades 9-12. That effort resulted in seven provocative papers (Carr & Strobel, 2011; Denson, 2011; Eisenkraft, 2011; Hynes et al., 2011; Jonassen, 2011a; Schunn, 2011; Sneider, 2011) that are accessible on the NCETE web site at <http://ncete.org/flash/research.php>

NCETE hosted two Caucuses, each consisting of “a group of people united to promote an agreed-upon cause” (Merriam-Webster, 2009, p. 196). Ten individuals who were early innovators in introducing engineering design activities in high school STEM settings were invited to each Caucus. Both Caucuses were held on the Utah State University campus in Logan; the first August 2 and 3, 2011 and the second May 22-24, 2012. The invited papers and an annotated bibliography were made available to the Caucus participants to provide background information. The Caucus groups engaged in intensive dialogues during their on-campus sessions, prepared statements on aspects of the development and selection of authentic engineering design challenges, and suggested revisions of successive drafts.

Caucus Participants (and the years of their Caucus participation)

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We gratefully acknowledge the varied and substantial contributions of the Caucus participants, Matthew Lammi, Rebeca Olsen, Joy Brisighella, Kiley Downs, NCETE fellows and faculty members, and the support of Gerhard Salinger, NSF program officer.

Daniel L. Householder and Christine E. Hailey, Editors

Introduction

Successful strategies for incorporating engineering design challenges into science, technology, engineering, and mathematics (STEM) courses in American high schools are presented in this paper. The developers have taken the position that engineering design experiences should be an important component of the high school education of all American youth. In most instances, these experiences in engineering design are infused into instruction programs in standards-based courses in science, technology, or mathematics. Sometimes the courses are designated as engineering courses and the engineering design component is emphasized.

Engineering design challenges are ill-structured problems that may be approached and resolved using strategies and approaches commonly considered to be engineering practices. The problems typically arise in the human-made environment and affect some aspect of the quality of human life. The term includes “engineering” because developing solutions to the problems involves processes similar to those used in the professional practice of engineering, in addition to the integration of knowledge and practice from mathematics, science, and technology. The term includes “design” because problem solutions typically require the creation or modification of artifacts or procedures used by humans in dealing with the physical environment. The term includes “challenge” to indicate the fact that learners are being asked to confront an unresolved problem in the human-made environment. The focus of the challenge is on solving the problem, not competing with other learners.

There is a lack of consensus regarding what constitutes appropriate engineering design instruction at the high school level. There is little agreement concerning activities that should be provided to all students in order to acquaint them with the habits of thought and action that distinguish engineering from other fields. Developmental sequences have not yet been identified in high school engineering education, a situation that stands in stark contrast to traditional course design in science, technology, and mathematics. Even more perplexing is the stark fact that engineering design challenges have multiple possible solutions of varying applicability under differing sets of constraints. Detailed lesson plans, laboratory exercises, and listings of required materials are insufficient instructional strategies for approaching such ill-defined challenges. There is a need for more definitive guidance about what makes quality design challenges and how they can be implemented well in existing courses. There is also a need for clarity concerning the outcomes that may be expected and the effective arrangement of developmental sequences. These understandings inform innovation and facilitate early adoption of effective strategies for infusing engineering design challenges into high school STEM courses.

From its inception, NCETE has focused its efforts on grades nine through twelve. During these years in school, students experience a wide range of STEM courses and are able to approach relatively complex engineering-related problems. We recognize the outstanding work that has been accomplished by studies focused on elementary and middle school engineering design experiences. In contrast, relatively few organized efforts have been directed at the inclusion of engineering experiences in high school STEM courses. The authors of this paper have chosen to focus specifically on engineering design challenges for all students during the high school years.

Purpose

A growing number of researchers seek to understand whether the development of engineering habits of thought and action in high school STEM courses leads to improvements in problem solving abilities, systems thinking, integration of STEM content, increased interest in engineering, and feelings of self-efficacy about pursuing additional engineering activities. We have attempted to integrate these findings,

to draw inferences that reflect the current body of knowledge, and to call attention to promising contemporary practices.

This paper is intended to provide guidelines for the development of authentic engineering design challenges, to describe instructional strategies for introducing engineering design experiences to high school students, and to offer suggestions for the assessment of the outcomes of engineering design activities. The information is intended to be useful in planning, organizing, and implementing the infusion of engineering design challenges in high school STEM courses. The paper is not intended as a detailed guide for curriculum development, comprehensive instructional design, or the assessment of achievement across the range of high school STEM courses.

This paper is an exploration of the available research on the following questions dealing with the implementation of engineering design challenges in high school STEM courses:

- Does the development of engineering habits of thought and action lead to improvements in problem solving abilities, systems thinking, integration of content, increased interest in engineering, and feelings of self-efficacy about pursuing additional engineering activities?
- What is the anatomy of the engineering design process and what are its essential components?
- What are the distinguishing characteristics of authentic engineering design challenges?
- In what ways do engineering design challenges fit into the national STEM scene and the high school STEM organizational structure?
- What are the content, context, and process elements of appropriate engineering design challenges for high school STEM courses?
- What instructional practices based upon engineering design challenges are effective in supporting student learning?
- In what ways can teachers design and implement an authentic system for assessing student progress and completion of engineering design challenges? How can the assessment provide support for using engineering principles to solve design challenges in contrast to simple trial and error approaches?

Procedures

The developers synthesized relevant findings of currently available research in engineering education. In addition, they referenced experiences of successful innovators who have prepared instructional materials, developed engineering design experiences, provided professional development to assist teachers in implementing engineering design challenges, studied classroom implementation of engineering design challenges, or developed theoretical models to guide instructional design, student investigations, or teacher professional development. Although time constraints did not permit consensus via face-to-face discussions, successive development and review procedures during the preparation of the paper provided opportunities for the participants to offer feedback.

Organization

The first section of the paper includes an examination of goals for incorporating engineering design challenges into the high school STEM setting. The second section includes an exploration of the meaning of design in this context, followed by a review of current models of the engineering design cycle. The third section describes issues related to classroom implementation, such as student motivation, teaching practice, and managing dimensions of engineering design in the school setting. Guidelines for selecting and implementing engineering design challenges are described in the fourth section, using the nine steps in the Hynes et al. (2011) model as an organizing framework: (1) identify need or problem; (2) research

need or problem; (3) develop possible solutions; (4) select the best solution; (5) construct a prototype; (6) test and evaluate the solution; (7) communicate the solution; (8) redesign; and (9) finalize the design. Research results and practice-based recommendations are included where relevant to the discussion.

Assessment of the quality of student work on engineering design challenges poses new responsibilities for learners and teachers. Promising approaches to assessment are explored and described briefly in the fifth section. The national educational milieu is changing rapidly and many of these adaptations are likely to have major influence upon possibilities for including engineering design challenges as a part of the education of all Americans. Current proposals, frameworks, and national influences are explored in the sixth section of the paper. The paper concludes with discussion of findings, themes and issues in section seven.

Section One: Goals of Engineering Design Challenges in the High School STEM Setting

Engineering design, as practiced by engineers in the workplace, is a highly social, highly iterative process where, often, no single right answer exists. Dym (1994) described the context in which engineering design occurs as necessarily open-ended, suggesting a plethora of acceptable (though not optimal) solutions, and ill-structured, indicating that solutions cannot be found routinely by simply applying mathematical formulae in a structured way. Similarly, in their analysis of engineering design, Jonassen, Strobel, and Lee (2006) described the inherently ill-defined context in which engineering design problems are embedded, alluding to the vagueness of goals, implicit constraints, and availability of multiple solutions and paths to reach solutions.

In the high school setting, elements of the design experience should reflect professional practice in engineering by cutting across a range of complexities that allow students to frame problems iteratively, test and evaluate their ideas, generate and construct prototypes (where applicable), and balance competing constraints and criteria in order to create an optimal solution and communicate their work to stakeholders. However, the fundamental goals for providing students with opportunities to engage in engineering design at the high school level are different than those of practicing engineers. Fundamental cognitive goals include improving students' problem solving abilities; system thinking abilities; and understanding of science, technology, and mathematics concepts, while the affective goals include generating interest in engineering and enhancing self-efficacy to solve engineering problems.

K-12 engineering education aids in the development of an *engineering habit of mind* which includes "1) systems thinking, 2) creativity, 3) optimism, 4) collaboration, 5) communication, and 6) ethical considerations," (Katehi, Pearson, & Feder, 2009a, p. 5). The process of solving engineering design challenges requires learners to engage both in analytical reasoning and in active creation and testing of solutions. Both thought and action are involved as learners develop *engineering habits of thought and action*, often referred to as design and problem solving skills. The modifier, "engineering," before the words "design challenges" is important for developing students' engineering habits of thought and action. Science and technology courses may include design projects without specific consideration of engineering design principles and students may enjoy these projects and develop creative solutions to them. However, without guidance in applying principles of engineering design, students miss the opportunity to approach the design problems as engineers might approach them, with an emphasis on finding the best solution based on constraints and tradeoffs, and iteration (Sneider, 2012).

The goal of developing engineering habits of thought and action through engineering design challenges results in multiple learning outcomes for students, one of which is improved abilities to solve ill-structured problems with a problem based learning (PBL) approach. PBL has been found to increase student motivation, performance on transfer tasks, and build a deeper understanding of content particularly in the form of long-term retention (Oliver & Hannafin, 2001; Strobel & van Barneveld, 2009). In addition, experiences in PBL aid in building mental models of difficult science and mathematics concepts (Linn, diSessa, Pea, & Songer, 1994). PBL particularly emphasizes problems characterized as *ill-structured* (Jonassen, 1997). Jonassen (2011b) argued that problems vary in terms of structuredness, complexity, and context. On the structuredness and complexity continua, design problems tend to be the most ill-structured and most complex. Kapur (2008; 2011) presented groups of students with well-structured problems, while others were assigned ill-structured problems in mathematics and physics. The students solving more complex and ill-structured problems without assistance experienced frustration while other groups received teacher-directed facilitation. Despite appearing to fail in their problem-solving efforts, the unsupported students solving the ill-structured problems significantly outperformed their counterparts on both the well-structured and higher-order transfer problems. Although it is frustrating, productive failure may lead to deeper learning and improved problem solving abilities (Jonassen, 2011b; Petroski, 2006).

Another cognitive goal of providing engineering design experiences in the high school is to develop systems thinking abilities. “Systems thinking” involves an understanding of how parts of a whole interact and interrelate with each other. When engaging in an engineering design challenge, students must keep a wide range of interrelated variables in mind as a solution is developed. While analytical thinking pervades engineering design activities, the integration of the performance of components and sub-systems is vital to the success of all but the simplest design problems. Consequently, the role of systems thinking is vital in solving complex engineering design challenges while simultaneously considering environmental issues, safety, ethical implications, and economic factors (Lammi, 2011). Systems thinking permits students “to break out of the narrow definition of a problem and reflect on the relevant systems and how they affect, and in turn are affected by, new and improved technologies” (Sneider, 2010, p. 140).

The implications of systems thinking include focusing on deeper concepts and behaviors, multiple variables and their interactions, optimization, sketching, and analogical reasoning. When these techniques are implemented, students may be more inclined to think in terms of systems. By integrating systems thinking experiences into early engineering design challenges, students may become more excited about engineering, while learning the holistic approach that the modern engineer must take to solving engineering problems (Jain, Sheppard, McGrath & Gallois, n.d.).

Engineering design can be integrated into STEM curricula to provide a mechanism through which students learn relevant STEM content (Hmelo, Holton, & Kolodner, 2000; Mehalik, Doppelt, & Schunn, 2008; Schunn, 2009). Design thinking demands the application of mathematics and science principles. Engineering design is a thoughtful process where pertinent variables governing the behavior of systems are used to optimize the solution. Science and science inquiry inform identification of variables and their relationships. Mathematics is essential for describing relationships that enable explanations of system behavior. Error will exist in any model because variables used to explain performance will be limited by our capacity to understand and precision in measurement. Variables requiring complex mathematics and specialized measuring equipment may be beyond the scope of high school education. The mathematical descriptions are only as valuable as the model’s capacity to predict performance and serve as a guide for experimentation. Error can be reduced as the model is calibrated through physical testing. Data can be gathered as variables are manipulated so that trends may be identified and described. This mathematical modeling serves to guide physical experimentation and narrow the range of acceptable solutions.

Engineering design naturally supports multiple solution paths, but how does one ensure that the design challenge stays on target to support the relevant STEM content? Schunn and his team found that a systems design approach helps to achieve this goal. For example, to teach key thermodynamic concepts in chemistry class, students were asked to design chemically-based heating or cooling systems. “In order to make progress on such systems, students needed to learn key big ideas in chemistry, regardless of which kind of system they wanted to design (e.g., a headband that cools them on the dance floor, or a therapeutic blanket that heats athletes, or a heated toilet seat)” (Schunn, 2011, p. 1). High school science textbooks such as *Active Physics* (Eisenkraft, 2010) illustrate the use of engineering design challenges to introduce the engineering design cycle and to use engineering vocabulary. Aspects of the engineering design challenges appear at multiple times in the units – in the introductions, the mini-challenges and the chapter challenges. Throughout each unit, the author has reminded students of the need to connect their new science concepts to the challenges after each section (Eisenkraft, 2011).

Well-crafted engineering design challenges can increase students’ interest in engineering and their self-efficacy in solving engineering problems. For example, high school students who participated in an eight-week engineering design-based unit exhibited increased interest in engineering careers (Apedoe, Reynolds, Ellefson, & Schunn, 2008). The importance of increased interest and its relationship to understanding and self-efficacy have been reported by Denson, Austin, and Hailey (2012) and by Hailey,

Austin, Denson, and Householder (2011). Unfortunately, many students are discouraged from pursuing STEM careers because they lack a sense of self-efficacy in science and mathematics (Austin, 2010). Well-designed engineering design challenges provide learning experiences that stimulate students to believe that they are capable of accomplishing complex engineering tasks. These supportive learning experiences are established in part through providing appropriate scaffolding for approaching the engineering design challenges. Effective scaffolding requires careful attention to several factors, such as breaking larger design problems into more manageable sub-tasks and being cognizant of students' current background knowledge as it compares to the types of knowledge required by particular engineering design challenges (Puntambekar & Kolodner, 2005). Mathematical and scientific language is often especially challenging to understand (Halliday & Martin, 1993), so it may be helpful if scaffolds also include activities that support students' comprehension of texts relevant to the engineering task, such as manuals, informational websites, and textbooks. Because problem-solving requires affective dispositions such as self-confidence, thoughtfully-crafted engineering design challenges are also essential to building students' self-efficacy in problem solving (Jonassen, 2011b).

Section Two: Anatomy of Engineering Design in the High School Setting

While engineers refer to their work simply as engineering or engineering design and problem solving, the profession is broad in scope and defies simple definition. Engineers design artifacts that range in scale from drug molecules and microchips to aircraft, buildings, and the electrical grid. The time scales over which the designs are implemented range from seconds to decades. The testing, evaluation, and iteration done on designs may include mechanical, electrical, and chemical testing as well as complex simulations and customer testing. Even with this great diversity of scale and application, there have been numerous attempts to describe the common elements of an engineering design process, in part, as means to improve the efficiency of the design process in terms of cost, safety, and sustainability. Cross (2008) provided a review of several models of the design process in the professional setting including descriptive models and prescriptive models. Descriptive models focus on the importance of generating a solution concept early in the design process followed by analysis, evaluation, refinement and development of the solution. Prescriptive models emphasize the importance of analytical work to fully understand the design problem prior to solution generation.

A general model of engineering design is well illustrated by the spiral model of product development presented by Sheppard, Macatangay, Colby, and Sullivan (2009). The process begins with user studies and problem identification; continues through the development of a conceptual design, prototyping, and testing; and ultimately culminates in a sustainable implementation plan resulting in the creation of the marketable product designed to solve the problem. The model is especially helpful in visualizing the “iterative and intertwined nature of defining, generating, testing, and evaluating ideas” (p. 104).

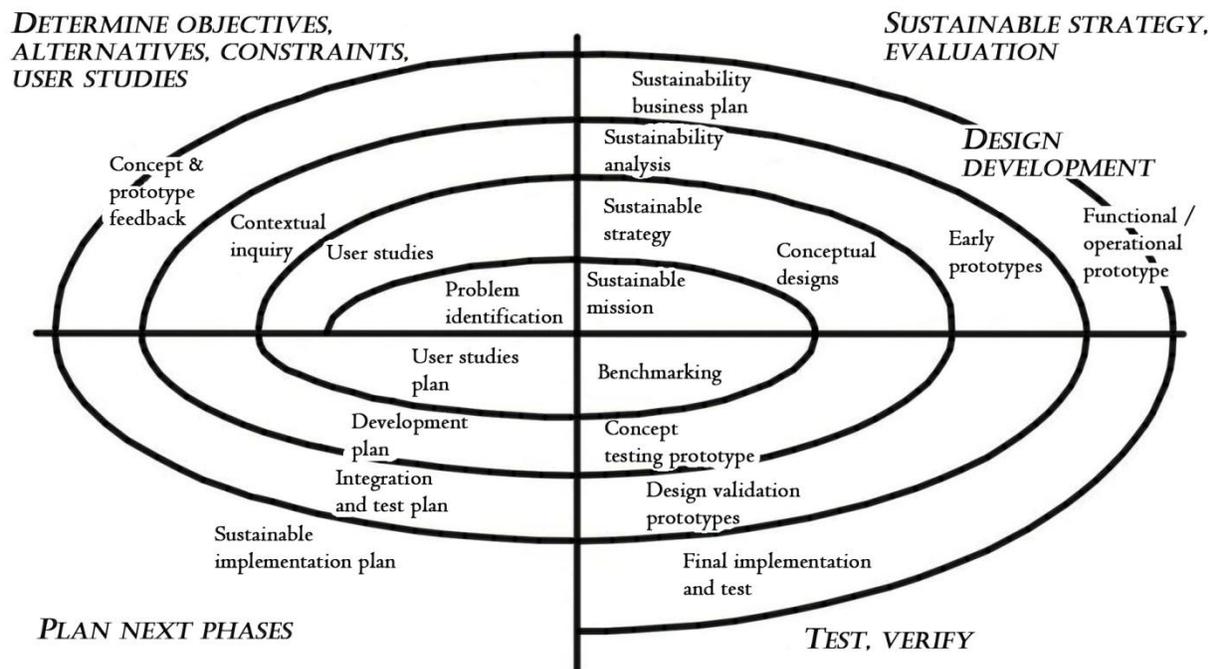


Figure 1. Spiral model of product development
Source: Sheppard, Macatangay, Colby, & Sullivan, 2009, p. 105

In moving from the workplace and the practice of engineering to the high school educational setting, there are also multiple representations of the engineering design process that highlight key features of a

process appropriate for high school engineering design challenges. There is variation in the labels used for the key steps and how the steps are connected together. The variations among engineering design process representations may be due to their dependence upon the context, the type of engineering design, and the resources and abilities of the individuals involved. After a meticulous review of a wide range of contemporary approaches to introducing engineering design to high school students, Guerra, Allen, Crawford, and Farmer (2012) synthesized their common features:

- Identify and define a need, often through discussions with prospective customers
- Quantitatively characterize and analyze the system, converting customer needs into engineering specifications; this may often be an iterative process also involving the definition of the need
- Generate and select concepts
- Select concepts for detailed evaluation; this can often involve building and testing a prototype
- Refine the concept
- Finalize and communicate the results of the design

Building on the synthesis work of Guerra et al. (2012), the UTeachEngineering program developed the comprehensive model of the engineering design challenge process illustrated in Figure 2. This generalized model symbolizes the engineering design process as it appears in the professional practice of engineering and in undergraduate engineering education programs.

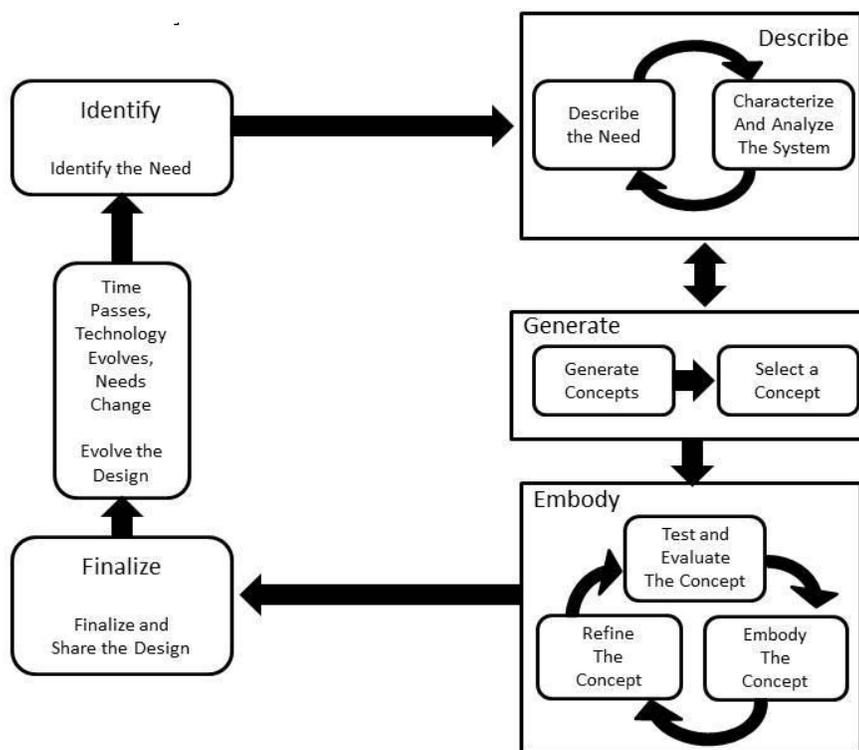


Figure 2. The UTeachEngineering model of the engineering design process
Source: Farmer, Allen, Berland, Crawford, & Guerra, 2012.

The “Describe” step in the model includes both the description of the need and the analysis of the system in which the need occurs, with the expectation that this cycle may be repeated as necessary.

During the “Generate” step, there is an implied expectation that several potential solutions will be identified and studied before one concept is selected for further development. The “Embodiment” step illustrates the cycle of prototype development, testing, and refinement. This cycle may be repeated until the decision is made to finalize the design and communicate the results of the design process.

The UTeachEngineering model includes two steps or stages following the usual engineering design cycle: “Finalize and Share the Design” and “Time Passes, Technology Evolves, Needs Change – Evolve the Design” These stages initiate a re-examination of the need and re-start the engineering design cycle. The UTeachEngineering project uses this model as a guide in pre-service preparation of university students and in the professional development of practicing teachers to enable both groups to teach design-based engineering. In addition, the model has been used to guide the development of a full-year engineering course to serve as a science elective for high school seniors in Texas.

Engineering and technology were included as integral components of science education in the 2006 version of the Massachusetts K-12 curriculum framework. This formal recognition of the role of engineering in science education was a new milestone in the incorporation of engineering and technology in science education. The model of the engineering design process intended for all students studying science, engineering, and technology in grades K-12 is illustrated in Strand Four of the Massachusetts Science and Technology/Engineering Curriculum Framework (Massachusetts Department of Education, 2006). The Massachusetts student-focused model employs the engineering design process shown in Figure 3.

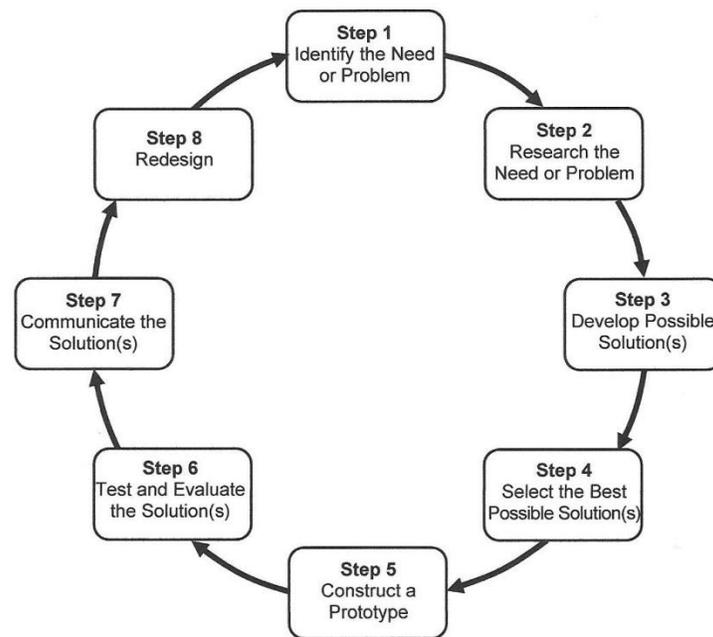


Figure 3. Massachusetts engineering design process
Source: Massachusetts Department of Education, 2006, p. 84.

A group of engineering educators in Massachusetts recently developed a more detailed model of the engineering design process (EDP). The model adds several features to illustrate the complexities of the engineering design process. Hynes et al. (2011) wrote

Recently, we worked with the Massachusetts State Department of Education to produce a revised engineering design document that describes a learning progression for the EDP [engineering design process] from kindergarten through high school. . . . This depiction of the EDP implies a cyclical, stepwise process that is rarely the case in solving real-world engineering problems. Oftentimes the task requires some jumping around from step to step, as shown in the figure below. (p. 8)

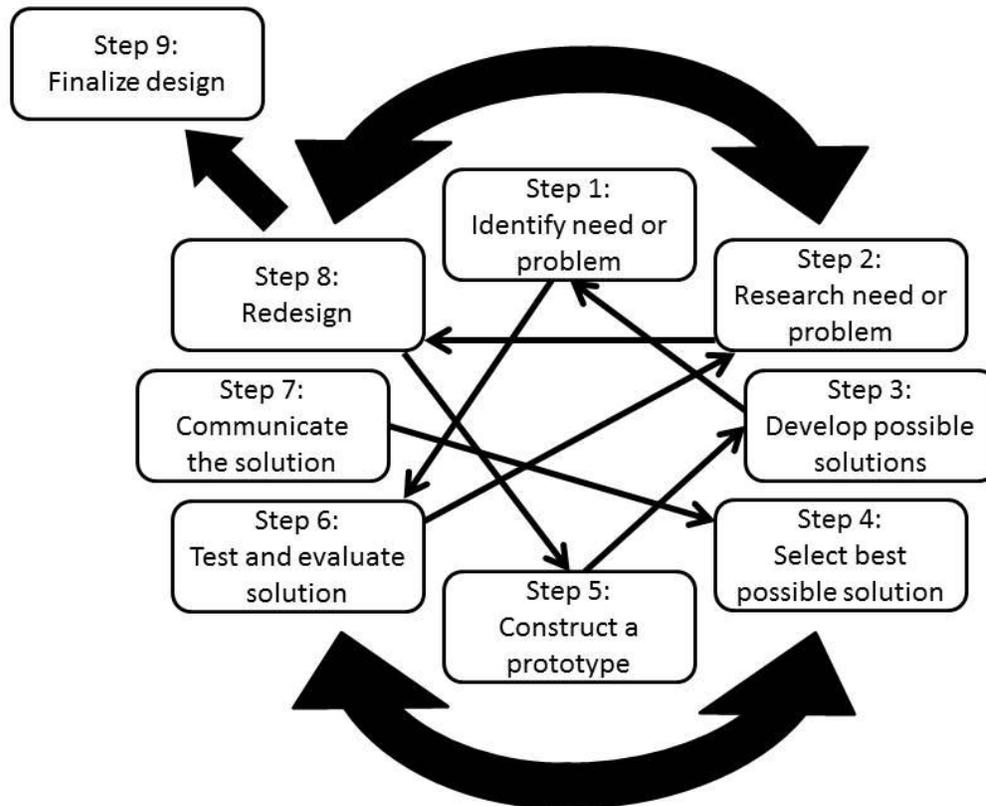


Figure 4. The NCETE engineering design model
Source: Hynes et al., 2011, p. 9

Secondary students may lack the time, expertise, and inclination to undertake the sophisticated long-term design challenges that characterize undergraduate engineering education. However, it is helpful if they have opportunities to work through the engineering design cycle from early problem identification through the development and testing of a satisfactory resolution of the issue. Their experience in engineering design is enriched if the process allows for recursion, returning to previous steps in the cycle to revisit and improve tentative decisions in order to enhance the outcome of the process. The arrows cutting across the center of the figure illustrate the recursive nature of the model. While the Hynes et al. model is quite complex, it is especially realistic in recognizing the need for attention to progress at each stage in the design cycle. By encouraging frequent re-examination of earlier design decisions, the model provides a more accurate, enriched perspective of the engineering design process. Also, this model highlights the completion decision as Step 9, where the design satisfies the customer and is finalized.

The model of the engineering design cycle shown in Figure 4 provides a comprehensive and accurate representation of the processes involved when authentic engineering design challenges are infused into high school STEM courses. For the purposes of this paper, the model is designated the “NCETE Engineering Design Model.”

What Is Not an Engineering Design Challenge?

One major goal of this paper is to provide an explicit definition of an engineering design challenge. The NCETE Engineering Design Model discussed in the previous section highlights what we believe to be the most important characteristics of engineering design challenges. In order to establish limits, it seems helpful to consider engineering design challenges in contrast to similar and related instructional activities that are often found in present-day high school STEM classes. These contrasting types of activities may have useful roles as one part of an engineering design activity, but by themselves are not sufficient to help students engage fully with the engineering design process.

Scientific inquiry activities provide an obvious contrast to engineering design challenges. Inquiry is motivated by the interest in developing an understanding of what is going on in an indeterminate situation. The inquiry process may well lead to hypotheses that invite empirical verification. However, inquiry does not necessarily involve the creation of a new process or a modified product to resolve a need arising in the physical environment. Finding, inventing, or creating a satisfactory solution to a problem in the human-made world, however, is the domain of engineering design.

Many types of problems are posed in textbooks and laboratory manuals for standards-based STEM courses. The procedures outlined for solving these problems may be as simple as a checklist or as complex as troubleshooting manuals for complex equipment. Such explicit step-by-step instructions are intended to help everyone obtain the same or similar results. While these approaches are quite common in STEM courses, and may facilitate acquisition of many instructional objectives, they clearly are not engineering design challenges.

Craft activities may be creative and frequently result in unique design solutions, but they also do not qualify as engineering design challenges. It is the case that the prototype of a solution to an engineering design challenge may be fabricated with an aesthetically pleasing and functional design, may meet high standards of quality, and may have a durable finish. However, the distinctiveness of the engineering design challenge is dependent upon the implicit reliance upon analysis and close adherence to the applications of science in the product design; neither craft design nor technological design has such rigorous expectations.

For a problem to be considered an authentic engineering design challenge, its solution must not be solely dependent upon tinkering, “gadgeteering,” or making random modifications without basing those changes upon mathematical and/or scientific analyses. An engineering design activity should be firmly grounded in principles from mathematics and science. Iterations of the design must be built upon a sound rationale and analyses of the data resulting from earlier trials rather than relying upon simple trial and error. Gadgeteering is often associated with the trial-and-error invention process, in which an inventor may tinker with alternative materials and procedures to find more workable solutions. The engineering design process involves understanding of the science undergirding physical relationships and the mathematical foundations of models that guide engineering design.

One Caucus participant (T. Bayles, personal communication, May 22, 2012) offered this example of an approach that could not be considered an authentic engineering design challenge:

A teacher in our professional development group agreed to allow us to video tape a class session during which the teacher would be teaching the engineering design process. The design challenge that the teacher selected was having the students design a pinwheel – the student teams were given the identical sets of materials and a step by step instruction sheet and proceeded to construct identical pinwheels – some of the student teams finished their pinwheels before the class ended, and they did make modifications to their pinwheels – but these modifications were not grounded in any rationale from mathematics or science.

Engineering design challenges that meet the criteria for authentic engineering design at the high school level while also targeting standards-based STEM content are ideal. Educators who seek to create rich, stimulating engineering design learning experiences for their students need to consider the characteristics of the engineering design activity. These characteristics include the criteria, processes, and habits of thought and action, as well as characteristics of the learning environment that empower students to engage in engineering design challenges to meet learning outcomes.

Section Three: Creating the Milieu for High School Engineering Design

Several barriers may prevent traditional high school classrooms from fully supporting engineering design, including pedagogical traditions that emphasize passive student participation, limited classroom space, restricted availability of supplies and equipment, classroom management issues, and a limited amount of time for recursion throughout the design process. In this section, the authors explore approaches that may assist teachers to strengthen student motivation, enhance collaboration, encourage effective communication, and foster creativity. We also offer suggestions about ways to adjust typical school settings and manage learning processes in order to enhance the engineering design experience for all students.

Student Motivation

Teachers can create experiences that allow students to draw connections to real engineering projects such that students are motivated to engage in the design problem for reasons other than evaluation. Teachers can also make real world applications explicit, using obvious examples of instrumentation technologies used by engineers enriched with stories of inventions that spurred technological advancement. Although engineering self-efficacy—a belief that one is *able to* successfully accomplish engineering tasks—is important to students’ overall motivation in engineering design, an individual still may not want to participate in these tasks if he or she does not perceive the challenges as personally or socially relevant and interesting. Though what is relevant and interesting varies from individual to individual, promising practices for establishing relevance are described in a growing body of theoretical and empirical literature (Ashbacher, Li, & Roth, 2010; Wigfield & Eccles, 2001). These practices include incorporating engineering design challenges from the students’ communities into service learning activities, allowing students a degree of choice in selecting challenges to be addressed, and providing challenges that align with students’ interests. Social relevance in STEM can also be established by drawing from students’ funds of knowledge (Moll, Amanti, Neff, & Gonzales, 1992) and utilizing the strategic and cultural resources in their communities and neighborhoods (Barton & Tan, 2009; Moje et al., 2004). For example, if students have lived or worked on farms in arid areas, their knowledge and experiences may be valuable when working on design challenges related to water distribution.

A socially relevant approach to engineering design is especially important for students from groups that have historically been underrepresented in engineering, including women, African Americans, Native Americans, Hispanics, and Asian/Pacific Islanders (Katehi et al., 2009a). However, it is also important to be aware of the fact that engineering related social practices, ways of using language, and ways of using particular types of tools can alienate people whose preferred social, linguistic, and material practices do not align with those of engineers (Foor, Walden, & Tryten, 2007; Godfrey & Parker, 2010; Walker, 2001). Sensitive identification of problems that are grounded in students’ existing communities, practices, and interests may help in attracting underrepresented students to engineering design challenges.

Teachers need to be inclusive of and responsive to diverse populations in other ways as well. Culturally responsive engineering instruction includes the careful selection of engineering texts to depict engineering as a situated activity that is relevant to diverse groups. Moreover, teachers can actively solicit and encourage the ideas of all students while fostering constructive peer-to-peer interactions in which each individual has opportunities to contribute actively to the design process. Teachers can also actively recruit underrepresented students into their elective courses and show how various branches of engineering serve and enhance their daily lives and their communities.

Engineering design challenges should be grounded in science, technology and mathematics, and they should be set in an appropriate context to serve as examples of the design process. Engineering design challenges are more likely to engage students if they are closely related to issues that are of interest to the learners, especially if their lives would be positively impacted by successful resolution of the issues. In *Changing the Conversation*, the Committee on Public Understanding of Engineering Messages of the National Academy of Engineering (2008) reported that “examples of engineering related to familiar objects and activities stimulated the most interest [among students] in learning about engineering” (p. 7). The Committee further reported that defining the work of engineers as improving people’s lives and helping others was more appealing: “Engineers make a world of difference” (p. 8). Addressing real needs and real issues engages participants in the first step of the design process – defining needs of the customer, client, or user (Svihla, Petrosino, & Diller, 2012). In an underwater robotics design challenge that required students to design a remotely operated vehicle to traverse a pool of water in the shortest time possible, students were engaged to a much greater extent when the design challenge was contextualized to specify that the objective of the remotely operated vehicle was to rescue an exhausted swimmer on the other side of the pool (McGrath, Lowes, McKay, Sayres, & Lin, 2012).

The process of identifying and addressing authentic issues in the lives of the learners requires concerted attention both by the learners and by their teachers. Implementation is a major challenge; for example, 94% of teachers surveyed during professional development strongly agreed that it was important for their students to work on real-world engineering design problems; however, only 44% of the teachers indicated that they implemented engineering design challenges in their classes (Ross & Bayles, 2007). This gap suggests the need to make a greater diversity of engineering design challenges available to students and teachers. These data also emphasize the importance of ensuring that students and teachers have access to the resources needed to resolve those challenges.

Teacher Practice

Designing engineering experiences and a learning environment that is conducive to engineering practices is no simple feat. Teaching practices in science, technology, engineering, and mathematics contexts extend far beyond those employed in traditional instruction. Teachers play many roles, from knowledgeable expert to psychologist to coach to disciplinarian (Hammer & Schifter, 2001). They must attend to a multitude of affective, cognitive, and behavioral needs of their students and act responsively on a moment-to-moment basis. Teachers are also expected to meet educational standards in specific content areas and to prepare students for optimal performance on standardized tests and in subsequent courses. Thus, in navigating the complex dimensions of classroom expectations, teachers must be strategic in designing optimal learning experiences for their students.

Presenting students with opportunities to engage in engineering design requires a paradigm shift from the traditional classroom environment in which students work individually on well-defined problems with single right answers to a situation where teams of students work on problems with multiple possible solutions. The learning environment should facilitate collaborative student work on authentic, ill-defined problems of personal and social relevance. The teacher plays an integral role in creating and sustaining a culture that encourages students to become agentive problem solvers. Students need an environment that encourages them to take ownership of the engineering design challenge, identify needs or wants that are personally important or relevant to them, frame the problem within applicable criteria and constraints, generate alternative solutions, evaluate competing ideas, and carry out the construction and testing of prototypes.

As students engage in an authentic engineering design task, their perception of *failure* (e.g., a malfunction discovered during testing) in engineering design may shift, allowing them to embrace the opportunity to learn why something does not work well and to redesign it for optimal functionality.

Throughout this experience, students may engage in iterative engineering design, not because it is what their teacher requires, but because they are invested in the design process and motivated to solve the problem. Moreover, students engaged in the search for solutions to design challenges recognize the need to collaborate and communicate effectively with each other, capitalize upon each other's expertise, and learn to contribute systematically to the design process.

Under certain conditions, even ill-defined, complex, divergent, and seemingly unproductive processes have a hidden efficacy about them that requires a paradigm shift. Kapur (2008) argued that avoiding the over-structured problem-solving activities of learners, and permitting them to struggle or even fail, as this can be a productive experience. However, for failure to be perceived as an opportunity to learn and improve, teachers must frame the testing and evaluation process of engineering as a critical learning process for students that will allow them to iteratively overcome obstacles in the process. To do so effectively, a teacher may provide support structures or reflective questions, express interest and curiosity when something does not work as expected, and display excitement at the possibility of exploring alternatives to the design and revising. This notion also resonates well with Brown's (2008) notion of tinkering as a mode of knowledge production; that is, designing learning in ways that provides opportunities to "play" with knowledge, generate ideas, share and critique, and ultimately strive to understand the effectiveness of one's ideas. Having opportunities to engage in processes that afford such tinkering may also help students expand their repertoire of epistemic resources situated within the context of classroom-based problem solving activities (Hammer, Elby, Scherr, & Redish, 2005).

Teachers, however, may need to prompt students to draw connections to foundational mathematical or scientific concepts in order to understand why something does or does not work. A teacher's prompts may be as simple as "Does that make sense?" to encourage students to reflect on their designs and think about the possible causes for failure. In doing so, students may refer back to mathematical or scientific concepts or models with the intent of improving their designs, rather than simply fulfilling requirements.

Teachers may set up engineering design challenges to reflect "productive failure," which leverages the hidden efficacy in the complex, divergent interactional process that students experience when they are not given explicit or direct instruction (Kapur, 2008; Kapur & Bielaczyc, 2012). Students from groups that solved ill-structured problems but were not given direct instruction encountered "failures" or barriers in the process. However, in a subsequent comparison of effectiveness in solving ill-structured problems, those who had initially encountered failure in attempting to solve ill-structured problems outperformed their counterparts who had initially confronted and solved well-structured problems (Kapur, 2008).

Teachers may employ different levels of scaffolding throughout an engineering design process depending on students' experiences with open-ended problems, strengths in content areas, and the degree of support they require to overcome obstacles. Accordingly, teachers may deliberately design learning experiences that embody five core independent mechanisms: (a) activation and differentiation of prior knowledge in relation to the targeted concepts; (b) attention to critical conceptual features of the targeted concepts; (c) discussion around specific features or unexpected occurrences; (d) organization, assembly, and synthesis of the critical conceptual features into the target concepts; and (e) reflection throughout the iterative design process.

Because there is no single correct way to design and implement an engineering design experience, teachers may vary levels of complexity, dimensions of the problem, or applications. Teachers may choose to introduce students to engineering through well-structured problems, providing explicit criteria (e.g., build a prototype to travel a specific distance using given materials). As students become more comfortable with engineering design experiences, a teacher may suggest less structured engineering design activities, providing an opportunity for students to identify and frame problem constraints (e.g., design a method of transportation for a community whose population does not have access to fossil fuels).

Creating engineering design challenges that are at an appropriate level of complexity may require several iterations. Teachers should select challenges that are within a student's zone of proximal development, described as the cognitive distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance, or in collaboration with more capable peers (Vygotsky, 1978). Kapur and Bielaczyc (2012) described this location as the "sweet spot" (p. 50) and suggested that students achieve deeper levels of understanding when they grapple with complex concepts. However, if the concepts are too challenging, students may become frustrated and give up trying. Teachers must gauge what can be accomplished, then propose a problem or task that is not beyond the existing skill set and abilities of the learners, with appropriate levels of complexity and structure (Brown, Collins, & Duguid, 1989; Scardamalia & Bereiter, 2003).

The teacher must also strike a balance between what is possible in the classroom and what engineers do in their work. This choice may include students, engaging them to reflect on differences in purpose, process, and product at levels that they understand. Teachers may also improve their skill in selecting appropriate levels of engineering design challenge complexity as they gain experience observing their students solving challenges.

Collaboration in the Classroom

Engineering relies more on social involvement, cooperation, and collaboration to get its work done than is the case in many other fields. Roschelle and Teasley (1995) wrote, "collaboration is a process by which individuals negotiate and share meanings relevant to the problem-solving task at hand. . . . Collaboration is a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem" (p. 70). Collaborative problem solving is an enabling strategy that allows students to share, elaborate, critique, explain, and evaluate shared work (Chi, Glaser, & Farr, 1988; Scardamalia & Bereiter, 2003). Diverse teams, whose members contribute different competencies and perspectives, may cultivate ideas, develop expertise, enhance creativity, and expand the range of possible design solutions. Examples from industry show very clearly that innovation and teamwork go hand in hand (Barak & Goffer, 2002). Developing a shared meaning of the problem in a team based situation requires negotiation and development of a common understanding. "Group decision making is also distinguished by fairly heavy task demands, including social problem space construction, negotiation, and resolution" (Jonassen & Kwon, 2001, p. 41).

When implementing engineering design activities in a classroom context, a teacher may either allow students to choose their own teams or may group students into teams for collaboration. Regardless of the grouping method, a teacher must attend to students' cognitive strengths, to their affective sensitivities, and to behavioral issues. If all students are working on the same engineering design challenge, teachers should group students with varying abilities to enhance within-group learning of concepts, awareness of engineering design issues (e.g., awareness of implications, ability to optimize), and *technical know-how* or familiarity with tools and materials (Ropohl, 1997). In this approach, a teacher's main goal is to diversify student strengths across groups, identifying expertise across a range of skill sets. For example, a teacher may aim to assemble a group comprised of a student who is detail-oriented and strong in mathematical ability with one whose strength is social studies, and another who may be more comfortable with hands-on construction. Each group member must strive to learn from other members of the group; each component is equally important and communication and collaboration is imperative.

It is also possible for a teacher to take a systems approach and utilize this methodology to help students understand the concept of systems engineering. Sub-groups may be created for each part of the design to orchestrate a collective engineering design approach. For instance, if the class is designing for a

sustainable energy source, one group may be responsible for the environmental design implications, another for the mathematical model development, and another for manufacturing. In this approach, each group must understand the work performed by the other groups in order to collaborate effectively. In collective team efforts, students may hold each other accountable for meeting criteria. Accomplishing class goals requires good communication both within groups and between groups.

Regardless of the system used to group students, the teacher must remain vigilant about workload distribution. While diversity within groups may engender collaboration across elements of the design, it may also segregate students into their own specialties, inhibiting them from participating or learning all parts of the design process. Teachers may minimize this tendency by requiring engineering notebooks from all students or providing other opportunities for individual and group reflections on the holistic design process.

Encouraging Effective Communication

Communication is an essential component of the engineering design process – it is central to each of the steps of the process. Students must learn to document their work and to communicate effectively with one another as well as with their “client,” sharing information about the progress that they are making at each step of the design process. This communication is often documented in their engineering design notebook and includes: (a) the design requirements; (b) constraints; (c) prioritization of the design goals; (d) safety considerations; (e) ideas from the brainstorming session; (f) key mathematics and science concepts that influence the design; (g) rationale for design decisions; (h) detailed illustrations and specification of the prototype; (i) design decisions or changes made while building the prototype; (j) performance predictions; (k) data collected during testing; (l) data analysis, interpretation, and rationale for interpretation; (m) cost and safety analysis; (n) summary of the redesign process and changes made; (o) rationale for changes made; (p) detailed illustrations of the new design; (q) cost and safety analysis of the new design; (r) experiments performed on the new design; (s) data collected; (t) analysis and interpretation of the data; and (u) the decision to end the design process and communicate a final solution (once the finished product meets specifications and design goals). One example of this is the Design Cycle Worksheet used in the INSPIRES curriculum (Ross & Bayles, 2007).

Documentation may also serve reflective and analytical roles in the design process. For example, Sadler, Cole, and Schwartz (2000) required their students to create storyboards as they went through the steps of the design process:

These storyboards serve a quite different purpose than “lab reports” in that they document the sometimes curious routes to discovery and include predictions, interim results, insights, and failures. The storyboard provides a pictorial as well as a literal database of student progress in trying to meet the goal of improvement. Student devices are either attached to or drawn in each frame. (p. 321)

Sadler et al. found the storyboards to be particularly powerful in justifying design choices, as students in design problems often consider making only one change at a time to be too slow. The storyboards provide a basis for others in the class to consider alternative explanations about which design change was indeed the most important. The storyboards also enable the designers to substantiate their contention that the causal explanations are in fact accurate and central to the process.

Engineers routinely use a variety of representations—including graphs, two- and three-dimensional drawings, tables, schematic diagrams—to reason through problems and to communicate their initial and final designs to others. DiSessa (2004; cf. diSessa & Sherin, 2000)

argued that proficiency with multiple representations requires *metarepresentational competence*, which includes the ability to “critique and compare the adequacy of representations and judge their suitability for various tasks” and to “understand the purposes of representations generally and in particular contexts and understand how representations do the work they do for us” (p. 293).

High school students who have developed metarepresentational competence know how to effectively organize information throughout the design process (e.g., in tabular or list form), and they select the types of representation that can most fully help them reason through particular aspects of the design when they face difficulties or challenges. Moreover, they can use concise and elegant methods, such as graphs or moving three-dimensional visuals, to explain their final designs to others as they persuade them to accept their solutions. Developing metarepresentational competence requires the production and critique of multiple forms of representation as students compare their informal and formal representations to others’, discussing the strengths and limitations of each in achieving the desired goal.

Fostering Creativity

The design process may be characterized as an iterative loop of convergent and divergent thinking (Dym, Agogino, Eris, Frey, & Leifer, 2005). Many activities in engineering education and in other STEM disciplines focus exclusively on convergent thinking, where the emphasis is on reasoning and using systematic analytical methods to reach a verifiable solution. All problems that have a single answer are of this form. However, it is important to consider a broad array of possibilities when confronting engineering design challenges. Engineering design challenges that encourage divergent thinking may help students to avoid design fixation, where they focus prematurely on a single idea to the exclusion of all other alternatives.

Emergent research suggests that imposing some structure to open-ended design problems may assist in encouraging more creative thinking (Lewis, 2009). For example, particular routines can be utilized to enhance creative thinking both in real-world engineering design and in the classroom. Such routines can include instruction and practice in systematic methodologies for thinking about the problem and for provoking ideas (Barak, 2004; Barak & Goffer, 2002). Similarly, simple heuristics may enable designers to consider new parts of the problem space that they would not have considered otherwise, and this approach may ultimately lead to more creative design solutions (Yilmaz, Seifert, & Gonzalez, 2010). This work helps us to understand that creativity is not exclusively a function of free association or some other haphazard process or individual trait.

Creativity may also be a function of goal-oriented activities that proceed by breaking the problem into manageable segments, each of which is amenable to the application of rules or heuristics. Larger insights may accrue by the synthesis of the outcomes of a number of smaller, less creative steps (Lewis, 2009). Barak (2004) recommended that systematic and structured methodologies may be most appropriately used in addition to other less structured activities that encourage more open-ended brainstorming where students can consider a wide range of alternative ideas without evaluating them.

A related finding is that creative thinking may benefit from a broad, solid knowledge base. Webster, Campbell, and Jane (2006) found that when students were designing recycling devices, they developed more creative ideas in contexts that included more structured lessons earlier in the year. In addition, those students who had knowledge of related systems were more likely to incorporate those ideas into their designs, thereby enhancing the creativity of their solutions. In general, the theory of design thinking

processes and the evidence in design learning suggest that engineering design challenges should foster creative solutions by including support for both convergent and divergent ways of thinking within the design process and by facilitating productive interaction among the two approaches.

Managing Engineering Design Challenges in the School Setting

Providing an appropriate space for student work on engineering design challenges is, in many cases, a substantial design challenge in itself, since few existing buildings provide adequate space or equipment, storage facilities, and supply inventories to support intensive classroom implementation of authentic engineering design challenges. In fact, in many school systems, there is a shortage of adequate laboratory facilities for science instruction as well. (Singer, Hilton, & Schweingruber, 2005).

Space

To date, there is no generally recognized standard for facilities for engineering design experiences in the high school. While it seems clear that it would be desirable for learners to have access to a design studio environment, a rudimentary fabrication laboratory, a range of prototyping equipment, relevant materials testing capabilities, and appropriate spaces for small groups to work concurrently on different engineering design challenges, there is no professional consensus on minimum requirements or clear descriptions of optimal settings. Effective engineering design work may require access to computing capabilities, technology laboratories, science laboratories, educational media centers, and flexible spaces for construction of prototypes.

Few facilities planning standards consider the possibility of interdisciplinary involvement across the STEM subjects. For example, the most recent facilities planning guide from the International Technology and Engineering Educators Association (Neden et al., 2010) offered comprehensive suggestions for a “Center of Applied Learning.” These suggestions included a wide range of instructional areas in technology, but did not make specific provisions for engineering design and prototype testing. Planning for and providing such capabilities in the typical school require a shared vision, close collaboration among STEM teachers, and administrative and community resources and support. A promising possibility for conversion of existing laboratories was described by Palmer (2012a), who reported that the Eugene, Oregon School Board was considering a proposal to convert former wood shop and auto mechanics space into technology and engineering design studios with project construction areas, storage, demonstration, and testing areas to serve STEM classes and a competitive robotics initiative. The proposal was approved by the board, which allocated \$2 million in bond funds for the project (Palmer, 2012b).

Equipment and Supplies

Teachers incorporating engineering design challenges into their STEM courses need to be attentive to the needs of their students for the requisite design and fabrication tools, testing apparatus, computers, and software. They must also have ready access to a variety of materials for the construction of prototypes, though these need not be retained in inventory if there is some flexibility in local or on-line purchasing of consumable materials. While there are a number of sources of helpful products and resources, the infusion of engineering design challenges requires additional attention to planning and classroom organization, since few school systems have been proactive in facilitating the infusion of engineering design into existing programs.

Management Skills

Teaching students how to manage and effectively use time, space, energy, and materials to complete an engineering design challenge is a complex task. It is helpful to review approaches used in the professional engineering setting and to identify parallel strategies that are useful in classroom management of engineering design challenges in high school STEM courses. Todd, Brown, Pimmel, and Richardson (2000) provided a helpful analysis that incorporates such professional skills as teamwork, time management, and project management in ways that can be implemented in the high school setting. These authors suggested several steps that should be completed before the start of an engineering project:

- Set long term and short term goals
- Know how they are spending their time
- Arrange typical tasks according to priorities
- Distinguish between ‘urgent’ and ‘important’ tasks
- Recognize the need to schedule blocks of time
- Monitor and evaluate their time usage
- Apply these skills to typical student time demands

Many facilitators of engineering design challenges also instruct their students to use additional kinds of organizational tools, such as a virtual notebook, a “to do list,” or a Gantt chart. These strategies are useful for recording activities, noting progress, and planning the next steps in the design process. Kelley (2011) provided a particularly helpful discussion of the value of notebooks in the management of the engineering design process.

Section Four: Guidelines for Selecting and Implementing Engineering Design Challenges

The subsequent discussion of the engineering design process in this paper is based upon the NCETE Engineering Design Model shown in Figure 4. The model is used here to provide a guide for a comprehensive review of the research on engineering design challenges for all high school students in STEM courses. Its nine steps provide the organizational scheme for this discussion. The richness of the interaction among the steps becomes apparent as one examines the reports of research and the recommendations of experienced K-12 engineering educators. The selection of engineering design challenges should reflect the interests and capabilities of all students, because the educational values of experiences with engineering design challenges are not limited to high school students with aspirations to become engineers.

Step 1. Identify Need or Problem

There is a natural temptation for a teacher to select an engineering design challenge that appears to be closely related to the topic under study in a course (or for an author of instructional material to select a related engineering design challenge using the same criterion). However, such an arbitrary and authoritarian decision is unlikely to attract a high level of student interest in the assignment or to sustain their engagement throughout the lengthy engineering design process. Exceptional curriculum materials consider these issues when selecting challenges for students (Eisenkraft, 2010). Ideally, students should identify engineering problems that arise in their personal lives, in the lives of people they know, or in their schools or communities. The process of problem-finding can engage the students in preliminary analysis of difficulties and involve them in interviewing others who are experiencing problems that are amenable to engineering solutions. It is highly desirable for learners to “own” the problem before they begin the engineering design process; the best way to insure this ownership is to engage them in the identification and study of the need or problem at the outset.

Appropriate engineering design challenges are real problems. They are not hypothetical questions or contrived situations with known solutions, like word problems or laboratory experiments. Wang, Dyehouse, Weber, and Strobel (2012) identified key factors that are essential for context authenticity, task authenticity, impact authenticity, and personal authenticity. Authentic problems currently affect real-life situations encountered by the learners, their families, and their communities – and they do not have a generally recognized “right answer.” To be authentic, engineering design challenges, particularly those involving interrelated disciplines of science, technology, and mathematics, are grounded in the theoretical perspectives of situated cognition (authenticity of design experience) and distributed cognition (collaboration). From a situated cognition viewpoint (Brown et al., 1989; Lave & Wenger, 1991), the sociocultural nature and multidimensionality of the problem situates the use of science concepts and thereby lends meaning and purpose to them.

The problematic situation should also be relevant to the goals and objectives of the course in which the learners are enrolled. The solution to the challenge should add to learner understanding of concepts related to the respective course. And the solution to the problem should make a difference in the social setting of the course, the school, and the community as well. Apedoe et al. (2008) found that

using a task that has personal relevance to students will encourage student ownership and increase student excitement and interest in science. The *Heating/Cooling System* is such a design task because students are able to posit a number of design possibilities that can connect to their everyday needs. (p. 460)

Problem definition is a critical step in design thinking. It is the first stage of engineering design and it sets the foundation for developing solutions. Atman et al. (2007) found that experts tended to spend more time on this stage than beginners. Jain and Sobek (2006) found that the more time students spent on problem definition, the more satisfied clients tended to be. “Research has uncovered differences in the breadth of problem-scoping exhibited by novice student engineers and expert designers, who are typically advanced professionals with significant work experience” (Kilgore, Atman, Yasuhara, Barker, & Morozov, 2007, p. 322). Christiaans and Dorst (1992) reported that novices looked for less information and demonstrated less thorough problem scoping in comparison to expert designers. In a study of engineering design thinking at the college level, Bogusch, Turns and Atman (2000) concluded that freshmen considered fewer aspects of the design problem than did seniors. Using an experimental protocol developed in college level studies, Becker, Mentzer, and Park investigated the design thinking of high school students in a series of studies (Becker, Mentzer, & Park, 2012; Becker, Mentzer, Park, & Pieper, 2011; Mentzer & Becker, 2010). The most substantial problem they discovered was the fact that high school students spent very little time on problem definition.

Problems vary considerably in the degree to which their structure is apparent. Engineering design problems are most often ill-structured; that is, their organizational patterns are not immediately apparent (Jonassen, 2011a). However, before the beginning designer (the high school student confronting the problematic situation) can make meaningful progress toward potential solutions, it is necessary to analyze the problem to identify its structural components and the relationships among those aspects. For example, if traffic safety is a major area of concern, an appropriate engineering design challenge related to traffic safety must focus on a carefully delineated problem area, such as reducing the risk of serious injury to pedestrians in the school parking lot or the reduction in accident rates due to driving while texting.

Dym et al. (2005) suggested that successful designers begin the design process by asking questions: No sooner had a client or professor defined a series of objectives for a designed artifact than the designers - whether in a real design studio or a classroom - wanted to know what the client really wants. What is a safe product? What do you mean by cheap? How do you define the best? Questioning is clearly an integral part of the design process. As students begin to identify a problem, they should be encouraged to ask questions about it. The problem framing experience may be teacher initiated or student initiated, depending on their comfort levels, the goals of the learning experience, and the maturity of the designers.

Designers typically encounter ill-structured problems in daily practice and find that they need to clarify constraints, define goals and identify existent, but unstated constraints (Jonassen, 1997). Educators need a sense of comfort in managing the clarification and structuring of problems which can be drawn out through questioning (Dym et al., 2005).

Step 2. Research Need or Problem

The process of researching the need or the problem was well described (Hynes et al., 2011):

Once a problem has been identified, instead of rushing to solve the problem with the first solution that comes to mind, students must conduct some background research. Students should understand that there are many things to consider when solving an issue and recognize that they need to fully explore the challenge in order to be well-informed as to how to solve it (Crismond, 2001). As such, engineering challenges and associated curriculum must make the need for and benefit of research clear to the students. It should not appear as something to rush through to satisfy the teacher’s request. This student-driven research allows students to comprehend that research is integral to the process of engineering (Ennis & Gyeszly, 1991), and that it will improve the quality and efficiency of their work. Note that it is highly likely that as students research the need or

problem and discover new constraints or ideas that they will be redefining and clarifying the problem. (p. 3)

Empathy is suggested by Stanford's d.School as essential to developing an understanding of a problem (<http://dschool.stanford.edu/use-our-methods/>). Empathy for the users or clients of the design solution helps the designer clarify the problem. There is a wide range of empathy among groups of learners. The d.School suggests ethnographic techniques including interviews, observations and identification of themes for developing this understanding.

Berland, Allen, Crawford, Farmer, and Guerra (2012) developed a series of "STEM challenge activities." A primary principle in the design of these challenges was that students would need to incorporate science concepts in order to complete the design challenge successfully. However, Berland et al. were careful to explain that only those mathematics or science concepts that are necessary for the design are highlighted, and only after the students have identified a need for those specific concepts. This characteristic of the STEM challenge activities is consistent with Edelson's (2001) "learning-for-use" design framework.

Step 3. Develop Possible Solutions

Osborn (1953) and Litchfield (2008) suggested that brainstorming is a process of identifying multiple potential solutions. Their work indicated that the higher the number of potential solutions identified, the more likely the final solution would be of higher quality. Thus, teachers should encourage students to brainstorm multiple solutions and discourage fixation on the first solution that comes to mind (Gero & McNeill, 1997). Osborn (1953) suggested that suspension of judgment and welcoming unusual ideas are essential techniques for generating a substantial number of ideas. Teachers may explain the importance of suspending judgment and require the inclusion of unusual ideas as a process.

Constraints

Engineering design challenges are distinguished from other creative endeavors by the existence of constraints that limit the range of possible solutions. The constraints may arise from the problem space (no larger than), from economic limitations (cost no more than) or from quality expectations (last longer than). Time constraints, political constraints, and human resource constraints must also be considered. In many respects, constraints impose the most restrictive limitations to engineering design possibilities. Any flexibility among the constraints should be ascertained before the design processes proceeds too far (Jonassen, 2011a).

Brophy, Klein, Portsmore, and Rogers (2008) pointed out the need to meet multiple constraints, such as cost, safety, culture, environmental impact, and client needs. They indicate that students may experience difficulty in balancing conflicting constraints. Franske (2009) noted that the structured problem solving approach typically found in school settings may create serious obstacles for students who must identify and formulate the constraints that define successful solutions to design problems.

Trade-offs

Trade-offs often impose inescapable limitations upon creativity as increases or improvements in one variable must be considered in terms of effects upon other variables in the context. For example, while it would be desirable for a car to both have a roomy interior and high fuel efficiency, the larger and heavier the vehicle the less fuel efficient it will be. Cell phones should be light and operate for long periods of time, yet large, heavy batteries are required to store the energy required for extended operation. High

school engineering design challenges should reflect this tension by defining constraints that are in conflict (low weight vs. long battery life; spacious interior vs. high fuel efficiency). Leonard (2004) noted:

It's not always possible to satisfy all constraints and criteria, and trade-offs between them are required. The decision-making act should take into account personal and social values, values of the subculture, the local context of designing, and values of the customers or users. It follows that there is no 'perfect' design and that alternatives are possible. (p. 30).

Students may need prompting to consider the array of trade-offs that may apply in a specific design decision and to establish criteria for weighting the choices (Puntambekar & Kolodner, 2005). As Schunn pointed out, "dealing with trade-offs inherently means reasoning about many factors at once" (2009, p. 35). Silk and Schunn (2008) summarized their extensive review of literature on trade-offs:

Conceptual understanding of trade-offs is cognitively demanding, and K-12 students are unlikely to have a normative understanding of interactions between variables in a general sense. Despite this, students can consider trade-offs by utilizing mathematical representations that make the relationships between variables more explicit and by engaging in successive iterations of design activities in which they are able to first consider variables in isolation and then together. (p. 23).

Analytical Thinking

All engineering design challenges should be grounded in science and mathematics. However, the choice of specific principles of mathematics and science vary with the specific problematic situations. Students should learn to use science and mathematics to facilitate and analyze their design. The analysis can happen at multiple points in the design process, such as when students are trying to characterize the problem and the relevant concepts, when they are developing and choosing between models that serve as the basis for their designs, and when they are evaluating their designs and devising ways to optimize them (Burghardt & Hacker, 2004).

Expert-novice studies of design suggest that expert practitioners spend more time than novices gathering information that helps to define the problem and implement their solution. Experts make intentional and purposeful shifts between problem scoping and problem implementing processes so that they inform each other (Atman et al., 2007). The experts are also more likely than the novices to utilize mathematics and science as bases for making informed design choices (Crismond, 2001).

Analytical thinking is an important component of systems design. The identification of requirements and needs, alternative possible solutions, specification of information inputs and outputs, and establishing bases for decision-making are all heavily dependent upon analytical thinking (Mehalik et al., 2008).

Step 4. Select the Best Solution

Dym and Little (2009) suggested the use of a decision matrix as a tool for evaluating design solution alternatives on criteria. The decision matrix makes explicit the alternatives and permits designers to quantify the degree to which each solution satisfies the criteria. This treatment of the decision making process facilitates group discussion and sense making while enabling students to be cognizant of their rationale for solution selection. Dym et al. (2005) suggested that "the common underlying concept in these decision-based design frameworks is that design is a rational process of choosing among design alternatives. Some have questioned whether design decisions are scientifically or mathematically sound" (p. 107).

Defending solutions is essential in the design process. Students need to compile a log documenting their work, recording their decisions and the bases for those decisions. Simply putting students together in groups and expecting them to communicate and negotiate shared understanding without scaffolding may not be successful (Gruenfeld & Hollingshead, 1993; Hackman & Morris, 1975; Hill, 1982; Shaw, 1976). Stasser and Stewart (1992) reported that group decision making is jeopardized when groups tend to consider only shared understandings and eliminate from consideration information that is known only by individual members. In citing work by Nagasundaram and Dennis (1993) and by Stasser and Stewart (1992), Jonassen and Kwon (2001) wrote, “Communication problems in group decision making, especially social pressure for conformity and dominance of group discussions by a few members, often lead to *production blocking* of idea generation and information-gathering during group decision processes” (p. 36). Effective communication is vital to the success of students in developing, sharing and promoting their unique ideas.

As designs are considered for viability, optimization is essential. Students should make their value structures and goals for design success explicit early in the decision process. This sense of clarity provides opportunities to select and promote designs that make the most successful balance of trade-offs. Decision matrices may help students externalize their perceived constraints and criteria, and allow their design to be optimized on the important parameters. Experimentation with variables governing the behavior of the system can permit students to gather data on performance. Identifying patterns and trends in the data allows students to optimize their system so that the solution addresses the problem more efficiently.

Step 5. Construct a Prototype

Engineering design challenges are most effective if they encourage students to design and construct a prototype. A physical prototype is a tangible artifact of the design process. It can be tested and evaluated to ensure that the design has met the design criteria and constraints. Many students find this part of the design process to be highly rewarding because they see their design come to realization. Carson and Sullivan (2003) argued that students are motivated to pursue engineering when they are provided with a hands-on learning curriculum that integrates math and science fundamentals through creative, self-directed learning. Construction of physical prototypes enriches the iterative process of engineering design by helping students to clarify their ideas and communicate them to others (Roth, 1996; 2001). Drawing out ideas has similar representational and communicative effects that enhance the design process (Anning, 1997; MacDonald, Gustafson, & Gentilini, 2007).

It should be noted that not all engineering design challenges require the construction of a physical model. However, it is most advantageous for high school students to be given the opportunity to construct, test and evaluate a physical prototype of their design.

Models and modeling are widely used in engineering education. Engineers construct models that are based on physical laws and mathematical descriptions, but these models are simplifications of the world around us. For example, an engineer might construct a model of the flow of air over an airplane wing in order to make the aircraft more fuel efficient, but assumptions and simplifications are embedded in that model. At best, the model is an approximation of reality. Because models are simplifications or approximations, at some point, they will be incorrect. The model of structural forces used by a high school student to design a bridge truss capable of supporting a specific weight may not account for the different distributions of weight created by a cinder block or a bucket of water placed on top of their model. Nevertheless, the models can be useful as they can be used to show trends and relationships between governing principles. The model can provide the student who is designing bridge trusses useful guidance on the types of structures that will be most efficient in their design.

Understanding distinctions between different quantitative models and physical laws as well as their applicability in specific situations are important parts of engineering education. High school engineering design challenges should involve students in the use of mathematics and science to create models, and to develop understandings of trends and relationships that facilitate the design process.

Hands-on Activities

Constructing a prototype is usually viewed as a “hands-on” activity. The term, hands-on, implies an active learning process. In his review of design in science education, Crismond (2001) listed hands-on tasks as the first major criterion for authentic design challenges:

Good design challenges involve authentic hands-on tasks. Authentic contexts (Mann, 1962, 1981) can motivate students and give them a compelling “need-to-know” (Hmelo, Holton, & Kolodner, 2000; Sadler, Coyle, & Schwartz, 2000) new knowledge and skills. Hands-on activities can help students build or reconnect with substance schemas (Reiner, Slotta, Chi, & Resnick, 2000) that may be important to doing design and can activate device knowledge (McCormick, 1996) and mechanism schemas that naive designers understand only poorly (Miller, 1995). (Crismond, 2001, p. 793)

Bayles, Rice, Russ, and Monterastelli (2007) reported that 58% of student participants stated that the hands-on activities were the best portion of the Young Engineers and Scientists Seminars (YESS) for gifted high school students. Brophy et al. (2008) cited the value of “hands-on activities with technology to develop a qualitative sense for material properties, spatial reasoning, physics, mechanics, number sense, and general problem-solving strategies” (p. 371). They went on to suggest that “more advanced lessons can build on the formalisms of mathematics and science to enhance students’ ability to construct conceptual prototypes for their ideas” (p. 371).

Step 6. Test and Evaluate the Solution

The decisions involved in solving engineering design challenges include significant components, though even the most serious ethical concerns may not be immediately obvious from an initial description of the problem. Dilemmas are often posed by the human implications of the choice of vehicle fuels, the addition of preservatives to food products, or unavoidable risks involved in manufacturing processes. Environmental concerns frequently require choices between damage and efficiency in production or transportation. The need to avoid negative unintended consequences may override the popularity of exciting technological innovations. Product life cycle management also poses a range of choices, such as the need to provide for efficient disposal or recycling. The responsibilities and costs of product life cycle management must be allocated among designers, producers, distributors, and consumers.

An important feature of engineering design challenges is that the artifact students design should be judged against the constraints and criteria of the problem, not some external authority. Most often this authority is either some external disciplinary authority (“the experts think this”) or the teacher’s judgment (Boaler, 2002; Scott, Mortimer, & Aguiar, 2006). When students rely on a teacher’s judgment, even when that judgment is based on the teacher’s own informed understanding of the design requirements, students may come to see their positive evaluations as the primary goal in and of itself. An alternative situation in which students are able to assess and evaluate their designs according to the requirements of the design problem may help the students to become better design decision makers. Having the requirements drive the students’ own assessments and evaluations helps to monitor progress in the middle steps of the design process and determine conditions that will meet the given requirements.

Design requirements establish the primary assessment criteria when students evaluate their work. It is important to make sure that the engineering design challenge has a clear and explicit goal that can be readily observed by students. Sadler et al. (2000) referred to this characteristic as having tests against nature with a large dynamic range. They classified their tests as: (1) those tests that have competitive goals where teams are engaged in head-to-head competitions; or (2) those tests against nature that all groups can achieve (as opposed to differentiating between winners and losers). Tests against nature involve measurement and being explicit about how design changes result in significant improvements as opposed to random fluctuations or experimental error. For example, designing a wind turbine for maximum lift, measuring the outcome, and determining which variable (such as vane pitch or area) is the primary determinant of the outcome.

Step 7. Communicate the Solution

Once the students have finished the design process and have a functional product that meets design specifications and goals, the teams must clearly communicate their results to the customer. This communication step often requires both written documentation and a professional presentation. Because engineering design is often complicated, it is very important to focus on a clear explanation of ideas. Regardless of the mode of communication, students must remember to use drawings, schematics and graphs to help explain their ideas and their results. Comparison of the design to the original goals, criteria, and constraints must be included. Engineers have to be able to effectively communicate their great designs and sell them to their clients (Dym et al., 2005). Some engineering design projects require different teams to work effectively together. One team may be responsible for the design, while another team is responsible for the construction and yet another team is responsible for the testing and evaluation of the design. Therefore, it is essential for the teams to document and communicate their designs and analysis. Ross and Bayles (2007) found that requiring designing teams to have their designs constructed and tested by an independent team led to an increase in the number of projects that met the design criteria.

Design portfolios and engineering notebooks provide students with an organized, structured medium for documenting their work (Kelley, 2011). Teachers should provide examples of successful and well documented portfolios prior to engaging students in the design process so students can understand what data they need to document. Teacher checks of portfolios with feedback on a regular basis will strengthen student documentation.

Connections to English literacy are significant in writing and presenting the design. Students should be acquainted with examples of technical writing styles associated with engineering. Teachers may also need to provide examples to help students understand effective ways to organize content in context and to develop effective technical reports. Students' outlines and drafts may be evaluated by peers or teachers in a formative evaluation model. Final evaluation of student documentation and presentation may be conducted by the teacher alone, but authentic delivery to external members of the community or peers provides a more appropriate venue and emphasizes the need for effective written and oral communication.

Students need experience in communicating with an audience that is unfamiliar with their work in order to strengthen their ability to develop shared meaning and understanding. "Studies of spoken language have established that the meanings of utterances are contextual and negotiated only to the level of agreement needed to support action. . . . the same is true of nonlinguistic representations" (Koschmann, Suthers, & Chan, 2005, p. 135).

Step 8. Redesign

The engineering design process must be iterative so that the quality or the functionality of the design can be improved. The iterations must be grounded in relevant mathematics and science rationale(s) in

order for the redesign to be effective. One way to think of the design process is as a structured method for searching through a large space of possible solutions. Because the space is large and often not well defined, and because the designer has limited time and resources, an effective search of the space requires searching as much of the space as possible while also focusing the search on the most promising parts of the space. Iteration may help with this search process in a number of ways. First, by simply creating more designs, the student will have considered more of the possible designs. In addition, successive iterations may help learners improve their understanding of the problem space and help them to focus on the most promising possible solutions.

As a complement to iteration, modeling helps to define and focus the search space. Modeling provides a foundational basis for understanding the space of possible designs, and determining which are likely to be more effective. The modeling can thus help guide subsequent iterations (Gainsburg, 2006).

Crismond (2001) studied naïve, novice, and expert designers as they investigated the redesign of simple mechanical devices. He found that only the expert designers connected science and engineering abstractions to the redesign problem. He argued that the application of science ideas to the redesign process required additional scaffolding. The redesign step provides teachers an opportunity to introduce mathematics and science principles that students could employ to understand and improve the design.

Reflection

Reflection is an essential element of learning. Students must be prompted to reflect on their product and process. Teachers should draw student attention back to the problem to address solutions so that they are within the constraints and criteria. Engineers “satisfice” which means that they have addressed the problem and developed a solution that is viable and worthy of implementation but can still be improved (Jonassen, 2011a). The identification of “good enough” is difficult for students and should be addressed in reflection. There will be opportunities to iterate and improve on the final solution. Multiple iterations are critical for improving the final product by reflecting on successes and failures. While iterations could be conducted indefinitely, time is a valuable resource and also a limiting factor. The reflection process should allow students to consider when additional time is more costly than the benefit yielded from that investment.

Students can use multiple iterations and reflections to make recommendations on future use, redesign, significant discoveries and challenges faced in the design and implementation of their solution. This form of communication promotes reflection and technical communication skills. Teachers should utilize multiple media to represent ideas, including written descriptions, visual representations, mathematical expressions and formulae, and physical objects.

Reflection may be continuous and synchronous with teaching, in which case it is called concurrent or reflection-in-action (Schön, 1983; 1987). Reflection may also occur asynchronously at some time outside the class period, and thus be disconnected from teaching actions. In either case, reflection should provide students with an opportunity to make connections among their learning experiences.

Step 9. Finalize the Design

In order to bring some sense of closure to the engineering design process, it is helpful to establish the point at which further design work is terminated. When documentation has been completed and edited, and the design team has made oral and written presentations describing the final design solution and demonstrating the prototype to customers, clients, or stakeholders, a moratorium is declared on further development of the design. In the professional practice of engineering, this stage may lead to the production of designed products, the creation of structures, or the implementation of processes. In the

school setting, it is more likely that the completion decision results in a display exhibiting the outcomes of the student design projects, a ceremony acknowledging the accomplishments of the groups, or the transition from the engineering design process to implementation of the design solution in the school, home, or the life of the community.

Hynes et al. (2011) described this phase of the engineering design cycle succinctly:

The very last step of the EDP results in the determination that a final product has been achieved. This product is not simply the result of passing a set of predefined tests, but is based on whether or not students believe they have sufficiently optimized their product to the selected constraints. In this step, students make a decision that they have sufficiently met the design requirements and are ready to implement their prototype as a final product. (p, 5)

Summary

This review is intended to provide a benchmark for the research community and suggestions for practitioners. The comprehensive study of guidelines for the development and selection of engineering design challenges for high school STEM courses reflects the research and experiences of a large number of educators and research teams. Though the recommendations are based upon the 2012 research base, the need for further research, exploration, and knowledge building is obvious. If teachers are to implement engineering design strategically in high school STEM courses, there must be more comprehensive understanding of the effectiveness of different approaches. As researchers and practitioners continue to build the knowledge base on classroom implementation of engineering design choices, their work will also continue to inform the preparation of teachers to enable them to participate effectively in this exciting educational innovation.

Section Five: Assessment of Student Achievement in Engineering Design Challenges

Indicators of success, in terms of student achievement of the learning outcomes, involve best practices in assessment. Identifying the objectives or targets for learning is a key component. Evaluations of many innovations in STEM courses follow the Wiggins and McTighe (2006) “backward design” model. This approach begins by identifying the desired outcomes of instruction, determining the acceptable evidence indicating that those outcomes are accomplished, then planning the learning experiences and organizing instruction so that the outcomes are observable and quantifiable. Wiggins and McTighe argued for an assessment approach that emphasizes big ideas, teaching for understanding, and performance assessment on six facets of understanding: explanation, interpretation, application, perspective, empathy, and self-knowledge.

These facets of understanding provide a framework when identifying the desired results of instruction or specific learning outcomes. Within the context of engineering design challenges, these outcomes include systems thinking, the engineering design process (i.e., exploring multiple solutions, selecting and developing the best solution), professional skills (i.e., collaboration, communication, accounting for ethical considerations and consequences), conceptual knowledge (i.e., mathematics, science, and technology content), and affective behaviors and beliefs (i.e., self-efficacy, career awareness). With these outcomes in mind it is important to develop specific and measurable indicators of success, the evidence that can be evaluated to determine achievement, and a strategy or process by which to make that determination (assessment).

Some guiding principles of sound assessment strategies that are important to consider within the realm of engineering design challenges are use of authentic, performance-based assessment strategies, multiple assessment strategies, formative and summative feedback, documenting student learning progressions, and enabling and assessing students’ metacognitive reflection abilities. Authentic assessments ask that students perform real-world tasks while demonstrating meaningful use of essential knowledge and skills (Mueller, 2011). Such assessments typically include the performance of a skill or demonstration of knowledge within a context where students demonstrate achievement of the targeted learning outcomes in an authentic setting (Avery, 1999; Cumming & Maxwell, 1999; Gulikers, Bastiaens, & Kirschner, 2004; Newmann, 1992; 1996; Newmann, Secada, & Wehlage, 1995). Authentic assessment is also student-centered; whereby students construct or apply their understanding within the context of a task or problem. Engineering design challenges that are complex, contextualized, and authentic provide a rich setting for comprehensive assessment procedures.

An important consideration in assessing student learning outcomes in the engineering design challenge paradigm is the use of multiple, layered assessment strategies that provide a holistic picture of student learning. Engineering design challenges that target several domains of learning in a complex environment typically require multiple strategies for collecting evidence. A single assessment strategy will not provide a complete picture of student understanding. A series of several assessments administered throughout the learning experience can provide both formative and summative feedback, as well as providing quantitative and qualitative data on student achievement. In addition, repetitive approaches to assessment can provide pictures of student learning progressions during the engineering design process as they engage in multiple engineering design challenges. Pre-test, posttest assessment designs are commonly used when documenting student abilities to transfer their understandings to different engineering design challenges.

Metacognitive reflection is an important strategy for documenting a student’s learning progressions as well as an indicator of success in solving engineering design challenges. Metacognition is the ability of individuals to reflect on their learning. Metcalfe and Shimamura (1994) defined metacognition as

“knowing about knowing.” Metacognition refers to the ability to actively control the thinking process, plan an approach to the task, monitor the learning, and evaluate and maintain motivation toward progress being made toward completion. This ability is particularly important in the context of engineering design challenges because metacognition includes self-management and self-appraisal (Lawanto, 2011). Engineering design challenges require that students process the complexities of the problem and plan approaches that enable them to learn more about the problem, define it more rigorously, and develop an effective solution path.

Metacognitive reflection can be included in the overarching assessment strategy of the engineering design process. Metacognition is manifested in the students acquiring sound habits of mind and action, using engineering design language effectively, and making meaning of their engineering design solutions. Atman, Kilgore, and McKenna (2008) found that college students studying engineering design for four years used common language in ways that shaped their knowledge of the engineering design process. In terms of assessment, engineering design language can provide information on student’s metacognitive reflection abilities.

Overview of Assessment Strategies

Numerous assessment strategies are available to high school teachers and researchers studying learner responses to engineering design challenges. Artifacts of the engineering design process include portfolios and engineering design notebooks which provide opportunities for authentic assessments that can be used to document and evaluate student learning. Portfolios are generally a collection of student’s work specifically selected to document progress within a given task. Similar to portfolios, engineering design notebooks provide a comprehensive record of the work of the individual student throughout their response to an engineering design challenge. Rubrics are a common strategy to assess the artifacts using a scoring scale along a task-specific set of criteria. Abts (2011) developed a rubric for assessing an engineering design challenge; it can be used to assess specific learning outcomes outlined in the rubric. Notebooks may be assessed individually to study the work of the individual student, or the notebooks of the members of a design team may be aggregated for a comprehensive assessment of the detailed record of the work of the team and its members. Metacognitive reflections can be included in the assessment strategy of engineering design notebooks or portfolios.

Oral presentations provide an opportunity for individual students or the design team to describe their intermediate or final design solution and their rationale for arriving at this solution. Demonstration of a prototype can be part of the presentation. Poster sessions also provide opportunities for students to describe their design solution and demonstrate their prototype.

Design notebooks, portfolios, and oral presentations can be evaluated by high school teachers or by external reviewers with a vested interest in the design solution. For example, students working on a design for a person with a disability might benefit from a review of their design solution by the person with the disability or a family member or associated rehabilitation professional.

Good assessment includes both formative and summative assessment. Formative assessment should occur at the end of the problem definition phase, and summative assessment should occur at the end of the solution generation phase (Davis et al., 2009). Furthermore, assessments in this environment should occur at individual and team accountability levels.

Assessment Using a Logic Model

A widely accepted approach to assessment design utilizes a logic model to guide the investigation of the degree to which inputs and activities yield outputs and outcomes that accomplish the goals of an

intervention or an instructional program. The model provides a visual image of the relationship between planned work and intended outcomes (W. K. Kellogg Foundation, 2004). A typical logic model is shown in Figure 5. This general logic model was constructed using the RAND Logic Model Template (Greenfield, Williams, & Eisman, 2006).

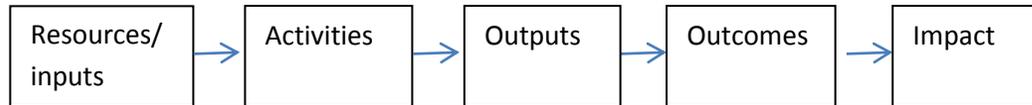


Figure 5. General logic model

The Resources/Inputs and Activities represent the planned work to achieve a program goal and the Outputs, Outcomes, and Impact represent the desired program outcomes. The Resources/Inputs box represents all available resources that a program utilizes as it attempts to complete its work. The Activities box represents what the program does with the Resources. The Outputs box represents the direct products that result from the program Activities. The Outcomes box often reflects both short-term outcomes and longer-term outcomes. Short-term outcomes describe the changes in the program participants' behavior, knowledge, skills, status, and level of functioning at the completion of the program. Typically, long-term outcomes reflect participant changes several years after completion of the Activities. The Impact box reflects fundamental changes in the individuals, the group, or the environment that are direct results of the Activities. It is especially important to emphasize that Impacts should reflect the goals of the program.

The general model may be modified for a specific assessment of the classroom implementation of engineering design activities and may be represented by the model shown in Figure 6.



Figure 6. Logic model for assessment of engineering design activities

The assessment of the outcomes of student engagement in engineering design challenges should be based upon a model of this type. Evaluation of the effectiveness of the educational process requires careful observation of interactions in the classroom, meticulous recording of the results of the learning process, rich descriptions of observable classroom outcomes, and long-range assessment of the impact of the learning process.

The three examples below illustrate applications of the general logic model paradigm in classroom assessments of the accomplishment of three of the goals associated with high school engineering design: Improving problem solving abilities (Figure 7), Improving student self-efficacy (Figure 8), and Improving systems thinking capabilities (Figure 9).

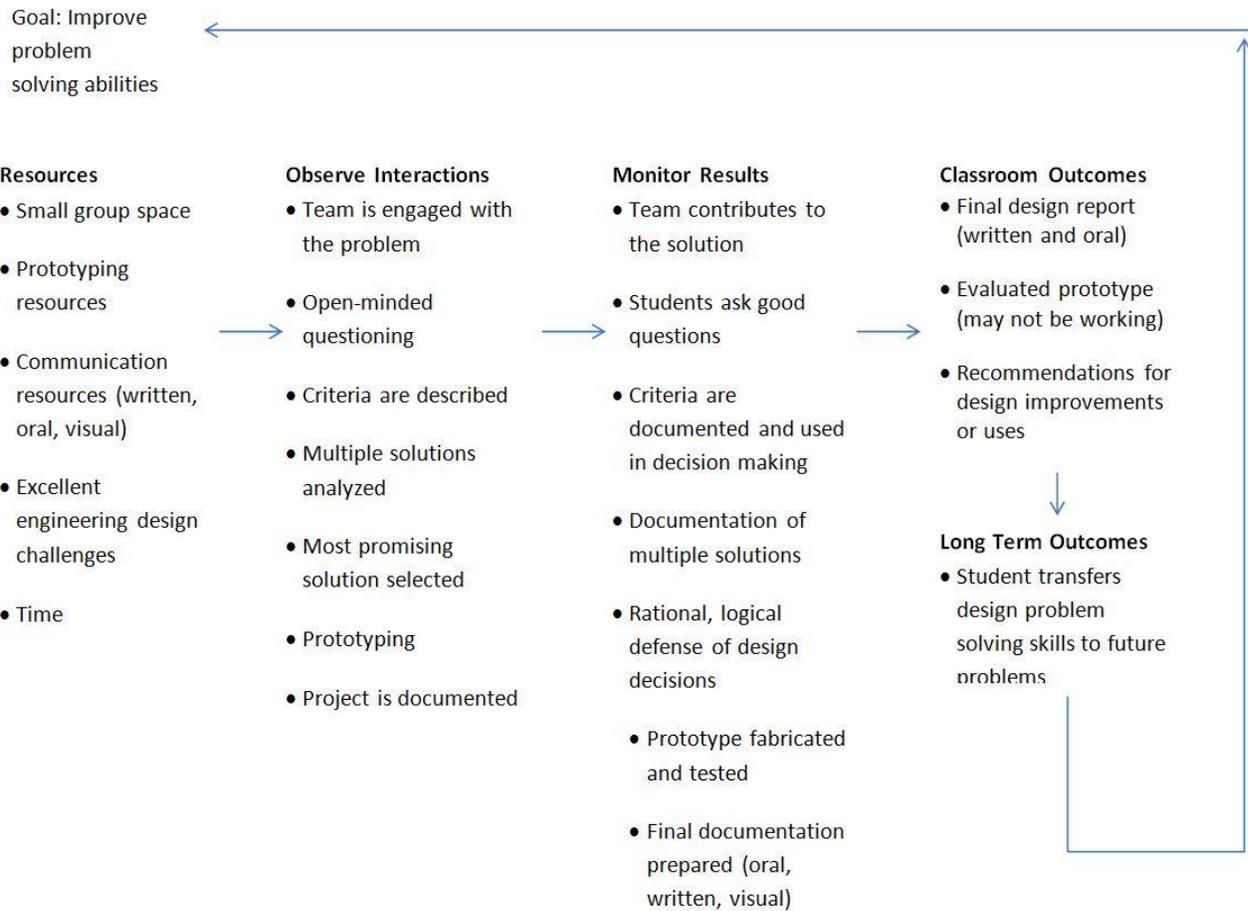


Figure 7. Logic model for assessing improvement in problem solving abilities
Adapted from Greenfield et al., 2006 and W. K. Kellogg Foundation, 2004

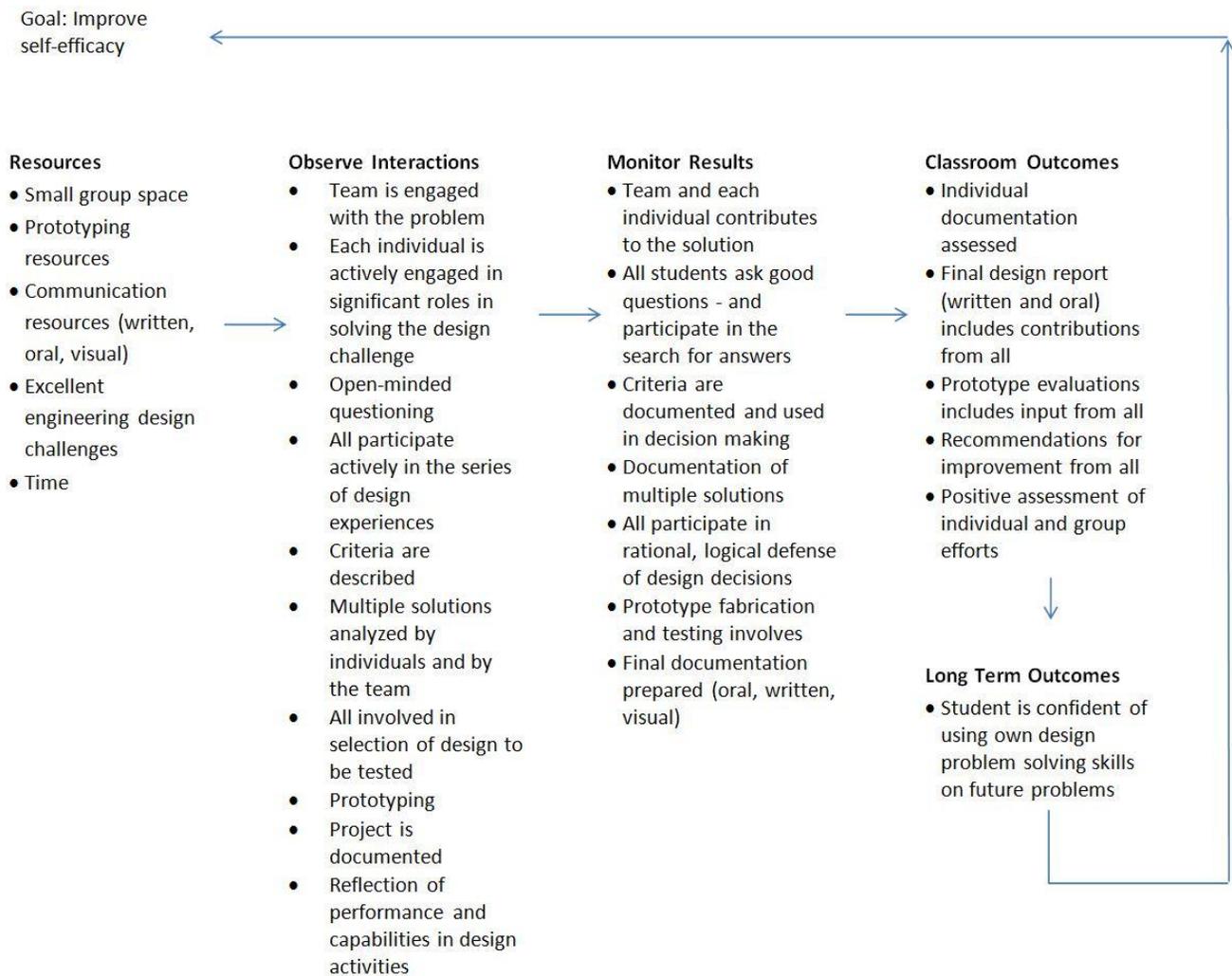


Figure 8. Logic model for assessing improvement in self-efficacy
Adapted from Greenfield et al., 2006 and W. K. Kellogg Foundation, 2004

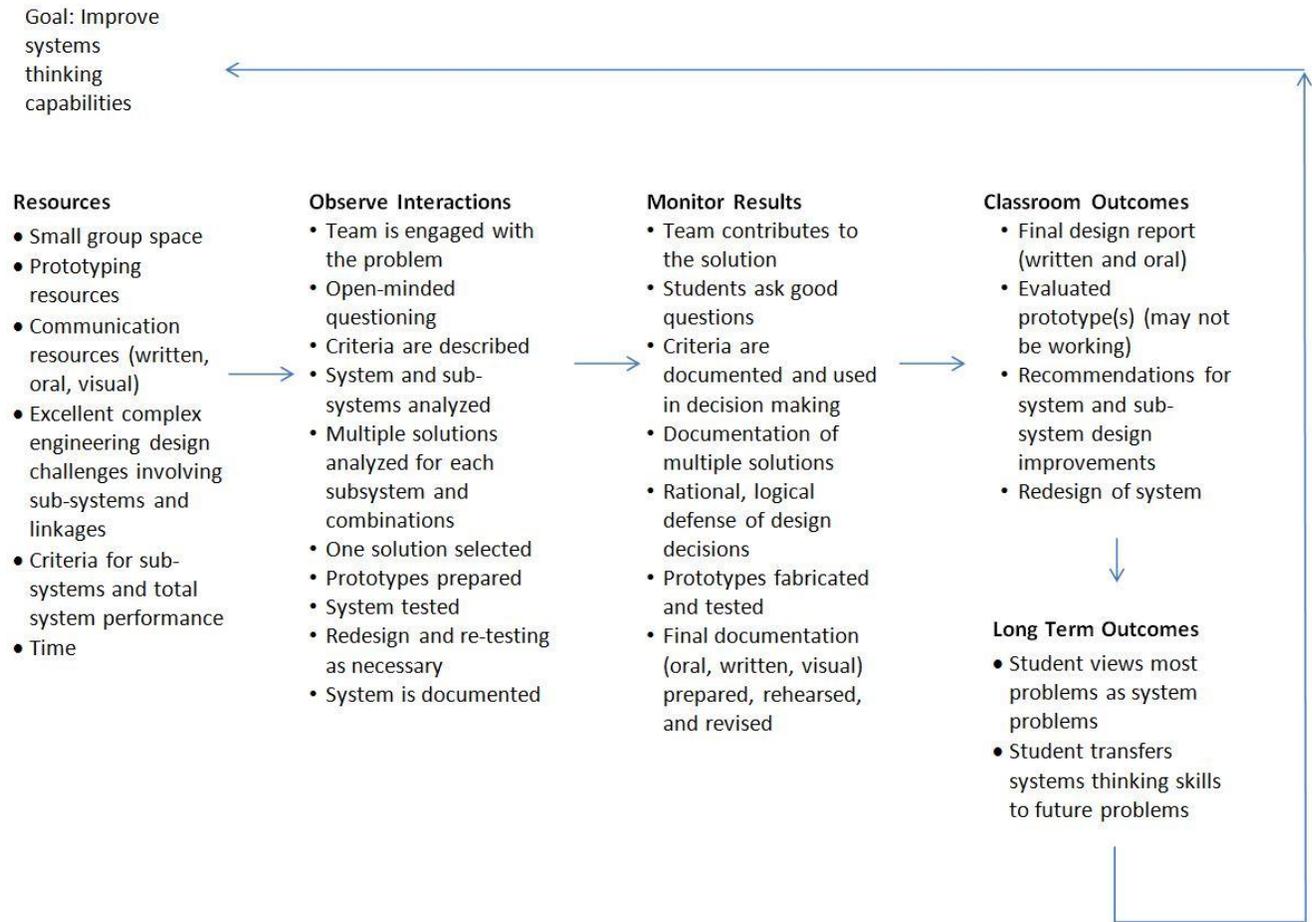


Figure 9. Logic model for assessing improvement in systems thinking capabilities
Adapted from Greenfield et al., 2006 and W. K. Kellogg Foundation, 2004

Selected Assessment Strategies

Common attributes of many engineering design challenges include systems thinking, engineering design process, collaboration skills, communication skills, and understanding of the broader impacts of engineering solutions. Potential assessment strategies for each of these attributes are presented below.

Systems Thinking

Both ABET (2011) and the National Academy of Engineering (NAE, 2005) emphasized the central role of systems thinking in the engineering process. “Engineering design is the process of devising a system, component, or process to meet desired needs” (ABET, 2011, p. 4). NAE (2005) emphasized the need for the next generation of engineers to be global, or systemic, in their thinking and practice. Additional support for the centrality of systems thinking in engineering comes from researchers, practitioners, and other preeminent national organizations.

Outcome	Assessment Strategy
Develop systems thinking knowledge	(1) Through an oral presentation or written document (a) demonstrates an understanding of how individual parts of a system function, (b) how parts of the system relate to each other; and (c) how parts, or combinations of parts, contribute to the function of the system as a whole. (2) Participates in the iterative process by applying new ideas and lessons learned in the design process that positively impact subsequent actions. (3) Participates in troubleshooting and reverse engineering (investigating someone else's design to repair it, replicate it, or refine it); (4) Demonstrates the ability to plan, adjust, and revise an engineering design.
Develop systems thinking skills	Through an oral presentation or written document (a) demonstrates an understanding of how the behavior of a system arises from the interaction of its agents; (b) discover and represent feedback processes (both positive and negative) hypothesized to underlie observed patterns of system behavior; (c) identify stock and flow relationships; (d) recognize delays and understand their impact; (e) identify nonlinearities; (f) recognize and challenge the boundaries of mental (and formal) models.
Develop systems thinking disposition	Through oral presentations or written documents, the dispositions are exhibited (a) to develop reflections are evident that communicate the thinking that informs each step and explains the bases for observations, interpretations, actions and decisions, and (b) to participate in the iterative process by applying new ideas and lessons learned in the design process that positively impact subsequent actions.

Engineering Design Process

Important elements of the design process include definition of the problem, generation of multiple possible solutions, evaluation of possible solutions, and the rational determination of a final solution which includes a prototype. Abts (2011) provided an assessment rubric associated with the review of an engineering design portfolio which is modeled to a considerable extent after the AP® Studio Art Portfolio. The comprehensive Engineering Design Process Portfolio Scoring Rubric (EDPPSR) is currently undergoing trial application.

Outcome	Assessment Strategy
Solve a complex, ill-structured problem by employing an engineering design process	Through the review of a design portfolio (a) presentation and justification of a problem and solution requirements including presentation and justification of the problem; documentation and analysis of prior solution attempts; and presentation and justification of solution design requirements (b) generation and defense of an original solutions including design concept generation, analysis, and selection; application of STEM principles and practice and consideration of design viability (c) constructing and testing a prototype including construction of a testable prototype; prototype testing and data collection plan; and testing, data collection and analysis (d) evaluation, reflection and recommendations including documentation of external evaluation; reflection on the project design, and presentation of designer's recommendations (e) documentation and presentation of the project including presentation of the project portfolio; and writing like an engineer

Asunda and Hill (2007) described assessment procedures to measure design knowledge, design process skills, and the design product. Their approach is similar to that used by Abts (2011) in that Asunda and Hill relied on documentation of the design process in an artifact such as a design notebook or

portfolio. The documentation should involve a collection of notes, mathematical equations, graphics, drawings, records of imposed constraints, descriptions of the steps that were carried out to construct the product, documented criteria that were developed to analyze and compare each generated solution, and descriptions of the decision-making process used to select the best solution. Asunda and Hill suggested that when conducting assessment of an engineering design activity one should ask the following questions:

- Did the students complete or perform each of the steps in the design process?
- Did they document the process they undertook and any other relevant information?
- Did the design team work as an interdisciplinary team?
- Did the engineering design team analyze models?
- Did the engineering design team conduct an economic feasibility study?
- Did they try to optimize the design before implementing it?
- Did they develop criteria and a process for analyzing each solution, comparing each?
- What was the quality of the solution and how was it selected? (Asunda & Hill, 2007)

Additional strategies developed by the 2012 Caucus team include review of both written documentation such as a design notebook or portfolio as well as review of oral presentations. Interviewing teams or individuals was also a strategy to assess design thinking.

Collaboration

Katehi, Pearson, and Feder (2009b) described engineering as a “team sport” in which

collaboration leverages the perspectives, knowledge, and capabilities of team members to address design challenges. Communication is essential to effective collaboration, to understanding the particular wants and needs of a ‘customer,’ and to explaining and justifying the final design solution. Ethical considerations draw attention to the impact of engineering on people and the environment, including possible unintended consequences of a technology, the potential disproportionate advantages or disadvantages for certain groups or individuals, and other issues. (p. 7)

Outcome	Assessment Strategy
Ability to function in multidisciplinary teams	(1) Demonstrates a willingness to be a contributing member of an engineering design team by participating in problem-solving team initiatives. (2) Through an oral presentation or a written statement, the team member (a) clearly and objectively identifies the design problem; (b) reviews prior attempts to arrive at a solution to the design problem; (c) presents a proposed solution that is well-substantiated with STEM principles; etc. (3) Respects the rights and feelings of other members of the team by collaboratively writing team reports. (4) Participates in the engineering design process through contributions made in the development of drawings, recording notes of team meetings, making journal entries, etc. (5) Shares responsibility in goal setting initiatives.
Demonstrates leadership by supporting team building (<i>Business Dictionary</i> , n.d.)	(1) Contributes to writing team reflections of the engineering design experience. (2) Communicates with individual team members and with the team as a whole. (3) Willingly accepts tasks/assignments originating from the team. (4) Applies safe systems of work
Self-motivation	(1) Propose a plausible solution to a design problem. (2) Construct and tests a prototype of a proposed solution to the design problem. (3) Gathers and analyzes testing data. (4) Initiates discussions that lead to interactions with other team members. (5) Demonstrates enthusiasm in the development of a solution to a design problem. (6) Manages resources and time. (7) Demonstrates thinking and communicating with clarity and precision.
Demonstrates professional and ethical responsibilities of team membership	(1) Recognize the important role that the stakeholder(s) plays in being impacted by the problem or by the proposed solution. (2) Abides by team rules. (3) Effectively communicates an argument related to the design problem. (4) Effectively uses information technology to communicate with team members. (5) Demonstrates independence of mind, with intellectual integrity. (6) Demonstrate the ability to manage and assess risks. (7) Demonstrates an understanding of the impact of engineering solutions on society. (8) Takes responsible risks.
Generates positive outcomes	(1) Contributes to (a) developing a list of design requirements, (b) developing a defensible design solution, (c) written reflection on the design project, (d) writing the final team report.
Shares decision-making responsibilities	(1) Contributes to writing the final team report. (2) Communicates ideas that lead to the development of design solutions.

Communication

Communication is essential for effective collaboration, to understand the wants and needs of a “customer,” and to explain and justify the final design solution (Katehi et al., 2009a). Engineering design challenges provide opportunities to introduce students to new purposes for communicating and new communication genres as well as improving their current oral, written and visual communication skills. In particular, developing engineering design notebooks and engineering design portfolios are communication skills relatively unique to the engineering design process.

Outcome	Assessment Strategy
Write a variety of written texts associated with engineering design	Examples from Abts (2011): (1) Students write consistently clear and well organized texts in standardized form, (2) Students demonstrate the ability to adjust language, style and tone to address the needs and interests of a variety of audiences, (3) Students use a wide variety of written forms which are commonplace among STEM disciplines (e.g. progress report, final design report)
Prepare and deliver a variety of oral presentations associated with engineering design	(1) Students develop clear and well organized presentations (McKenna & Hirsch, 2005), (2) Students deliver oral presentations with attention to pace, volume, eye contact, clarity of language, (3) Students are able to listen to and respond to questions during and after their presentation (Framework for 21 st Century Learning, 2009)
Incorporate visual communication elements in documentation	(1) Students develop two- and three-dimensional representations of their design concepts, (2) Students represent elements of the design process and results using a variety of methods including graphs, tables, and models (NAGB, 2010; Katehi et al., 2009a)
Employ multiple communication technologies throughout design process	(1) Students utilize multiple media and technologies to communicate elements of the design process and results and know how to judge their effectiveness a priori as well as assess their impact (Framework for 21 st Century Learning, 2009), and (2) students develop electronic design portfolios or electronic engineering notebooks

Awareness of Impact

Societal benefits, and possibly unintended consequences, are significant outcomes of engineering design. Consequently, awareness of the engineering design solution during the design process itself is considered an important attribute to be assessed. According to ABET (2011), it is important for post-secondary engineering students to have knowledge of the impact of engineering solutions in a societal and global context. Four areas were specified in the 2014 NAEP technology and society area: (a) interaction of technology and humans, (b) effects of technology on the natural world, (c) effects of technology on the world of information and knowledge, (d) effects of technology on the world of information and knowledge; and (e) ethics, equity, and responsibility (National Assessment Governing Board [NAGB], 2010). Within the sub-area of ethics, equity, and responsibility, students should be able to understand the profound effects that technologies have upon people, how those effects can widen or narrow disparities, and the responsibility that people have for the societal consequences of their technological decisions. Students should be able to analyze and compare advantages and disadvantages of a proposed solution; investigate environmental and economic impacts of a proposed solution; and evaluate trade-offs and impacts of a proposed solution.

Davis et al. (2009) outlined criteria for assessing the outcomes of engineering design:

- Must meet needs of the user with regard to its intended functionality, appearance, operability, and dependability; provide value to investors; feasible; reflect human-centered design that addresses issues of human and environmental well-being in its production, implementation, and retirement
- Social impact – meets ethical and professional norms for human well being and environmental sustainability on local and global scales

Outcome	Assessment Strategy
Describe potential/awareness for consequences of solution (ethical values)	(1) Investigate environmental and economic impacts of a proposed solution, (2) Evaluate trade-offs and impacts of a proposed solution, (3) Describe how the solution meets ethical and professional norms for human well being and environmental sustainability on local and global scales, (4) Justify how the design solution meets societal safety needs, (5) Provide a cost-benefit analysis (economic consequence) of the design solution, (6) Explain how the design solution benefits and improves quality of life, and (7) Develop a design solution that reflects human-centered design principles (that addresses issues of human and environmental well-being in its production, implementation, and retirement)

Summary

Assessment is a complex, challenging endeavor. It involves authentic, performance-based criteria and the use of multiple assessment strategies. Assessment should provide formative and summative feedback, document student learning progress, and examine students' metacognitive reflection abilities. Possible assessment artifacts and strategies include rubrics, portfolios, design notebooks, presentations, observations, and interviews. The assessment process should provide opportunities to consider both individual accountability and team-based accomplishments within the rich, complex context of engineering design challenges. Assessment strategies should explore learner progress in systems thinking, selecting and implementing appropriate engineering design processes, collaboration among team members, the design and delivery of communication related to the design process, and individual, social, and environmental impacts of proposed solutions. Logic models are useful for assessing learner performance and may be applied in several components of the design process.

Section Six: National Influences

The purpose of this section is to review current national efforts shaping curriculum guidelines, content standards, and program parameters that impinge upon the emerging role of engineering design in the high school STEM spectrum. It is not yet clear how the rising clamor of organizations and institutions will settle into a working alliance to provide American high school students with interesting and effectively organized engineering design experiences. The material presented here draws heavily from reports and draft materials that are currently available, and upon the work of many interested individuals and organizations, including the authors of this paper and their collaborators.

ABET Influences

ABET is the internationally recognized accrediting organization for post-secondary engineering programs. The ABET Engineering Accreditation Commission Criteria (2011) shape undergraduate engineering programs and have influenced K-12 engineering education. Specifically, General Criterion Five, Curriculum, defines engineering design:

Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs. (p. 4)

ABET General Criterion Three, Student Outcomes, describes the outcomes expected of graduates of engineering programs. Most undergraduate programs achieve these outcomes through a capstone design experience, though many engineering programs incorporate design experiences earlier, often beginning in the freshmen year. ABET (2011) specifies these student outcomes:

Student outcomes are outcomes (a) through (k) plus any additional outcomes that may be articulated by the program:

- (a) an ability to apply knowledge of mathematics, science, and engineering
- (b) an ability to design and conduct experiments, as well as to analyze and interpret data
- (c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
- (d) an ability to function on multidisciplinary teams
- (e) an ability to identify, formulate, and solve engineering problems
- (f) an understanding of professional and ethical responsibility
- (g) an ability to communicate effectively
- (h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
- (i) a recognition of the need for, and an ability to engage in life-long learning
- (j) a knowledge of contemporary issues
- (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice. (p. 3)

The ABET definition of engineering design and many of the student outcomes described above are important elements of high school engineering design challenges. Educational outcomes of an engineering design experience in high school that are also outcomes of post-secondary engineering programs include the application of mathematics and science, design with realistic constraints, ability to

function on a team, formulate and solve problems, effective communication, and understanding societal impacts of engineering solutions.

Influences of the National Academy of Engineering Study of K-12 Engineering Education

A two-year study by the Committee on K-12 Engineering Education of the National Academy of Engineering resulted in an influential document describing the scope and nature of efforts to teach engineering in the K-12 setting. In the report, Katehi et al. (2009a) opened their discussion with the Medieval Latin derivation of the word engineering, or *ingeniare*, meaning to design or devise. They then provided a helpful and concise statement: “Thus, a short definition of engineering is the process of designing the human-made world” (p. 27). The report went on to distinguish and describe similarities between engineering and science. Engineers, it noted, do not literally construct artifacts; they develop plans and directions for how artifacts are to be constructed. They also design processes, ranging from the manufacturing processes used in the chemical and pharmaceutical industries to procedures used in assembly lines; and design and improve a wide range of tangible products, ranging from medical equipment to water filtration systems to smaller, faster microchips.

While Katehi et al. (2009a) acknowledged wide variation in the ways engineering is taught in elementary and secondary classrooms, they proposed three general principles for K-12 engineering education:

K-12 engineering education should emphasize engineering design. The design process, the engineering approach to identifying and solving problems, is (1) highly iterative; (2) open to the idea that a problem may have many possible solutions; (3) a meaningful context for learning science, mathematical and technological concepts; and (4) a stimulus to systems thinking, modeling and analysis. In all of these ways, engineering design is a potentially useful pedagogical strategy. (p. 4)

K-12 engineering education should incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills. Certain science concepts as well as the use of scientific inquiry methods can support engineering design activities. Similarly, certain mathematical concepts and computational methods can support engineering design, especially in service of analysis and modeling. Technology and technology concepts can illustrate the outcomes of engineering design, provide opportunities for ‘reverse engineering’ activities, and encourage the consideration of social, environmental, and other impacts of engineering design decisions. Testing and measurement technologies, such as thermometers and oscilloscopes; software for data acquisition and management; computational and visualization tools, such as graphing calculators and CAD/CAM (i.e., computer design) programs; and the Internet should be used, as appropriate, to support engineering design, particularly at the high school level. , including science and mathematics concepts, scientific inquiry skills, computational methods that may support engineering design, particularly for analysis and modeling, and technologies (e.g., instrumentation, computer-aided design, the Internet) should be used to support engineering design, particularly at the high school level. (p. 5)

K-12 engineering education should promote engineering habits of mind [values, attitudes, and thinking skills (AAAS, 1990)] that are essential skills for citizens in the 21st century. These include (1) systems thinking, (2) creativity, (3) optimism, (4) collaboration, (5) communication, and (6) attention to ethical considerations. Systems thinking equips students to recognize essential interconnections in the technological world and to appreciate that systems may have unexpected effects that cannot be predicted from the behavior of individual subsystems. Creativity is inherent

in the engineering design process. Optimism reflects a world view in which possibilities and opportunities can be found in every challenge and an understanding that every technology can be improved. Engineering is a ‘team sport;’ collaboration leverages the perspectives, knowledge, and capabilities of team members to address a design challenge. Communication is essential to effective collaboration, to understanding the particular wants and needs of a ‘customer’ and to explaining and justifying the final design solution. Ethical considerations draw attention to the impacts of engineering on people and the environment; ethical considerations include possible unintended consequences of a technology, the potential disproportionate advantages or disadvantages of a technology for certain groups or individuals, and other issues. (pp. 5-6).

Katehi et al. (2009a) noted that design is the approach used by engineers to solve problems. It includes such problems as creating devices or artifacts and developing processes that serve a particular purpose. Further, design is both open-ended and purposeful (i.e., it has a particular goal); shaped by specifications and constraints; systematic and iterative; social and collaborative; creative; and allows many possible solutions. Further, it is a non-linear process that involves personal, social and technical considerations and often provides a meaningful context for learning science, technology and mathematics. Engineering design experiences may also stimulate systems thinking, and use of modeling and predictive analysis to predict behavior of certain designs.

Anticipated Influences of Future National Developments

As this paper is being prepared during August 2012, several important national developments are also taking place, but the implications—on educational policy and classroom practice—are not yet known. It is, however, important to understand that the context in which engineering design in Grades 9-12 is likely to be implemented may be influenced substantially by these developments.

Among these developments are: the National Assessment of Education Progress (NAEP) 2014 Technology and Engineering Literacy Assessment; the inclusion of engineering within the core knowledge and practices of the *Framework for K-12 Science Education*; the recently released draft of the Next Generation Science Standards; and the inclusion of engineering as a STEM priority (rather than a focus only on science and mathematics) within the Investing in Innovation grants program of the U.S. Department of Education.

National Assessment of Education Progress (NAEP) 2014 Technology and Engineering Literacy Assessment

The National Assessment of Education Progress (NAEP) Technology and Engineering Literacy (TEL) Assessment is being developed for administration to a representative subset of the US 8th graders in 2014 (NAGB, 2010). It will be the first large-scale effort to assess technology literacy at the national level. The NAEP TEL 2014 has been informed by the recommendations of experts, leaders, and practitioners in three distinct areas: Information and Communications Technology (ICT); Design and Systems (DS), (the domain addressing engineering literacy), and Technology and Society (TS) as shown in Table 1. In formulating this taxonomy, the Framework committee recognized the significantly different conceptions and definitions of commonly used terms in educational practice, policy, and general societal contexts. Therefore, the NAEP committee intentionally used the term, “technology and engineering literacy,” in the Framework document and in the specifications for the instrument currently under development to assess general literacy about the use, effects, and design of computer-based and broader forms of technology in the human-designed world.

Engineering design constitutes a major assessment target within the Design and Systems domain; it is broadly defined to include architectural design, manufacturing design, industrial design, and software

design. Key principles in the area of engineering design that all students can be expected to understand at increasing levels of sophistication are:

- Engineering design is a systematic, creative, and iterative process for addressing challenges.
- Designing includes identifying and stating the problem, need, or desire; generating ideas; evaluating ideas; selecting a solution; making and testing models or prototypes; redesigning; and communicating results.
- Requirements for a design challenge include the criteria for success, or goals to be achieved, and the constraints or limits that cannot be violated in a solution. Types of criteria and constraints include materials, cost, safety, reliability, performance, maintenance, ease of use, aesthetic considerations, and policies.
- There are several possible ways of addressing a design challenge.
- Evaluation means determining how well a solution meets requirements.
- Optimization involves finding the best possible solution when some criterion or constraint is identified as the most important and other constraints are minimized.
- Engineering design usually requires one to develop and manipulate representations and models (e.g., prototypes, drawings, charts, and graphs). (NAGB, 2010, p. 2-23)

Technology and Society	Design and Systems	Information and Communication Technology
A. Interaction of Technology and Humans	Nature of Technology	A. Construction and Exchange of Ideas and Solutions
B. Effects of Technology on the Natural World	Engineering Design	B. Information Research
C. Effects of Technology on	Systems Thinking	C. Investigation of Problems
D. Ethics, Equity, and Responsibility	Maintenance and Troubleshooting	D. Acknowledgement of Ideas and Information
		E. Selection and Use of Digital Tools

Figure 10. Areas and Sub-areas of 2014 NAEP Technology and Engineering Literacy Assessment
Source: NAGB, 2010, p. 2-2

A more comprehensive treatment of the practices and detailed descriptions of each assessment target may be found in the NAEP TEL 2014 Framework (NAGB, 2010, pp. 3-12--3-13). The relevant engineering design practices in the Design and Systems assessment target problem-solving, developing designs, proposing and critiquing solutions after being provided with criteria and constraints, considering tradeoffs, constructing and testing a model or prototype.

Examples of collaboration practices, “integral to achieving the goals of technological design and systems” (NAGB, 2010, p. 3-12), include such tasks as: design assignments are distributed among team members; progress and results are integrated and shared; products are presented jointly; instructions for system assembly and documentation of a procedure for maintaining a system; use of understanding to communicate and collaborate toward the development and presentation of a design.

The NAEP Framework defines an advanced proficient 12th grader (in the Design and Systems domain) as being able *to know that*: “The evolution of tools and materials has played an essential role in the advancement of civilization, from the establishment of cities and industrial societies to today’s global trade and commerce networks;” and *be able to*: “Construct and test several models to see if they meet the requirements of a problem. Combine features to achieve the best solution” (NAGB, 2010, p. A-35).

While the NAEP Technology and Engineering Literacy Assessment 2014 is a low stakes probe assessment intended to gauge the level of technology and engineering knowledge and skill among U.S. eighth graders, its impact on policies, funding priorities and classroom practice may be substantial.

Framework for K-12 Science Education and Next Generation Science Standards

Two important national developments that seem likely to influence the prevalence and characteristics of engineering design in secondary science classrooms are the National Research Council (NRC) *Framework for K-12 Science Education* (NRC, 2012) and the May 2012 draft of the *Next Generation Science Standards* (Achieve, Inc., 2012). These documents explicitly position engineering within the broad science requirements for all K-12 students. The shift in emphasis of these new documents reflects the “real world interconnections” of science and engineering and the active engagement of students in science and engineering practices and their application of crosscutting concepts to deepen their understanding of core ideas in these fields (NRC, 2012). The *Framework for K-12 Science Education* is described further in the section on Science Standards below.

National Standards

National standards in mathematics, science, and technology describe what all students should know, understand and be able to do within these domains. National standards in mathematics, science, and technology have been developed by their respective professional communities and involved national dialogues seeking input and review from the multiple constituencies that might be impacted by the standards. The documents reflect the common goal of improved learning for all students. Measures of their effectiveness will only be available after the standards are widely accepted at the state level (NRC, 1997). Engineering design challenges support learning as described in the mathematics, science, and technology standards.

Mathematics Standards

Principles and Standards for School Mathematics, developed by the National Council of Teachers of Mathematics (NCTM), describes the mathematics students should learn in grades K-12 (NCTM, 2000). Although engineering design is not explicitly stated in any of the high school mathematics standards, essential elements of mathematical problem solving needed to support engineering design are described in several of the standards.

The Problem Solving Standard provides an obvious connection to engineering design challenges. “A major goal of high school mathematics is to equip students with knowledge and tools that enable them to formulate, approach, and solve problems beyond those that they have studied” (NCTM, 2000, p. 335). The Problem Solving Standard supports (1) building new mathematical knowledge through problem solving, (2) solving problems that arise in mathematics and other contexts, (3) applying and adapting a variety of appropriate strategies to solve problems, and (4) monitoring and reflecting on the process of mathematical problem solving.

Engineering design challenges can be included in mathematical instructional programs to support additional mathematics standards. For example, the Algebra Standard states that the instructional programs should enable all students to “use mathematical models to represent and understand quantitative

relationships” (NCTM, 2000, p. 296). Students in grades 9-12 should be able to draw reasonable conclusions about a situation being modeled. The Geometry Standard states that the mathematic instructional program should enable all students to “use visualization, spatial reasoning, and geometric modeling to solve problems” (NCTM, 2000, p. 308). Students in grades 9-12 should be able to use geometric ideas to solve problems in, and gain insights into, other disciplines and other areas of interest such as art and architecture. The Data Analysis and Probability Standard states that instructional program should enable all students to “develop and evaluate inferences and predictions that are based on data” and to evaluate published reports that are based on data by examining the design of the study, the appropriateness of the data analysis and the validity of conclusions” (NCTM, 2000, p. 324).

Science Standards

National Science Education Standards describe a direct connection between science education and engineering design challenges. Content Standard E, Science and Technology, addresses students’ abilities in technological design and their understandings about science and technology. The section on Abilities of Technology Design includes brief descriptions of these processes:

- Identify a problem or design an opportunity
- Propose designs and choose between alternative solutions
- Implement a proposed solution
- Evaluate the solution and its consequences
- Communicate the problem, process, and solution (NRC, 1996, p. 192).

Framework for K-12 Science Education

Observers expect that the next generation of Science Standards will be shaped by the *Framework for K-12 Science Education* (NRC, 2012). The *Framework* describes the knowledge and practices of science and engineering for K-12 students. “Dimension 1 describes (a) the major practices that scientists employ as they investigate and build models and theories about the world and (b) a key set of engineering practices that engineers use as they design and build systems” (NRC, 2012, p. 30). Bybee (2011) contrasted the description of science practices with engineering practices as described in the *Framework*. Within Chapter Eight of the *Framework*, Core Ideas in Engineering, Technology and Applied Science (ETS) are described. ETS1 describes engineering design, including the details of defining and delimiting an engineering problem, developing possible solutions, and optimizing the design solution (p. 203). Sneider (2012) built on the ETS discussion in the *Framework* by pointing to some of the issues associated with teacher preparation and describing what engineering might look like in the classroom.

The *Framework for K-12 Science Education* describes two core ideas in engineering, technology, and applications of science: (1) engineering design; and (2) links among engineering, technology, science, and society. Three component ideas comprise engineering design: (1) defining and delimiting an engineering problem; (2) developing possible solutions; and (3) optimizing the design solution. Two component ideas comprise the links among engineering, technology, science, and society: (1) interdependence of science, engineering, and technology; and (2) influence of engineering, technology, and science on society and the natural world. Clear conceptual bases are presented for each of the component ideas in the *Framework*, followed by benchmarks for expected conceptual understandings at the completion of grades 2, 5, 8, and 12.

Taken together, the three descriptions of component ideas comprising engineering design provide a concise indication of the outcomes envisioned for successful completers of high school engineering, technology and applications of science. By the end of grade 12, the writers of the *Framework* suggest that students should have attained these understandings and capabilities related to Core Idea ETS 1.A: Defining and delimiting an engineering problem:

Design criteria and constraints, which typically reflect the needs of the end-user of a technology or process, address such things as the product's or system's function (what job it will perform and how), its durability, and limits on its size and cost. Criteria and constraints also include satisfying any criteria set by society, such as taking issues of risk mitigation into account, and they should be quantified to the extent possible and stated in such a way that one can tell if a given design meets them.

Humanity faces major global challenges today, such as the need for supplies of clean water and food or for energy sources that minimize pollution, which can be addressed through engineering. These global challenges also may have manifestations in local communities. But whatever the scale, the first thing that engineers do is define the problem and specifying the criteria and constraints for potential solutions. (NRC, 2012, pp. 205-206)

By the end of grade 12, students should have attained these understandings and capabilities related to core idea ETS 1.B: Developing possible solutions:

Complicated problems may need to be broken down into simpler components in order to develop and test solutions. When evaluating solutions, it is important to take into account a range of constraints, including cost, safety, reliability, and aesthetics, and to consider social, cultural, and environmental impacts. Testing should lead to improvements in the design through an iterative procedure.

Both physical models and computers can be used in various ways to aid in the engineering design process. Physical models, or prototypes, are helpful in testing product ideas or the properties of different materials. Computers are useful for a variety of purposes, such as in representing a design in 3-D through CAD software; in troubleshooting to identify and describe a design problem; in running simulations to test different ways of solving a problem or to see which one is most efficient or economical; and in making a persuasive presentation to a client about how a given design will meet his or her needs (NRC, 2012, p. 208).

By the end of grade 12, students should have attained these understandings and capabilities related to core idea ETS 1.C: Optimizing the design solution:

The aim of engineering is not simply to find a solution to a problem but to design the most satisfactory solution under the given constraints and criteria. Optimization can be complex, however, for a design problem with numerous desired qualities or outcomes. Criteria may need to be broken down into simpler ones that can be approached systematically, and decisions about the priority of certain criteria over others (trade-offs) may be needed. The comparison of multiple designs can be aided by a trade-off matrix. Sometimes a numerical weighting system can help evaluate a design against multiple criteria. When evaluating solutions, all relevant considerations, including cost, safety, reliability, and aesthetic, social, cultural, and environmental impacts, should be included. Testing should lead to design improvements through an iterative process, and computer simulations are one useful way of running such tests. (NRC, 2012, p. 210)

Technology Standards

Standards for Technology Literacy: Content for the Study of Technology was developed by the International Technology and Engineering Educators Association (ITEEA). Learning about engineering design is a clearly stated outcome of several of the standards for technology literacy, a marked contrast to the current mathematics and science standards that are silent on the topic.

The design process described in Standard 8, “Students will develop an understanding of the attributes of design” (ITEEA, 2007), is quite similar to the introductory engineering design process described in

freshman engineering design textbooks (e.g., Dym & Little, 2009), with two notable exceptions noted by Hailey, Ereksen, Becker, and Thomas (2005). The first exception is that the central role of engineering analysis is not mentioned in the technology design sequence, which moves directly from the development of a design proposal to the making and testing a model or prototype. The second exception emphasized by Hailey et al. is the importance ascribed to role of “creating or making” the design as an important step in the design cycle, a step that is often not included in descriptions of the engineering design cycle in college freshman engineering programs (2005, p. 25)..

Standard 9 states that “Students will develop an understanding of engineering design” (ITEEA, 2007, p 99). Within Standard 9, Benchmark K describes the role of prototyping in the design process and Benchmark L describes some of the realistic constraints that students should include in the design process such as safety, reliability, and economic considerations. Standard 11, “Students will develop abilities to apply the design process” (ITEEA, 2007, p. 115), describes opportunities for students to evaluate the design solution using physical and mathematical models. This standard also stresses the importance of the communication of the results of the design process using verbal, graphic, quantitative, virtual, and written means as well as three-dimensional models.

Engineering Standards

In 2008, the Committee on Standards for K–12 Engineering Education (CSK-12EE) of the National Academy of Engineering embarked on a two year study to assess the value and feasibility of developing and implementing content standards for engineering education at the K-12 level. The committee concluded that it would be difficult to ensure that such a large undertaking as developing national standards would be useful and effective in the educational environment in the United States at that time. Their conclusion was supported by the following findings:

- (1) there is relatively limited experience with K–12 engineering education in U.S. elementary and secondary schools, (2) there is not at present a critical mass of teachers qualified to deliver engineering instruction, (3) evidence regarding the impact of standards-based educational reforms on student learning in other subjects, such as mathematics and science, is inconclusive, and (4) there are significant barriers to introducing stand-alone standards for an entirely new content area in a curriculum already burdened with learning goals in more established domains of study. (CSK-12EE, 2010, p. 1)

The Committee recommended that appropriate constituents interested in K-12 engineering education initiate an effort to define the core ideas of engineering that would be appropriate for all students. The core ideas would include the core concepts, skills and dispositions of K-12 engineering education. Furthermore, the core ideas would be embedded in guidelines for the development of instructional materials. The committee recommended that guidelines describing the elements of engineering design should emphasize that the process is nonlinear and there is no single “correct” solution. The guidelines should describe how engineering design can be used to encourage contextual, student-centered learning as well as to provide an opportunity to apply mathematics and science understandings (CSK-12EE, 2010).

In its report, the Committee also described relationships between engineering concepts, skills and dispositions for K-12 students and existing technology standards. Other investigators have also described the interrelationships among engineering education and other STEM Disciplines. Chae, Purzer & Cardella (2010) examined the commonalities among engineering, technology, science and mathematics through their analysis of the *Standards for Technological Literacy*, the *National Science Education Standards*, and *Principles and Standards for School Mathematics*. Commonalities include processes, modeling, and societal impacts. The processes of scientific inquiry, technological design, and mathematical problem solving are similar to process of engineering design; all seek to improve students’ problem solving skills.

Modeling is another commonality, where students learn to organize their understandings to represent relationships and communicate phenomena. The third commonality, societal impact, describes the importance and responsibility that each STEM discipline has to consider the outcomes and results of their work relative to society.

Chae et al. (2010) reported that societal impact is an important consideration for each of the distinct STEM disciplines and suggested that a review of standards for other subjects might provide insight into ways that engineering design education might impact multiple curricula. For example, the *National Curriculum Standards for Social Studies* indicates that high school social studies programs should include experiences that consider the relationships among science, technology and society. Theme Eight indicates that learners will understand that “predictions, modeling, and planning are used to focus advances in science and technology for positive ends” (National Council for the Social Studies, 2010, p 151).

State Standards

A comprehensive analysis of the presence of engineering in state K-12 academic standards by Carr, Bennett, and Strobel (2012) yielded a wealth of detail on the degree to which engineering was represented in the standards of 41 of the 50 states. In 39 of those states, engineering was included in high school standards. While 12 states included engineering in science standards and one in mathematics standards, the other 19 states included engineering as related to standards promoted by ITEEA (2007) or Project Lead the Way <http://www.pltw.org/>. Carr et al. (2012) summarized the consensus that they found among mentions of engineering standards with an inclusive list of ideas and activities comprising engineering:

- Identifying criteria, constraints, and problems
 - Evaluating, redesigning and modifying products and models
 - Evaluating effectiveness of solutions
 - Devising a product or process to solve a problem
 - Describing the reasoning of designs and solutions
 - Making models, prototypes, and sketches
 - Designing products and systems
 - Selecting appropriate materials, best solutions, or effective approaches
 - Explaining the solution and design factors
 - Developing plans, layouts, designs, solutions, and processes
 - Creating solutions, prototypes, and graphics
 - Communicating the problem, design, or solution?
 - Proposing solutions and designs
 - Defining problems
 - Brainstorming solutions, designs, design questions, and plans
 - Constructing designs, prototypes, and models
 - Applying criteria, constraints, and mathematical models
 - Improving solutions or models
 - Producing flow charts, system plans, solution designs, blue prints, and production procedures.
- (p. 556)

The evidence from this analysis seems substantial enough to encourage the re-examination of the potential gains from more formal inclusion of engineering in standards-based STEM instruction.

Section Seven: Conclusions

One principle seems clear from this review of existing research: Engineering experiences in K-12 education can offer all students an opportunity to get acquainted with and practice engineering habits of thought and action. However, there are few specific suggestions for identifying engineering design challenges that appeal to all students in our diverse school populations and a gap in our understanding about ways to provide culturally relevant engineering design challenges for learners from underrepresented groups. We have been unable to get a clear understanding of strategies for incorporating engineering design challenges in ways that support design thinking for academically, culturally, and linguistically diverse learners.

Experiences gained while solving engineering design challenges offer opportunities for learners to increase their self-efficacy in resolving ill-defined problems while improving their engineering and technological literacy. However, there is provocative evidence that learners do in fact strengthen their capabilities in those areas because of their work in solving engineering design challenges. While engineering design experiences may result in improvements in optimism, creativity, collaboration, communication, ethical considerations, and systems thinking, there is much to be learned about the differential effects of the design experiences upon the spectrum of learners who enroll in high school STEM classes.

The engineering design process is currently represented in a wide range of models and described in many pages of text. Though there is general agreement about the engineering design process and its components, there is a lack of unanimity concerning its details and the ways those details are presented. For the purposes of this review, we have chosen to utilize the model of the engineering design cycle proposed by Morgan Hynes, Meredith Portsmore, Emily Dare, Elissa Milto, Chris Rogers, David Hammer, and Adam Carberry in *Infusing engineering design into high school STEM courses*, available at <http://ncete.org/flash/pdfs/Infusing%20Engineering%20Hynes.pdf>. We have referred to this model as the NCETE Engineering Design Model throughout this paper. The complexity of the model and the description of the processes in the design cycle stand out clearly in contrast to activities that do not meet the criteria for engineering design challenges, such as the creation of gadgets, tinkering, trial-and-error invention, and attempts to short-cut the design process. Sharp distinctions have also been drawn between authentic engineering design challenges and routine teacher-planned and orchestrated laboratory exercises that limit student opportunities to those leading to well-known and consistent outcomes.

While there is widespread agreement on the importance of authenticity when selecting design challenges, the majority of teachers – even those who are motivated and prepared – are unable to implement real-world engineering design challenges in their classes without special external assistance, the involvement of resource persons, or an on-going support group of teacher colleagues. Teachers also find it difficult to make the paradigm shift required for them to facilitate student ownership of the engineering design challenges, to stimulate and reinforce productive problem solving, and to encourage efforts to move toward solutions that are not known in advance by either the students or their teachers.

William A. Wulf, past president of the National Academy of Engineering, frequently described engineering as “design under constraint” (Wulf, 2004, p. 313). Teamwork, collaboration, and communication play important roles in fostering creativity, building group consensus, and moving toward agreement in selecting designs for development and testing. Facilitating this dynamic process in the classroom places unusual responsibilities on the teacher as a learning guide and instructional mentor.

Meticulous problem definition is paramount to success in the engineering design process. It seems to be especially challenging to nurture the development of this particular engineering habit of thought and

action among high school students, whose enthusiasm for action easily overwhelms the analytical and reflective processes required for precise problem description. Teachers may find it difficult to schedule adequate time for problem definition, but should suppress any tendency to impose their own structured descriptions of the problem in the interests of efficient use of instructional time.

There is a surprising shortage of research-based principles for assisting high school students in developing facility in thinking analytically in the identification and selection of alternative solutions to design problems. Similarly, there is a lack of evidence on effective ways to insure rationality when balancing trade-offs among conflicting constraints. The issue assumes critical importance when inexperienced decision-makers confront the need to focus upon an imperfect but adequate solution to a design challenge. Decision matrices may be employed to expedite the decision-making process, but decision matrix development itself may not always be informed by relevant empirical data.

The importance of hands-on activities and of the development of models and prototypes has general acceptance among engineering educators. Despite this consensus among practitioners, there is a dearth of empirical evidence on the precise contributions of hands-on experiences in the development of engineering habits of thought and action. Consequently, instructional designers and classroom practitioners have little guidance to insure optimum allocation of classroom time between hands-on activities and vicarious experiences.

As the authors have attempted to synthesize research evidence and relate it to informed classroom practice, we have become increasingly aware of the importance of effective communication to the success of the engineering design process. Authentic communication among design team members involves maintaining interactive accounts of the on-going iterations involved in decision-making, developing persuasive presentations describing the selected solution, and presenting a clear, concise, and objective report for the client.

The NCETE Engineering Design Model cycle includes two steps of the engineering design that are frequently overlooked or minimized: (1) redesign as a fundamental part of the iterative design process; and (2) the completion decision, which signifies a moratorium on the design process itself in order to realize the solution. Both of these steps are important in bringing a sense of (at least temporary) closure to the process, even though there is clear recognition that subsequent events may encourage a new visitation to the design cycle.

Themes and Issues

As we conclude this report on our exploration of the status of engineering design challenges in high school STEM instruction, we return to the themes and issues first framed in the introduction to this document. In doing so, we point out the need for continued dialogue on several important issues. The body of evidence is still inadequate to provide definitive answers to many of our research questions.

The overarching question guiding this effort was: Does the development of engineering habits of thought and action lead to improvements in problem solving abilities, systems thinking, the integration of STEM content, increased interest in engineering, and feelings of self-efficacy about pursuing additional engineering and STEM work? Despite the careful review of available research findings (many of which are encouraging), we are unable to provide a definitive answer to all aspects of this question. Additional studies are needed; they need to involve larger numbers of learners and extend over longer periods of time; and the specific criteria for evaluation need to be more precisely specified.

There appears to be substantial progress toward answering these questions:

- What are the goals of the inclusion of engineering design challenges in high school STEM instruction?
- What is the anatomy of the engineering design process and what are its essential components?

Limited progress has been made in finding answers to these questions:

- What are the content, context, and process elements of appropriate engineering design challenges for high school STEM courses?
- What pedagogical strategies and instructional practices are effective in supporting student learning based upon engineering design challenges?
- In what ways can teachers design and implement an authentic system for assessing student progress as well as their success in completing engineering design challenges?

It appears that interaction among the various standards for STEM subjects and other influences on the national scene will continue to be in flux for some time. Consequently, it seems unreasonable to expect definitive answers to this question at this time:

- In what ways do engineering design challenges fit into the national STEM scene, the high school STEM organizational structure, and the evolving network of national, state, and local standards?

This review does not attempt to address the issues of teacher preparation. It appears that much work remains to be done on teacher preparation before much progress can be made on the question:

- How can we best prepare a cadre of STEM teachers to enable them to incorporate engineering design challenges into their high school instructional programs?

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