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Are the Engineering Design Processes used in Engineering and Technology Education Classrooms an Accurate Reflection of the Practices used in Industry and other Technical Fields?

SESSION I: The Role and Impact of Engineering Design
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Introduction

The purpose of this paper is to investigate if the engineering design processes used in engineering and technology education classrooms are an accurate reflection of the practices used in industry and other technical fields (i.e., for purposes of this paper, the field engineering). In this paper, the terms "engineering design" and the "engineering design process" are considered to be problem solving approaches that have the same meaning and are defined as:

> *The systematic and creative application of scientific and mathematical principles to practical ends such as the design, manufacture, and operation of efficient and economical structures, machines, processes, and systems.* (ITEEA, 2000/2002/2007).

The paper begins with a brief review of how the "engineering design process" is taught and practiced in engineering. Then a review of its importance and use in K-12 in technology and engineering education is presented. The paper then presents a discussion if the design processes used in engineering and technology education classrooms are an accurate reflection of the practices used in industry and other technical fields.

The Engineering Design Process in Engineering

Engineering requires lots of problem solving. To solve problems, engineers learn an iterative problem solving process known as engineering design, or the engineering design process. This section examines how students at the collegiate level learn about engineering design and a brief discussion of how it is practiced by professionals.

Learning Engineering Design

Today, engineering students at the baccalaureate level will be introduced to "engineering design" in introductory as well as upper division engineering courses. The accrediting board for engineering, known as ABET, identifies a set of general level criteria for accrediting baccalaureate engineering programs. In its discussion on the requirements for engineering curriculum, it notes that students must receive one and one-half years of engineering topics, consisting of engineering sciences and engineering design appropriate to the student's field of study and it defines engineering design as follows:

> 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. (ABET, 2015, p. 4)

ABET accreditation requires that engineering faculty teach engineering design, but does not prescribe a specific model to teach. A popular textbook utilized in the teaching of engineering design is *Engineering Design: A Project-Based Introduction,* 4th Edition (Dym, Little, and Orwin, 2014). This book, suitable for all levels of engineering courses, helps students acquire design skills as they experience the activity of design by doing design projects. In this book, the authors define engineering design as:

> Engineering design is a systematic, intelligent process in which engineers generate, evaluate, and specify solutions for devices, systems, or processes whose form(s) and function(s) achieve clients' objectives or users' needs while satisfying a specific set of constraints. In other words, *engineer design is a thoughtful process for generating plans or schemes for devices, systems, or processes that attain given objectives while adhering to specified constraints.* (p. 7)

Dym, Little, and Orwin (2014) further note that that are many design process models and they can be either prescriptive or descriptive. A descriptive model describe what must be done during the design process. They provide examples of simple descriptive models. For example, they present a three-phase model (i.e., (1) Generation, (2) Evaluation, and (3) Communication) and a simple three-stage model (i.e., conceive, design, and implement).

A prescriptive model prescribes what must be done during the design process. Dym, Little, and Orwin (2014) present a five step engineering design process model that is comprised of the following steps:

1. Problem Definition: Detailing Customer Requirement
2. Conceptual Design: Translating Customer Requirements into Engineering Specifications
3. Preliminary Design
4. Detailed Design
5. Design Communication

In reviewing the introductory textbook entitled, *Thinking Like an Engineer: An Active Learning Approach* (Stephan, Bowman, Park, Sill, and Ohland, 2013) the authors discuss that there are many different models of the design process, but they have all have many similarities. They note design is a creative a process that requires the following steps: (1) problem definition, (2) ideas searches, (3) solutions development, and (4) solutions sharing.

In another introductory textbook entitled *Concepts in Engineering* (Holtzapple and Reece, 2005) the authors note that the engineering design method contains the elements of synthesis, analysis, communication, and implementation and present a 10-step engineering design model. This model contains the following 10 steps:

1. Identify the need and define the problem
2. Assemble the design team
3. Identify constraints and criteria for success
4. Search for Solutions
5. Analyze each potential solution
6. Choose the "best" solution
7. Document the solution(s)
8. Communicate the solution(s) to management
9. Construct the solution
10. Verify and evaluate

Horenstein (2010) in the textbook *Design Concepts for Engineers* (4th Ed.) presents an engineering design process that he refers to as the "design cycle." He notes that this design cycle model will vary depending on where it is used or how it is taught. The steps in the model presented include:

1. Define the overall objectives
2. Gather Information
3. Identify and Evaluate Possible Design Strategies
4. Make a First Cut at the Design
5. Model and Analysis
6. Build, Document, and Test

Applying Engineering Design in Practice

The above section reviews a variety of engineering design models that engineering students learn in their studies. This section tries to obtain a "snapshot" of how engineers apply the problem-solving practice in the real world.

A study entitled *Conceptions of the Engineering Design Process: An Expert Study of Advanced Practicing Professionals* conducted by Mosborg, Adams, Kim, Atman, Turns, and Cardella (2005) provided insights into how engineering design was used by practicing professionals. In their study, they discussed how engineering design was taught in engineering textbooks. They noted it was traditionally taught in a linear "block" method, but today it beginning to be taught as a "cyclical" process. Engineering design examples presented in their study were similar to the models presented in the above section. In their study they found that practicing engineers (N=19) do use an engineering design process and that most appear to follow the block method. However, they also noted that almost half of the engineers seem to follow alternate kinds of representations of the engineering design process as they discussed their approach to solving problems.

Sheppard, Colby, Macatangay, and Sullivan (2006) explored answers to the question: *What is Engineering Practice*? In their review, they note that engineering practice is about "problem solving" and there are different approaches to solving problems. In their discussions on problem solving, they note that problems being undertaken by an engineer may take the form of a need, real or perceived, or may be stated as a question. They emphasized that problem solving in engineering is constraint-based and discuss how "engaging in engineering problem solving often involves parsing and partitioning the problem by identifying sub-problems that can be worked on independently from one another" (p. 432). Furthermore, in their discussion on what engineers do, they note that very little engineering work is solitary, that few engineers are expert in all aspects of the engineering problem solving process, and many (if not most) engineering problems have timeframes and complexity that require teams of engineers to work on them.

Maffin (1998) completed a study in the UK to investigate how engineering companies use the engineering design practice. In this study, he looked at the context, theory, and practice of using engineering design models. He first did a review of engineering design models and discussed that all the models exhibited basic features. These features included such items as the breakdown of the design process into conceptually distinct stages or activities, the subdivision of the overall design problem into sub-problems, and varying emphases on iteration and interaction through the design process. However, interestingly he found that there had not been a widespread use by design practitioners of the design strategy proposed by most engineering design models. He contributed this to a lack of awareness of engineering design models and that companies' practices and strategies to solve the problem were often influenced by the context of the design problem.

Section Summary

This section looked at how engineering design is taught and practiced. In summary, it appears that engineering design (problem solving) is a very important part of what engineers learn in their undergraduate studies and what they do in practice. There are also many different engineering design models, but they are all similar features. Further review of the models show them to be mostly represented in a linear "block" fashion, but often discussed as being both an iterative and cyclical process. Also, it appears that engineers use a variety of problem solving approaches that are similar in nature to what they may learn in their formal training, but the process they use is often directed by the nature and context of the problem and customer needs.

The Engineering Design Process in Technology and Engineering Education

Today, teaching the engineering design process in K-12 technology and engineering education, as well as other STEM education subjects is important. To show this importance, this section presents a brief review of research related to engineering design in technology and engineering education, followed by a review of how engineering design is included in national science and technology education standards. Next a brief review of how engineering design is included in technology and engineering curricula is presented, followed by a short discussion of other organizations involved in the promoting engineering design.

Engineering Design in the Literature

In recent years, there has been a number of studies and reports on the use of engineering design in technology and engineering education. For, example, Asunda and Hill (2007) did a study to investigate the critical features of engineering design in technology education. In their study, they identified the concept of engineering design, the key features of the engineering design process, and critical elements that should be assessed in an engineering design activity. In addition, they developed a rubric that could be used in evaluating integration of engineering design as a focus for technology education. They also noted emphasized the importance of critical thinking and reflection about the iterative process and the use of analysis and optimization when using the engineering design process.

Lami and Becker (2013) did a study on "engineering design thinking." In their study they examined high school students' systems cognitive issues, processes, and themes while they engaged in a collaborative engineering design challenge. In their review of literature, they noted that engineering design is a process that has no agreed upon definition, that there are multiple K–12 programs and curricula that purport to teach engineering design, and that high school students can engage in engineering design.

Householder and Hailey, (2012) present in a report a comprehensive review of incorporating engineering design challenges into science, technology, engineering, and mathematics (STEM) courses. In their report, they review a few different engineering design models (e.g., those developed by UTeachEngineering, and Massachusetts Department of Education) and present an in-depth discussion on implementing engineering design challenges using the nine step NCETE engineering design model proposed by Hynes et al. (2011). The steps presented in this engineering design model included:

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;
9. Finalize the design.

Engineering Design in Educational Standards

The teaching of the "engineering design" and the engineering design process is promoted at the national level in educational standards developed for technology and science. In technology and engineering education, the *Standards for Technological Literacy: Content for the Study of Technology* (ITEEA, 2000/2002/2007) strongly promotes the teaching of design and related content in Standards 8-11. In Standard 8, benchmark H, the ITEEA Standards present a "design process," discussed as "technological design," that includes the following steps:

1. Defining a problem
2. Brainstorming
3. Researching and generating ideas
4. Identifying criteria and specifying constraints
5. Exploring possibilities
6. Selecting an approach
7. Developing a design proposal
8. Making a model or prototype
9. Testing and evaluating the design using specifications
10. Refining the design
11. Creating or making it
12. Communicating processes and results.

The ITEEA Standards discuss that there are different engineering design process models and present a general discussion on how they are typically used by engineers. Standard 9 focuses on students developing an understanding of the engineering design process and specifically references the "engineering design process." Standard 9 does not present one specific model, however, benchmark C states that the engineering design process involves:

1. Defining a problem,
2. Generating ideas,
3. Selecting a solution,
4. Testing the solution(s),
5. Making the item,
6. Evaluating it, and
7. Presenting the results.

The *Next Generation Science Standards, NGSS* (2013) make a commitment to integrate engineering design into the structure of science education by raising engineering design to the same level as scientific inquiry when teaching science disciplines at all levels, from kindergarten to grade 12 (NGSS, 2013). In the *NGSS*, they note the term "engineering design" has replaced the older term "technological design" and the *NGSS* uses recommendations from *A Framework for K-12 Science Education* (NRC, 2012) for the teaching of engineering design. The *NGSS* do not refer to engineering design as a process or list a series of problem solving steps. Rather, they encourage that students learn the core ideas of engineering design that includes the three component ideas described below.

A. Defining and delimiting engineering problems involves stating the problem to be solved as clearly as possible in terms of criteria for success, and constraints or limits.
B. Designing solutions to engineering problems begins with generating a number of different possible solutions, then evaluating potential solutions to see which ones best meet the criteria and constraints of the problem.
C. Optimizing the design solution involves a process in which solutions are systematically tested and refined and the final design is improved by trading off less important features for those that are more important. (NGSS, 2013, p. 2)

Engineering Design in K-12 Curricula

In national curricula developed for K-12 technology and engineering education, as well as for STEM education, the importance of engineering design is almost always promoted. The publication *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* (NRC, 2009) presents an excellent and detailed review of national curricula efforts in STEM that shows how the teaching of engineering design is included in most STEM curricula.

In reviewing popular national curriculum efforts for use in technology and engineering education, it was found that engineering design is an important concept emphasized in curricula where problem solving was the focus of learning. It also showed that most models presented similar features in their approach to solving problems, and that most models appear to be presented in a cyclical fashion. Examples of curricula where engineering design is emphasized include *Project Lead the Way's (PTLW)* engineering courses (see: www.pltw.org/our-programs/pltw-engineering), the International Technology and Engineering Educators Association's *Engineering byDesign (EbD)* courses (see: www.iteea.org/STEMCenter/EbD.aspx) and in the Boston Museum of Science Engineering curricula offerings (see: www.mos.org/engineering-curriculum). In addition to national curriculum efforts, States have also developed curricula that provides students an opportunity to learn about apply the engineering design process. For example, see Utah's *Engineering Course* (www.schools.utah.gov/CTE/tech/DOCS/strands/EngineeringTechnology.aspx).

Organizations Promoting Engineering Design

In addition to STEM curricula, there are many organizations promoting the use of the engineering design process in K-12 Education. For example, PBS's Design Squad (http://pbskids.org/designsquad) or Science Buddies (www.sciencebuddies.org), a non-profit organization promoting science, defines the engineering design process as a series of steps that engineers follow to come up with a solution to a problem. They identify the steps of the engineering design process as:

1. Define the Problem
2. Do Background Research
3. Specify Requirements
4. Brainstorm Solutions
5. Choose the Best Solution
6. Do Development Work
7. Build a Prototype
8. Test and Redesign

TeachEngineering (www.teachengineering.org), is an NSF supported digital library site that offers standards-based engineering curricula for use by K-12 teachers and engineering faculty to make applied science and math come alive through engineering design in K-12 settings, and they promote an engineering design process model that includes the following steps:

1. Ask: Identify the Need
2. Research The Problem
3. Imagine: Develop Possible Solutions
4. Plan: Select a Promising Solution
5. Create: Build a Prototype
6. Test and Evaluate Prototype
7. Improve: Redesign as Needed

For many years NASA and its educational programs have been supporting curricula that promote engineer design and engineering design challenges. Recently they have introduced a new program known as "Beginning Engineering, Science and Technology or BEST (www.nasa.gov/audience/foreducators/best/edp.html) that promotes teaching the engineering design process to younger audiences. Their engineering design process model, adopted from the Boston Museum of Science engineering design model, includes the following steps:

1. Ask
2. Imagine
3. Plan
4. Create
5. Experiment
6. Improve

Section Summary

This section showed the importance of teaching the engineering design process in K-12 technology and engineering education and in STEM education. It showed how the engineering design process is supported in national educational standards, STEM education curricula, and by other organizations involved in STEM education. Although this section did not show one agreed upon engineering design process model, it did show that most models were similar in the features they presented.

Discussion

The purpose of the paper was to investigate if the engineering design processes used in K-12 engineering and technology education classrooms are an accurate reflection of the practices used in industry and other technical fields (i.e., for purposes of this paper, the field engineering). In reviewing how engineers learn about and use the engineering design process and how it is presented in technology and engineering education, the author would have to agree that it is a "fairly accurate reflection" of the practices being used in industry and technical fields.

In this paper, one major theme emerged, that is, that problem solving is an important *(if not the most important)* skill that engineers must learn. The paper also found that there are many engineering design (problem solving) models being taught and used in both the fields of engineering and technology and engineering education. Many models reviewed noted the importance of good teamwork when solving problems and included the basic steps of identifying and describing the problem, brainstorming solutions, choosing a solution, building and testing the solution, and sharing the results. Inherent to all of these steps was the need to use good "decision making" practices. Interestingly, most engineering design models in technology and engineering education were presented in a cyclical fashion, while those in engineering presented in a "block fashion." However, the models discussed in engineering often noted noted that the process was iterative and not linear.

In the teaching of the engineering design process in K-12 technology and engineering education, most models reviewed were similar in the features they presented to solve problems. These features were also similar to those taught and and used in the field of engineering, however in engineering, when solving problems, there seemed to be more of an emphasis on the context of the problem, the needs of the customers, and more emphasis on analysis and constraints related to the problem. Those involved in the teaching of technology and engineering education, should consider also emphasizing these points, when teaching students how to apply the engineering design process. In addition, based on personal experiences, other important concepts to emphasize would include those related to creativity, ethics, and that it is all right "to fail" as designers often fail many times before succeeding.

Conclusion

Problem solving, (i.e., engineering design, or the engineering design process) is a very important skill needed in engineering and these skills should be taught in K-12 technology and engineering education. There are many engineering design models used in engineering, and technology and engineering education, but they are very similar in the features they use to solve problems. Those involved in the teaching of K-12 technology and engineering education should continue teaching the engineering design process as currently promoted in technology and engineering education, and STEM education. However, those involved in teaching engineering design in technology and engineering education should consider placing more of an emphasis on the context of the problem, the needs of the customers, analysis of the problem, and constraints related to the problem.

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