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Engineering Design: A Cognitive Process Approach

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ENGINEERING DESIGN: A COGNITIVE PROCESS APPROACH

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ABSTRACT

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The intent of this dissertation was to identify the cognitive processes used by advanced pre-engineering students to solve complex engineering design problems. Students in technology and engineering education classrooms are often taught to use an ideal engineering design process that has been generated mostly by educators and curriculum developers. However, the review of literature showed that it is unclear as to how advanced pre-engineering students cognitively navigate solving a complex and multifaceted problem from beginning to end. Additionally, it was unclear how a student thinks and acts throughout their design process and how this affects the viability of their solution. Therefore, Research Objective 1 was to identify the fundamental cognitive processes students use to design, construct, and evaluate operational solutions to engineering design problems. Research Objective 2 was to determine identifiers within student cognitive processes for monitoring aptitude to successfully design, construct, and evaluate technological solutions. Lastly, Research Objective 3 was to create a conceptual technological and engineering problem-solving model integrating student cognitive processes for the improved development of problem-solving abilities.

The methodology of this study included multiple forms of data collection. The participants were first given a survey to determine their prior experience with engineering and to provide a description of the subjects being studied. The participants were then

presented an engineering design challenge to solve individually. While they completed the challenge, the participants verbalized their thoughts using an established "think aloud" method. These verbalizations were captured along with participant observational recordings using point-of-view camera technology. Additionally, the participant design journals, design artifacts, solution effectiveness data, and teacher evaluations were collected for analysis to help achieve the research objectives of this study. Two independent coders then coded the video/audio recordings and the additional design data using Halfin's (1973) 17 mental processes for technological problem-solving.

The results of this study indicated that the participants employed a wide array of mental processes when solving engineering design challenges. However, the findings provide a general analysis of the number of times participants employed each mental process, as well as the amount of time consumed employing the various mental processes through the different stages of the engineering design process. The results indicated many similarities between the students solving the problem, which may highlight voids in current technology and engineering education curricula. Additionally, the findings showed differences between the processes employed by participants that created the most successful solutions and the participants who developed the least effective solutions. Upon comparing and contrasting these processes, recommendations for instructional strategies to enhance a student's capability for solving engineering design problems were developed. The results also indicated that students, when left without teacher intervention, use a simplified and more natural process to solve design challenges than the 12-step engineering design process reported in much of the literature. Lastly, these data indicated that students followed two different approaches to solving the design

problem. Some students employed a sequential and logical approach, while others employed a nebulous, solution centered trial-and-error approach to solving the problem. In this study the participants who were more sequential had better performing solutions. Examining these two approaches and the student cognition data enabled the researcher to generate a conceptual engineering design model for the improved teaching and development of engineering design problem solving.

DEDICATION

This dissertation is dedicated to my wonderful wife Krista and to all my family, friends, and mentors without whom none of my achievements or successes would have been possible.

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There is an extensive list of individuals who have contributed to the successful completion of this dissertation. I truly believe that it is impossible to complete a task as monumental as achieving a doctoral degree without help and support from others. Throughout the course of concluding my graduate studies, there have been numerous people who have been involved in helping me overcome various obstacles along the way. Because their assistance and endless support has been an invaluable resource to me, I felt it was necessary to acknowledge them for everything their help and understanding has meant to me over the years.

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CHAPTER I

INTRODUCTION

Technology and engineering education has an extensive history of providing students with opportunities for applying complex skills and concepts to solving problems embedded in consequential contexts. Support for learning such multidimensional concepts and developing creative problem-solving skills pull profoundly upon student information and cognitive processing. Students in complex learning situations follow a mental process in which they dissect a given task into separate informational components to be processed into steps for solving a problem. The learning and performance in engineering design problem-solving is influenced by fundamental cognitive processes and limitations in completing complex tasks (Schunn & Silk, 2011). However, little research has been conducted to provide an insight into the complete cognitive processes pre-engineering students use to solve engineering design problems in a practical manner.

A major theme that echoes across technology and engineering education literature is the need for more research to understand the cognitive science that underlies a student's ability to successfully produce a quality solution to an engineering design problem. In-depth comprehension of students' mental processes can be extremely beneficial for improving educators' methods when designing curriculum, instruction, and assessment in technology and engineering education. The challenge of connecting theories of cognition to improved evaluation processes of student aptitudes in engineering design problem-solving strategies requires an understanding of the mental processes, which can be mapped into a conceptual model for teaching (Folkestad & DeMiranda, 2000).

Researchers have been trying to understand the cognitive processes in general problem-solving for many years. However, the understanding of engineering design cognition has recently become a particular interest in technology and engineering education (Kelley & Rayala, 2011; Petrina, 2010). This may be associated with a national focus on creative problem-solving skills as a necessity for success in colleges and careers (Partnership for 21st Century Skills, 2011). Careers in this century have been increasingly thought to require employees' use of more technological skills and knowledge to creatively solve multifaceted problems. Coincidently, technology and engineering programs attempt to prepare students for these future careers by providing the opportunity to develop their ability to integrate and use multiple skill sets in resolving complex and complicated issues (Liao, 2011).

The improvement of technology and engineering education depends heavily upon the role researchers and educators take in developing and utilizing an understanding of the mental strategies students use to create the most effective solutions to engineering design problems with procedural fluency (Barak & Hacker, 2011). Enhancing the understanding of student problem-solving cognitive processes is justified by the opportunity that it provides for improving the way technology and engineering curriculum and instruction are developed (Kelley, 2008). Furthermore, the study of cognition can help inform assessing a students' development of problem-solving abilities through technology and engineering coursework.

Statement of the Problem

The purpose of this study was to identify the cognitive processes used by advanced pre-engineering students to solve complex engineering design challenges. This

research was undertaken to gain a better understanding of how pre-engineering high school students of an experienced level have learned to engineer viable solutions to problems from design conception to an end product for the purpose of improving student learning in technology and engineering education. With greater insight into student learning, educators can combat the difficulty in planning and assessing students' abilities in solving engineering design challenges from start to finish.

Research Objectives

The research objectives that guided this study included the following:

RO_1: Identify the fundamental cognitive processes students use to design, construct, and evaluate operational solutions to engineering design problems.

RO_2: Determine identifiers within student cognitive processes for monitoring aptitude to successfully design, construct, and evaluate technological solutions.

RO_3: Create a conceptual technological and engineering problem-solving model integrating student cognitive processes for the improved development of problem-solving abilities.

Background and Significance

The advancement of technology and engineering education for general instruction purposes of technological literacy has suffered from a lack of cognitive research in the development of the critical skills of engineering design problem-solving (Zuga, 2004). A committee on K-12 Engineering Education, developed through a collaboration of the National Research Council and the National Academy of Engineering, stated in their report, *Engineering in K–12 Education: Understanding the Status and Improving the Prospects* (2009), there was very little research conducted in cognitive science involved

in engineering. The report also recommended that cognitive research in engineering should be expanded and mapped in a manner to be infused with developing instructional practices and theories. More recently, the National Academies' Committee on Standards for K-12 Engineering Education reported an insufficient amount of cognitive research has been conducted to inform the development of standards for engineering at the K-12 level (National Research Council, 2010). This committee provided a recommendation for a research agenda that includes understanding how students cognize and apply skills in engineering. Understanding the cognitive processes that students apply is critical for developing citizens who are ready to face the increasingly technological world of tomorrow. Student cognitive and meta-cognitive processes are important thinking skills that are essential for success as a technical problem solver (Kelley, 2008).

The initiative for the technology and engineering education profession seems to be identifying how students are learning in a way that is unique in technology and engineering, as well as what cognitive processes they are using to complete engineering design challenges. Using a focus on cognitive research and identifying the key factors in student strategies to solve problems can allow teachers to understand how students learn and determine methods for improving and evaluating their technical skill development. Although there have been various studies within technology and engineering education that have focused on cognition, it is often viewed as being too broad and not in-depth enough for the practical application of technical skills (Zuga, 2004).

In recent years, education has given considerable attention to the skills of creative problem-solving. With this increased interest, engineering design problem-solving within the confines of technology and engineering education has become of particular

importance for understanding the behavioral patterns that students display during their attempts to solve complex problems using advanced technologies and materials. These behaviors include how students planned to solve the problem, how they chose to make the solution, the technical procedures they used to solve the problem, how long the processes took, and how they evaluated their final product. All of these issues are further complicated because problem-solvers are often unaware of these processes and they are difficult for researchers to identify (Lester, 1980).

Cognitive psychology is one of the most problematic fields to study since it involves investigating the things that we cannot see, hear, or feel. The history of cognitive research has revealed many conflicting views about the nature of thought and thought processes (Lawson, 2005). This history and the lack of research have sparked a need for understanding the cognitive science in the act of engineering design problem-solving. Currently, there are many needs for research in technology and engineering education; however, a study undertaken by Martin and Ritz (2012) determined the most important issues requiring research in K-12 technology and engineering education. Using a Delphi study consisting of a panel of United States experts in technology and engineering education, the researchers discovered that the primary need requiring more research in the preparation of technology and engineering teachers was the understanding of cognitive sciences among students. Additionally, Ritz and Martin (2012) conducted a similar study at the international level, and it illustrated more need in moving toward research concerning student cognitive processes and student assessment of practical skills. The research themes ranked among the top ten pertaining to cognitive science and

the assessment of skill development in technology and engineering education were as follows:

1. Abilities students develop in technology education
2. Insufficient understanding of learning that takes place in technology education
3. Technological conceptual knowledge
4. The assessment of technological performance
5. How design activities should be taught by teachers
6. Methods of assessment in practical work
7. Nature of collaborative work in technology education (Ritz & Martin, 2012)

Based on the research needs that were concluded in the aforementioned studies, a necessary push to identify the cognitive processes students use in engineering design is essential for the profession as it might lead to a means to better understand how to effectively teach and assess practical work in solving complex engineering design challenges. Problem-solving is the major focal point in technology and engineering education (International Technology Education Association, 2002), and it may have lost clarity in the ever-changing mission of the profession. In the United States, as well as other countries, the focus has shifted to mostly teaching and assessing design and the design process. A focus on design and design processes is important; however, it is becoming evident that this should not be the only concentration. It is apparent throughout the technology and engineering education professional literature that students should be taught the importance of creative design, as well as the skills needed to produce solutions of quality. Evaluating problem-solving processes illustrates that students can follow a procedure, but little is done to determine how high school students actually solve

problems practically (Mouser, 2009). Developing students with the skills to be creative and practical problem solvers is what can provide them with the means necessary for success in the 21st century. However, there has been little done to analyze the cognitive processes that might lead to the production of more effective solution outcomes.

Understanding this process can help teachers monitor student development in the areas needed to be both creative and successful problem solvers. Moreover, this knowledge could help drive the development of new curriculum and instructional practices as well as innovative assessment strategies that can help increase student achievement in this field. To assess students' skill development, engineering design challenges are being used internationally more and more. However, students are often only graded by a rubric following the process, which can often be mistaken as linear. Using these types of assessments may not show that a student is capable of using advanced technologies and materials to produce real solutions (Kimbell, 2008). A conceptual map of a student's cognitive processes employed throughout the complete engineering design process can enable teachers to better understand, teach, and evaluate students' skills in producing real solutions to complex problems.

As previously mentioned, an important step in developing a theory of instruction is to study the processes that underlie successful performance in design and solution production. This method is quite different from an approach that focuses solely on the process that a student uses to solve a problem. This previous approach may have produced students who are good at thinking but not at doing. Therefore, it is important to focus student learning on the process to solve a problem (Designing) as well as on the products that a successful individual produces (Making). A second reason for

understanding the cognitive science involved with student technological skills is that it can help better prepare teachers to assist students who have difficulties. If a student is unable to produce successful results, a teacher can recognize the lack of ability and enact strategies to facilitate these students' cognitive strategies. Knowledge of a student's mental processes in producing quality solutions can allow a teacher to identify and correct student learning problems (Bransford & Vye, 1989).

Another factor displaying the need for increased knowledge of a student's technological aptitude is the way students are assessed nationally. Students are generally assessed on their ability to remember rote facts and skills rather than on their ability to apply high-order reasoning and continual learning skills. Studies from the National Assessment of Educational Progress have provided evidence that most students can recall simple facts. However, serious deficiencies occur at the higher levels of scientific and technological thinking (Folkestad & DeMiranda, 2000). Additionally, the majority of students are unable to apply their knowledge to solve more complex problems that require multiple steps and have no distinct answer or process to get there. Successful learning of the abilities to manipulate and make actual working solutions is a task that can take place in technology and engineering education if recommendations are provided on cognitive strategies involved in engineering design. Therefore, technology and engineering education instruction should continue to focus on both the design and making processes. Society now demands that students think critically, consider all options, evaluate their choices, and develop the processes to achieve the purpose or outcome of the lesson (Folkestad & DeMiranda, 2000).

Lammi and Becker (2013) have conducted research on cognition involved in designing solutions to engineering problems. These researchers sought to understand the complex cognitive process of engineering design thinking by using an exploratory triangulation mixed-method approach. The findings generated in their study provided an insight on the thinking process as involved when students solve design problems; however, the methods used in data collection had limitations. For example, the participants were not studied individually, which limits the accurate portrayal of individual thought processes. Additionally, the data collected as a verbalization of the students' thought processes were not actually what the students were thinking; rather, it detailed their conversations with classmates. Lastly, the researchers only studied their participants as they designed a solution to the problem and did not study the thought processes used to actually built, test, and evaluate their solutions. However, Lammi and Becker conclude that their research should be used to springboard more in-depth research in student design thinking. The limitations of their study combined with these researchers' recommendations support the need for additional research on student cognition involved in engineering design thinking.

Kelley (2008) has also conducted research on the cognitive processes students use in technology and engineering education. In his study, Kelley videotaped students while they articulated their thought processes during their attempt to solve an ill-defined problem. He then analyzed the results to heighten the awareness of what the students experience as they solve problems. The methods that were put in place for Kelley's research were beneficial in determining the procedures for this study. However, Kelley pointed out the weaknesses in his own study, which also provided recommendations for

this study. The first shortcoming Kelley noted was that he only observed students for a total of thirty minutes. This amount of time, of course, cannot provide much insight into students' abilities to completely solve a problem. Additionally, he did not focus on the student technological skills needed to produce a quality result. Although Kelley followed a well-planned procedure for studying problem-solving, the findings of his study were limited in their ability to be generalized for a larger population. Furthermore, the results did not allow for the development of a conceptual model of cognitive strategies used in engineering design problem-solving that would be beneficial to student learning and assessment.

In summary, there were several reasons for conducting research on the cognitive processes involved in engineering design and for determining how this knowledge can apply to improving learning in technology and engineering education. Those reasons stemmed from the small population of researchers within the culture of technology and engineering education. The research related to this study was previously considered to be very broad and as containing many gaps. Providing an understanding of cognitive processes through this study can help improve the way problem-solving skills are taught and evaluated. With education systems trying to understand the best way to assess student skills necessary for college and career readiness, the deepest possible understanding of cognitive strategies in problem-solving will aid in this endeavor.

Limitations

The limitations of this study were as follows:

1. The data collected were limited to high school students in grades 11 and 12 from two high schools in eastern West Virginia who have completed at least three *Project Lead*

the Way pre-engineering courses. The participants of this study were enrolled in a high school pre-engineering academy, which required them to take the capstone *Project Lead the Way* pre-engineering course at the career and technical education center. This sample allowed for an analysis of the cognitive processes experienced students used to solve engineering design problems. Additionally, data collected from these participants enabled the creation of a working model to use for monitoring student cognitive development in engineering design problem-solving throughout high school.

2. The data collected were limited to a purposeful sample of eight high school students from two feeder high schools for a West Virginia county career and technical education center. These schools were recommended as high performing high schools by the state coordinator for engineering and technology education.
3. The data collected were limited to analysis by the research team monitoring and coding the student cognitive processes. The creation of the student engineering design cognitive model was also limited by the synthesis of the researcher's findings.
4. The data collected were limited to student participants working alone to solve problems. It is important to determine the way in which students individually manage the cognitive load in problem-solving.
5. The data collected were limited to the time that students were engaged in the problem-solving activity during class. It is understood that some design ideas may take place outside of the classroom. Due to this limitation, a variety of data was collected to allow for a triangulation of results. No one source of data was relied upon

to provide all of the evidence for the cognition related to the student's technological problem-solving process (McCormick, 2008).

Assumptions

This study was based on the following assumptions:

1. The conceptual model of student engineering design cognition would be created with the intention to have a positive impact on future student learning and assessment.
2. The participants would possess similar cognitive processes in solving design problems, which would allow the process to be synthesized into a conceptual model of engineering design problem solving.
3. The participants would have enough prior knowledge in engineering design to be able to utilize effective cognitive strategies for creating viable solutions.
4. The participants would be successful in creating viable solutions to the given engineering design challenge with a developed level of technological skills.
5. The participants would be able to transmit their understanding of their own performance and process in achieving success in creating a solution to the given engineering design challenge (Bransford & Vye, 1989).

Procedures

Based upon the previous discussion on the insufficient effort in creating a technology and engineering education research base for engineering design cognitive science and recommendations from literature, a procedure for conducting meaningful research was determined. In order to establish a descriptive analysis of how students cognitively process complex engineering design challenges from start to finish, a variety

of data was collected through the use of case studies (Zuga, 2004). Case studies have become important in technology and engineering education research because of their effectiveness in capturing the pedagogy of the classroom and in understanding cognitive processes used in interactions among students and teachers in the completion of design activities (McCormick, 2008).

McCormick (2008) recommended that a researcher should answer the following three questions in their justification for employing case studies. The first question that was asked was "Why use a case study?" Case studies were selected for accomplishing the research objectives because of this method's ability to explore a real-life situation that has unclear boundaries of phenomena and context (Yin, 2003). In this instance, participant case studies provided a vivid picture for understanding the cognitive processes that students do or do not employ when solving engineering design problems. The results of this study build upon existing ideas and emerging theories in the cognitive science involved with technology and engineering education, thus providing a higher level of validity and reliability of the research results. It would have been illogical to think that there were no other theories that involved student problem-solving that could have been used to help understand what was observed in this study.

The next question used to justify the research design was "What kind of case study should be used?" Due to the nature of the research objectives in this study, it was determined that exploratory case studies were necessary. This method was selected because the research objectives focused on identifying what the cognitive processes of students were and not specifically why they were used (Yin, 2003). Selecting this approach led to answering the third question of, "how can unbiased data be collected and

analyzed in a way that provides results that can be generalized?" (McCormick, 2008). In case studies, the researcher must capture and portray the elements of a particular situation through the collection of information that provides the means for explaining the phenomena under investigation (Walker, 1986). This definition of a research approach requires a collection of multiple sources of evidence for analyzing students' cognitive processes in problem-solving. Multiple data sources allowed for a triangulation of information, so no one source of data was responsible for providing all of the evidence for the phenomena under investigation (McCormick, 2008).

The collection of multiple forms of data had stemmed from the contemporary research support for qualitative methods in observing student behavior, interviewing for student knowledge, and understanding how students solve-problems (McCormick, 2008). The forms of data gathered through this study included a collection of video and audio recordings of students working independently to solve an engineering design challenge, while verbalizing their thoughts using a "think aloud" method. Additionally, participant design artifacts were collected to aid in the coding of the data. The audio/video recordings were independently coded by two coders using the 17 mental processes for technological problem solving identified in a study conducted by Halfin (1973). The coding process enabled the identification of which processes the participants used to design, construct, and evaluate operational solutions to engineering design problems. The coding of the data was accomplished using an updated version of Hill's (1997) Observational Procedure for Technology Education Mental Processes (OPTEMP) computer analysis tool. This tool enabled the coders to simultaneously view and code the recorded participant observations. The coded data then guided the creation of a

conceptual model of how advanced pre-engineering students actually solve engineering design problems. Using these qualitative procedures allowed for an exploration of the relationships between cognition and engineering design problem-solving (Zuga, 2004).

However, case studies do not need to only use qualitative data. When case studies are conducted as entirely qualitative research, it is often viewed as a way to avoid statistical generalization (McCormick, 2008). In order to provide the necessary quantitative data for reaching reliable and valid results, additional procedural methods were added to the study. The major method was to capture video footage of the students working through the design challenge while incorporating the method of narrating their thought process. Kelley (2008) deployed this method in a similar study because of its strength in collecting student actions, body language, and mental processes. Data collected from these observational and verbal protocols enabled an analysis of the number of times each mental process was employed and the time taken for each identified and coded process during the engineering design sessions. The resulting data were also combined with teacher evaluations of student performance and quantitative data on the effectiveness of the student developed solutions to develop the conceptual model of engineering problem-solving integrating student cognition. With this variety of data the conceptual model can be used for the purpose of improving the development of student problem-solving abilities.

Definition of Terms

The following terms were used throughout this study:

- Case Study: an in depth study of particular individuals, programs, or events from a particular angle or perspective (Leedy & Ormrod, 2009).

- Cognitive Researchers in Education: a group that studies the mental processes underlying activities such as perceiving, thinking, and learning, by specifically studying the processes involved in reading, writing, mathematical, technological, and scientific thinking to make significant improvements in instruction (Bransford & Vye, 1989).
- Cognitive Science: is the study of mental processes (Lawson, 2005).
- Cognitive Processes: happen in the mind/brain and include perception, memory, attention, language, problem-solving, decision-making, thinking, and other processes (Sincero, 2011).
- Engineering Design and Development Course: the capstone course in the *Project Lead the Way* high school pre-engineering program. In this course, students work in teams to design and develop an original solution to a valid open-ended technological problem by applying the engineering design process.
- Problem-solving: a mental process that involves discovering, analyzing, and solving problems. The ultimate goal of problem-solving is to overcome obstacles and find a solution that best resolves the issue (Sincero, 2011).
- Design: a term that refers to anything that was made by a conscious human effort.
- Engineering Design: designing under constraint (Wulf, 1998). Engineering design is also a process that is used to systematically solve problems (Project Lead the Way, 2013).
- Engineering Design Challenge: an open-ended and ill-defined problem that students are asked to solve by applying previous knowledge while developing an in depth understanding of new and previously learned concepts.

- Engineering Design Process: a systematic, iterative problem-solving method that produces solutions to meet human wants and desires (International Technology Education Association, 2002).
- Practical Work: teaching and learning opportunities where students are engaged in observing or manipulating real objects and materials (Miller, 2004).
- Pre-Engineering: a course of study that explores the broad field of engineering for the purpose of preparing students for post-secondary studies in engineering.
- Problem-Based Learning: the process that replicates the commonly used systemic approach to resolving problems or meeting challenges that are encountered in life and career throughout the educational experience (Problem-Based Learning, 2004).
- Procedural Fluency: carrying out procedures appropriately and efficiently. This term will specifically apply to using technological tools and knowledge in solving problems (Schunn & Silk, 2011).
- Project Lead the Way: a standardized national K-12 pre-engineering education model designed for preparing students for post-secondary engineering programs.
- STEM Education: an integrative method for teaching the practical application of content and concepts in science, technology, engineering, and mathematics through real world contexts in problem-solving (National Research Council, 2011).
- Technological Problem-solving: the process of developing working solutions to ill-structured problems by applying critical thinking and creativity skills in the use of tools, machines, and materials (Petrina & Hill, 1998). Technological problems are synonymous with engineering design problems (International Technology Education Association, 2002).

- Technology and Engineering Education: provides opportunities to learn about the processes and knowledge related to applying engineering principles that are needed to solve technological problems and extend human capabilities (International Technology Education Association, 2002).

Overview of Chapters

This chapter discussed the role engineering design plays in technology and engineering education for developing students that have the practical skills to actually create valid solutions to complex problems. It also explained the importance in researching the cognitive strategies that students use to solve these engineering design challenges. It is important for the profession to focus on student success in creating effective solutions, as well as on the process they employ to create the solution. If teachers only monitor students' creative processes in designing, then they will likely produce students who do not have the real world skills to make quality technological solutions for these problems. The engineering design process is a vital part of problem-solving, but, in the real world, if one produces solutions that do not work well, then he or she will not be successful in engineering or technological careers. Meanwhile, there has been a lack of research on this particular topic. The results of this study may be used to alter the way educators teach and evaluate student skills in technology and engineering education.

The Review of Literature in Chapter II will discuss details of technological and engineering design educational approaches as related to problem-based learning. This chapter will also provide an explanation of cognition and cognitivism since both are related to complex thought. Furthermore, Chapter II will report relevant research on how

people actually think when it comes to designing solutions to problems, as well as the way in which they learn to do so.

Chapter III will then explain the case study procedure that was employed for researching the student participants in this study. Finally, Chapters IV and V will present the research results and how these data were assembled into a conceptual model for improving student learning and assessment of problem-solving abilities.

CHAPTER II

REVIEW OF LITERATURE

The field of technology and engineering education is an area of study with a long history of evolving in a manner to remain current by providing all students with the skills necessary for success in the workforce and economic trends of the times (International Technology Educators Association, 2000; Lewis & Zuga, 2005; Markert, 2011). More recently, initiatives in science, technology, engineering, and mathematics (STEM) education have placed an emphasis on the importance of technology and engineering education for preparing students to become creative problem solvers (Barlex, 2011; Bjorklund, 2008; National Reseach Council, 2011; Warner, 2011). As stated by Petrina (2010) and Kelley and Rayala (2011), the focus on cultivating creative problem-solving and design provides a necessity to explore how students think as it pertains to solving the engineering design challenges that are presented in this dynamic area of study. Conducting cognitive research on this topic can aid in understanding how technology and engineering education can support a student's development in the ability to solve real world problems (Zuga, 2004). Cognitive research in problem-solving continues to provide a foundation for the science of learning and the development of competent performance among students (De Miranda, 2004; National Research Council, 2005). However, Kelley and Rayala (2011) have proclaimed that as multiple K-12 engineering design curricula continue to be implemented in schools around the country, more research needs to be conducted to determine the cognitive processes that students employ as they creatively work at solving ill-structured engineering problems.

To report the crucial research in the realm of cognition and engineering design, this chapter will delve into three major topics. The first section will describe the evolution of engineering design problem-solving through technology and engineering education. Section two will describe cognition and design thinking as it relates to solving problems. Section three will explain the development of problem-solving skills. Exploring these topics will provide a background on the cognitive processes used to solve engineering design challenges and the role technology and engineering education plays in student problem-solving skill development.

Technological and Engineering Design Problem-solving

The T and E in STEM Education

Technology and engineering education has been described as a dynamic subject that aims to prepare all students to be technologically literate and proficient in the skills needed for success in an innovation-driven world (International Technology Educators Association, 2002; Frazier, 2009). Zuga and Cardon (1999) claimed that for more than a century, educators have wanted to include all students in the dynamic study of technology in order to provide them with the experiences needed to be progressive contributors to society. However, Lewis and Zuga (2005) have noted that throughout this time, there have been many undertakings within the field to continue to define and redefine its own identity. Nonetheless, an examination of the evolution of technology and engineering education can depict how this school subject has developed in ways to foster a society of innovative technological problem solvers necessary to support the current trends in STEM workforce development.

Technology and engineering education has historically reflected the trends and projections of economic and workforce needs (Zuga & Cardon, 1999). As Herschbach (2009) described, technology and engineering education is also a product of the social and education changes of the 1970s and 1980s. However, the conceptual and pedagogical roots of this field extend much deeper (Hershbach, 2009). Lewis and Zuga (2005) traced the field back to the earliest forms of apprenticeships. Apprenticeships developed in the Paleolithic time period as humans began to learn by imitating others (Hogg, 1999). These apprenticeships were needed to transfer the technological knowledge and skills necessary to solve societal problems confronted at the time to extend human capabilities for advancing the civilization (Lewis & Zuga, 2005). Planning this transfer of knowledge, combined with the "object method" of improving education by Pestalozzi and the methods of teaching technological skills generated by Salomon and Cygnaeus, Della Vos, Runkle, and Woodward, created a pathway for the earliest forms of formal technology and engineering education (Bennett, 1937).

The first formal programs for the study of technological and engineering skills and content began in the 1860s at the Manual Training School of Washington University in St. Louis and at the Mechanics School of Massachusetts Institute of Technology (MIT) (Zuga & Cardon, 1999). These programs drew upon the work of the trade school movement with the integration of academic subjects (Hershbach, 2009). Much like current technology and engineering initiatives, the teachers at these schools saw that students were able to learn more rigorous mathematics and science concepts through physically manipulating materials in a lab environment (Lewis & Zuga, 2005). The integration of academics through practical work is similar to technology and engineering

education today. However, these two programs took two different philosophical approaches to their technological education (Lewis & Zuga, 2005). The program at MIT sought to teach aspiring mechanics the technical and academic knowledge specifically needed for their job. The Manual Training School of Washington University saw a need to educate all students in this manner regardless of their career aspirations (Zuga & Cardon, 1999). This difference about the purpose of manual training was used to develop industrial arts as a component of general education rather than vocational education (Hershbach, 2009; Lewis & Zuga, 2005; Zuga & Cardon, 1999).

The foundation for technology and engineering education (Hershbach, 2009) was laid through the industrial arts movement of the mid-20th century. Industrial arts was a subject that was made available to all students in order to provide them with knowledge and skills that would be beneficial in any career field. Industrial arts focused on giving students the ability to learn by doing while allowing them to perform practical skills in completing projects (Barlow, 1967). Through the development of industrial arts in the 20th century, this type of teaching began to be organized into sequenced content that would help prepare all students to become informed citizens and societal contributors (Lewis & Zuga, 2005).

Late in the 20th century, changes to industrial arts were made in order for the profession to play a key role in future education. As Maley (1980) stated, it is obvious that with the advancements in technology and changes in society, people do not face the same problems and uncertainties as in the past. With this stance, it was presented that the future of industrial arts was reliant on developing a plan of action for education that will best serve humankind for the years to come. Additionally, inconsistency in the content

taught within industrial arts led to the transformation of industrial arts to technology education throughout the 1980s and 1990s. This transformation was assisted with the study by de Vries (1988) that focused on *Pupils' Attitudes Towards Technology* in the Netherlands. This study was used as a form of a needs assessment for changing industrial arts to technology education. The findings revealed that students 13 years of age held a vague and incomplete understanding of technology. The study was replicated around the world and resulted in similar conclusions. These studies helped form a group of practitioners for aiding in educational changes (Bame, Dugger, de Vries, & McBee, 1993). As a result, the *Technology for All Americans Project* (International Technology Education Association, 1996) was launched in response to a growing demand for the study of technology. The purpose of this project was to define the importance of technological literacy, promote technology education in schools, develop standards that define technology education content, and promote curriculum integration.

With the technology education movement, the former American Industrial Arts Association changed its name to the International Technology Education Association and led the development of standards to guide the study of technology. This standard movement was inspired by the need for a more technologically-skilled workforce that could produce innovation (International Technology Education Association, 1996). The standards movement defined technological literacy as the ability to use, manage, and understand technology. The content for study was then described as the universals of technology with the processes of designing and developing, determining and controlling the behavior of, utilizing, and assessing the impact and consequences of technological systems; knowledge of the nature and evolution of technology, linkages, and

technological concepts and principles; and context as information, physical, and biological systems (International Technology Education Association, 2002).

As technology education was developing, the National Science Foundation (NSF) began using the term "SMET" as shorthand for education in Science, Mathematics, Engineering, and Technology. Upon later review, NSF leaders decided that "STEM" would be a better acronym to describe an interconnectedness of the four subject areas. This term was created because of the growing concern for the motivation and preparation for students in the United States for these career fields. When Friedman published *The World is Flat* (2005), Americans began to realize that the United States might not be a world leader in STEM knowledge and innovation anymore. The lack of STEM abilities led people to believe that countries like China and India were on the fast track to surpass the United States as leaders in the global economy (Sanders, 2009).

The aforementioned concerns in the United States have been considered a "STEM Crisis". The STEM Crisis has been created by the troubling signs that have been brought to light because of how far the United States lags behind other countries in the ranks of STEM education, abilities, and careers (The President's Council of Advisors on Science and Technology, 2011). When compared to other nations, the mathematics and science achievement of U.S. pupils and the rate of STEM degree attainment appear inconsistent with a nation considered the world leader in scientific innovation. In the early 21st century, international reports were showing there were only less than one-third of eight graders in the United States that scored at a proficient level in mathematics and science (Kuenzi, 2008).

The U.S. STEM achievement concerns and the related initiatives created in education caused the science, mathematics, and technology school subjects, including career and technical education, to start staking their claims to STEM education. As a result, the International Technology Education Association added engineering to its title and proudly declared responsibility for the "T" and the "E" in STEM. The International Technology and Engineering Educators Association now has a focus of showing the importance of ensuring the "T and E" are equal partners within STEM in order to adequately prepare the workforce for the next generation and produce valued contributors to our communities and society. Technology and engineering education now has a stance that the superiority of a country as a leader in technology is a desired quality, as well as the ability of an educational system to produce individuals possessing technological abilities (de la Paz & Cluff, 2009). The International Technology and Engineering Educators Association described this view in its publication, *The Overlooked STEM Imperatives: Technology and Engineering K-12 Education*:

Education should be the cornerstone in terms of helping students to be creative problem solvers while, at the same time, helping to shape their futures. These characteristics are essential to our health, knowledge, wealth, and safety. Technology and engineering, while being a part of a solid STEM education, create unparalleled experiences to apply technology, innovation, design, and engineering in solving societal problems. Such problems may range from the evolution of new farming equipment to safer drinking water or food to electric vehicles and faster microchips. Students must be able to apply their knowledge to improve people's lives in meaningful ways. As creative problem solvers, students can gain a vision for how something should work and become dedicated

to making it better, faster, or more efficient. The latest science, tools, materials, and technology can be used to bring these ideas to life. (de la Paz & Cluff, 2009, p. 2)

One current focus of technology and engineering education is an integrative STEM education approach (Wells, 2013). This integrative STEM approach has been made evident by many advances of the various professional education organizations adding the different STEM subjects to their own plans. For example, the *Next Generation of Science Standards* (Next Generation Science Standards Lead States, 2013) has included the study of technology and engineering design as a disciplinary core idea. However, regardless of who is claiming what in STEM education, there is one seminal component that is captured in either STEM education or technology and engineering education. This component is the purposeful combination of engineering design, scientific inquiry, and mathematical computation in the context of real-life problem-solving (Wells, 2013). Such an approach has been a focus of many educational reforms in STEM education because of its potential to create an engaging and robust learning environment that can focus on developing a student's skills for success in the 21st century (Sanders, 2009).

A problem-based learning environment that purposefully applies mathematics, scientific inquiry, and engineering design in the context of an authentic problem can help mimic the way in which STEM professionals act in the workplace outside of school settings (Sanders, 2009). Roberts (2013) highlighted that technology and engineering fundamentals provide opportunities for students to be educated in creative problem-solving techniques needed for the jobs of the future. Throughout the evolution of the T and E in STEM, an educational focus on engineering design problem-solving is evident,

and current initiatives stress the importance of utilizing a problem-based learning environment to develop students' higher order cognitive skills.

A Focus on Problem-Based Learning in Technology and Engineering Education

As technology and engineering education has evolved along with STEM education, a driving force for these educational reform efforts has been the belief that technology and engineering is essential for students to develop higher-order cognitive skills (Barak, 2011; Barak & Hacker, 2011; Johnson, 1987). Higher-order cognitive skills can enable citizens to function in a complex society by increasing their ability to make meaningful decisions to solve the world's multifaceted problems (Martinez, 2010). Consequently, many educational stakeholders have modified their curriculum and instructional strategies as well as their assessment practices to reflect more authentic student experiences and to emphasize complex cognition through problem-solving activities (Bjorklund, 2008; Liao, 2011; Zoller, 2011). The major approach to developing learners' higher-order cognitive development, found throughout the literature, is problem-based learning (Combs, 2008; Hmelo-Silver, 2004; Johnson, 1987, 1992; Sellwood, 1989; Waetjen, 1989).

Hmelo-Silver (2004) described problem-based learning as a situated learning environment in which students must complete real-world relevant tasks that they have not previously experienced as a means to emphasize a meaningful, experiential learning experience. Also, problem-based learning is a term confused with project-based learning (Combs, 2008). Both approaches focus on student learning by receiving first-hand experiences (Combs, 2008). However, problem-based learning promotes higher-order cognitive thinking by requiring the development of new knowledge to solve ill-structured

problems (Sellwood, 1989; Thode, 1989). Problem-based learning also incorporates levels of learner meta-cognition by requiring students to reflect upon their experiences in designing a solution to a problem (Johnson, 1992). Conversely, project-based learning may only focus on developing specific knowledge or skills by experiencing more structured tasks (Waetjen, 1989). Problem-based learning has received more attention in the last few years because of issues with developing the skills necessary for students to be successful in the 21^{st} century (Liao, 2011).

Many educators find problem-based learning appealing because of its potential to transfer more complex concepts to students while actively motivating participation in the learning experience (Hmelo-Silver, 2004). Nonetheless, a study conducted by Ribeiro (2011) showed that some educators find problem-based learning environments to be unpredictable, causing them to lose control of covering the necessary content on the course syllabus. Additionally, the unpredictable classroom can present teachers with student topics or concerns for which they are not prepared. Some teachers found this unpredictability to make them feel vulnerable, which they feel tarnishes their professional identity in the classroom. Another concern highlighted in research is that longer planning times are needed to prepare for problem-based lessons. However, despite the obstacles of reduced control over content coverage, increased vulnerability, and an increased teaching workload, Hmelo-Silver showed that problem-based learning encourages teachers to continually improve their knowledge and teaching practices, which can increase a teacher's level of professional development.

Technology and engineering education has been a forefather of experiential problem-based approaches to education (Johnson & Thomas, 1994). Although, early

forms of technology and engineering education may have been more focused on craft or project-based learning, current curricular development activities highlight a problem-based learning approach (Bjorklund, 2008). Instructors of technology and engineering are encouraged to stress critical-thinking and decision-making skills by requiring students to solve real technological problems (Liao, 2011; Thode, 1989; Waetjen, 1989) by applying a problem-solving method to a problem that students did not know in advance (Hayes, 1989). According to Strimel (2014), technology and engineering education aims to provide the opportunity for students to analyze and define an authentic problem to solve, which allows them to have ownership of their work, compels them to become self-directed learners, and provides them the opportunity to conduct real research to generate innovative technological solutions.

Engineering Design Problems

The problem-based learning approach described above focuses on providing students with real-life experiences while still in an educational setting. This approach mimics real life because people frequently engage in problem-solving activities in their personal lives and careers (Jonassen, Strobel, & Lee, 2006). Solving these daily problems requires effort and concentration through goal-directed cognition (Anderson, 1980). However, there can be various types of problems that people must solve on a daily basis (Van Someren, van de Velde, & Sandberg, 1994). Engineering design problem-solving can be very different from other forms of problem-solving. Jonassen (2011) supported the claim that there are different types of problems by explaining that problems can vary according to their structuredness, complexity, and context. Understanding these ways in which a problem can vary helps create an understanding of engineering design problem-

solving that technology and engineering education now embraces.

Jonassen (2011) described problems as varying along a range of structuredness. Some problems people solve are considered to be well-structured, while others are less structured. Each requires a variety of lower-order and higher-order cognitive processes to solve. Examples of well-structured problems can be found in word problems presented in mathematical or physical science courses. These well-structured problems have specific equations and steps to follow in order to arrive at the correct solution. Examples of less structured problems include designing clothes, writing an article about the results of an experiment, or selecting a new employee. These activities may require solving many smaller problems to develop a final solution (Donovan & Bransford, 2005). Along the structuredness spectrum are design problems that also vary in their level of structuredness. Engineering design problems generally present an issue that forces students to work through a process to create a system or product that meets the solution requirements. This compulsion has been used extensively throughout engineering education (Jonassen, 2011). However, these types of problems can be considered well-structured and ill-structured as well. Well-structured design problems are often more constrained, allowing fewer degrees of freedom in their representations, processes, or solutions. Ill-structured design problems involve incomplete information, multiple conflicting goals, and changing solution requirements (Jonassen, Strobel, & Lee, 2006).

The complexity of a problem varies based upon the structuredness of the problem, as well as the difficulty level of the knowledge and abilities needed to solve it (Jonassen, 2011). The more ill-structured a problem is, the more complex cognitive processes are required to solve it. Research has shown that having students learn to solve well-

structured problems in an educational environment does not transfer well to the more life-like ill-structured problems (Jonassen, Strobel, & Lee, 2006). The *Standards for Technological Literacy* (2002) even described that, in real life, problems are seldom clearly defined with all criteria and constraints identified. Martinez (2010) promoted the idea that students should develop knowledge in real-life environments, thus gaining more transferrable higher-order cognitive skills. Mimicking real-world experiences in the classroom can help account for unanticipated challenges that students may face in their future, especially in engineering careers, because knowledge is deeply embedded in the experiences or situations in which it is learned (Brown, Collins, & Duguid, 1989).

Lastly, Jonassen (2011) believes problems vary by context. The context of a problem can help distinguish an engineering design problem from other types of problems (Waetjen, 1989). Problems occur in different environments every day, and in many instances people do not realize they are employing problem-solving processes (Bjorklund, 2008). Jonassen, Strobel, and Chwee-Beng (2006) conducted a qualitative study of workplace engineering problems to identify the problem attributes that engineers faced every day. Practicing engineers are hired, retained, and rewarded for solving ill-structured problems in the workplace. These problems require engineers to draw upon distributed knowledge and personal experience to work in collaboration for designing complex solutions. The researchers conducted case studies and interviews of practicing engineers and determined the following attributes of engineering problems: (a) engineering problems require communication skills, (b) engineers use multiple forms of problem representation, (c) engineers often encounter unanticipated problems, (d) engineers rely primarily on experiential knowledge, (e) most problems require extensive

collaboration, (f) problem-solving knowledge is distributed among team members, (g) most constraints are non-engineering, (h) ill-structured problems are solved in many different ways, (i) success is rarely measured by engineering standards, (j) ill-structured problems have multiple and often conflicting goals, (k) ill-structured problems include aggregates of well-structured problems, and (l) engineering workplace problems are ill-structured (Jonassen, Strobel, & Lee, 2006). All of these attributes require complex cognitive-thinking skills. These attributes imply that technology and engineering education curriculum and instruction should increase higher-order thinking skills by ensuring that engineering design problems transfer to the real world, by immersing students in a problem-based learning environment, by providing problems that are ill-structured with conflicting criteria, and by providing experience with various types of engineering tools and practices.

As the discussion has described how engineers address authentic problems, technology and engineering education can provide a context for using, assessing, evaluating, and creating technology to extend human capabilities to solve problems that meet the needs and desires of people (International Technology Education Association, 2002). Therefore engineering design problem-solving in technology and engineering education can be described as the process of developing working solutions to ill-structured problems requiring the application of critical thinking and creativity skills (Petrina & Hill, 1998; Warner, 2011) through the use of technology and the manipulations of materials (Waetjen, 1989).

Technology and Engineering Education Problem-solving Curriculum and Instruction

As technology and engineering education has evolved, it has also moved from teaching specific knowledge and particular technical skills to fostering higher-order capabilities such as critical thinking, decision making, creativity, and problem-solving (Liao, 2011; Warner, 2011). In its past, technology education was associated with teaching crafts and skills for industrial needs (Bjorklund, 2008). With engineering added to its title, however, educators hope it can portray the need for a rigorous approach to this subject (Fantz & Katsioloudis, 2011). By focusing on curriculum and instruction centered on higher-order cognitive processes, technology and engineering education can become a fundamental subject for all students regardless of their career pathways (Hershbach, 2009). With a mission that technology and engineering education can support the success of all students, multiple learning theories can be integrated into the subject to promote meaningful learning and nurture student development (Barak & Hacker, 2011).

Technology and engineering education is based upon a philosophy of fostering the development of student knowledge, aptitudes, and skills to address scientific, technical, and social-cultural dimensions of designing the most efficient and effective products, processes, or systems for addressing specific authentic technological problems (Barak, 2011). Cognitive-science research has started to provide support and direction for developing curriculum and instruction within technology and engineering education (Petrina, 2010). This research has provided some focus for creating learning environments that are most conducive to learning (Zuga, 2004). It is believed that technology and engineering education instruction can meet goal characteristics that can

promote powerful learning. As a result, Barak and Hacker (2011) claim that technology and engineering education has the following characteristics:

- Learning is meaningful to the learner
- Learning is challenging
- Learning is developmentally appropriate
- Learning is controlled by the learner
- Learning is built upon prior knowledge
- Learning provides social interaction
- Learning is supported by helpful feedback

The problem-based context of most technology and engineering curricula generally promotes the use of the engineering design process. This process, seen in Figure 1, is an iterative approach that proceeds to clearly define a problem, generate solution ideas, model/simulate solutions, create solutions, evaluate solutions, and refine solution designs. The engineering design process is considered by many to be the core problem-solving process for developing solutions to real life issues, which helps give structure to creative and innovative thinking (International Technology Education Association, 2002). Furthermore, Lewis (2005) expressed that design has been a focus in the practice and literature of technology education, often embedded within discourse on problem-solving. Additionally, *Standards for Technological Literacy* (2002) describe design as being the most fundamental component of technology, its importance similar to that of inquiry in the sciences. To become technology-and-engineering-literate, one must acquire the conceptual and procedural knowledge to create a solution design to a

technological problem through the use of the engineering design process, a design from which a product or system will usually be generated (National Research Council, 2006).

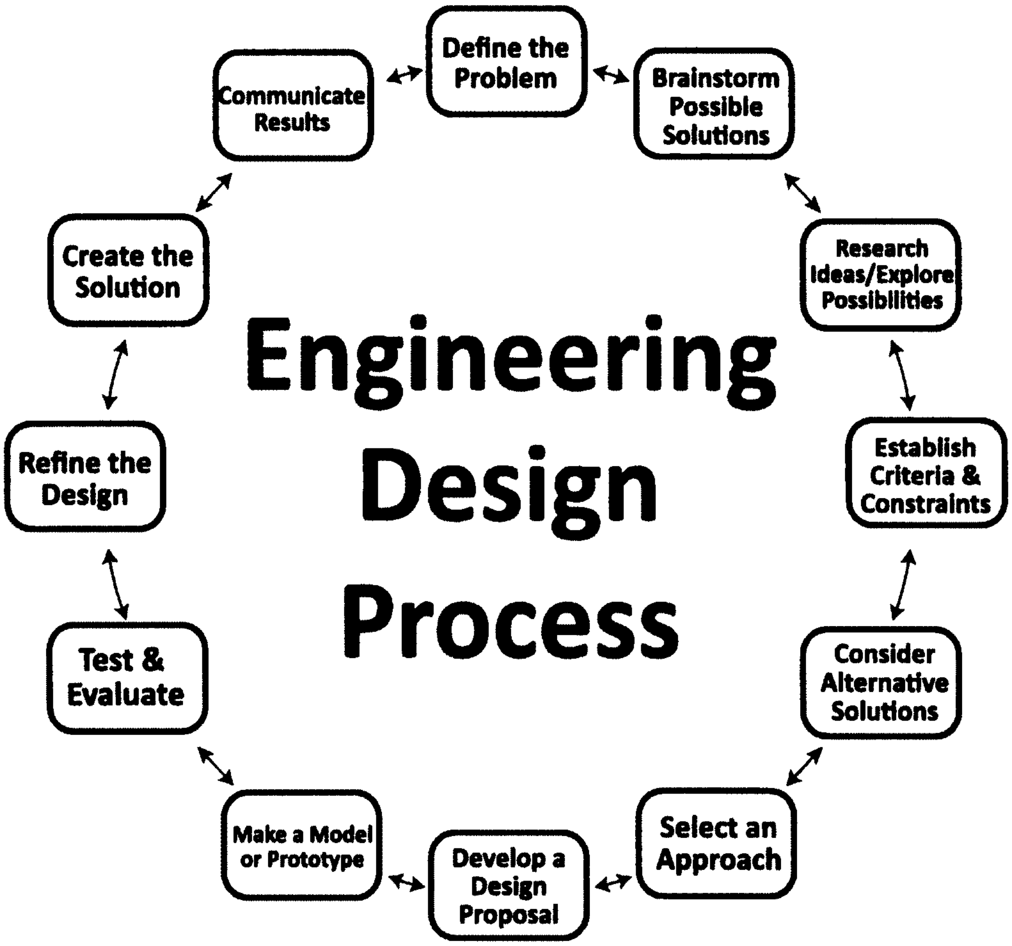


Figure 1. 12-step engineering design process (International Technology and Engineering Educators Association, 2013).

A technology and engineering literate person is someone who can use the engineering design process to solve a problem by designing a product or system that works while taking into consideration many factors such as safety, environmental impacts, risks, and benefits (International Technology Education Association, 2002). Therefore, problem-solving is the central component to technology and engineering education. It is often thought that the engineering design process is left to engineers or

designers, but it is an essential component that can be developed in every person to support complex thought for successful navigation through life. For students to succeed in this process, they should be able to cognitively understand what they are doing throughout its application. However, engineering design is not the only problem-solving process used in solving well-structured or ill-structured technological problems (Lewis, 2005). Some problems require different approaches to solving them, including troubleshooting, research and development, invention and innovation, and experimentation. The skills required in all these processes are valuable in themselves, and further developing these skills through first-hand experiences can allow students to become more comfortable with technological and engineering design processes.

Project Lead the Way is one of the leading providers of rigorous curricula across the United States that engages students in activities, projects, and problem-based learning experiences that incorporate the principles of technology and engineering education curricula. During the 2012–2013 school year, more than 4,700 schools in all 50 states and the District of Columbia were offering *Project Lead the Way* courses to students (Project Lead the Way, 2013). This innovative STEM education program provides hands-on classroom experiences that require students to create, design, build, and evaluate solutions to problems while applying what they have learned in mathematics and science. *Project Lead the Way* consists of two comprehensive curriculum pathways, one in pre-engineering and one in biomedical sciences. Both pathways have been collaboratively planned by a community of teachers, university faculty, engineering professionals, biomedical professionals, and school administrators to promote critical

thinking, creativity, innovation, and real-world problem-solving skills for students (Project Lead the Way, 2013).

Project Lead the Way's pre-engineering pathway is founded upon the fundamental problem-solving and critical-thinking skills taught in traditional career and technical education classes while integrating national academic and technological standards and STEM principles. This pre-engineering program is a sequence of foundational and specialized courses, as well as a capstone course that follows an established hands-on, real-world problem-solving curriculum. Throughout the program's courses, students learn and apply the design process and develop skills in critical thinking and problem-solving. The full sequence of program courses can be seen in Table 1.

The capstone course of the pre-engineering program, *Engineering Design and Development*, focuses on solving ill-defined and ill-structured problems. Students enrolled in this course work in teams to design and develop an innovative solution to a valid problem by applying the engineering design process. Students will perform research to choose, validate, and justify an authentic problem. After carefully defining the problem, teams of students will design, build, and evaluate their solutions. Finally, student teams will each present and defend their original solution to an outside panel of professionals in engineering.

The *Engineering Design and Development* curriculum developers have organized this non-linear engineering design process using flow charts that contain the problem-solving tasks of (a) defining and justifying a problem, (b) generating multiple solutions, (c) selecting a solution, (d) constructing and testing, (e) reflecting and evaluating, and (f) presenting results. These problem-solving tasks require students to perform research,

interview experts, survey consumers, write specifications, test concepts, create schedules, create sketches, create technical drawings, perform cost estimates, build prototypes, test prototypes, optimize designs, document work, and present solutions.

Table 1

Project Lead the Way Pre-Engineering Pathway

	Foundation Courses
Introduction to Engineering Design	Designed for 9th- or 10th-grade students Major Focus: › Design process and its application › Applying engineering standards › Industry-standard 3D-modeling software › Documentation and communication design solutions
Principles of Engineering	› Designed for 10th- or 11th-grade students › Major Focus: › Post-secondary engineering courses of study › Mechanisms, energy, statics, materials, and kinematics › Development of problem-solving skills › Applying knowledge of research and design to create solutions to various challenges
	Specialization Courses
Aerospace Engineering	› Designed for 10th-, 11th-, or 12th-grade students › Major Focus: › Evolution of flight, navigation and control, flight fundamentals, aerospace materials, propulsion, space travel, and orbital mechanics
Biotechnical Engineering	› Designed for 11th- or 12th-grade students › Major Focus: › Diverse fields of biotechnology › Engineering design problems related to biomechanics, cardiovascular engineering, genetic engineering, tissue engineering, biomedical devices, forensics, and bioethics
Civil Engineering and Architecture	› Designed for 11th- or 12th-grade students › Major Focus: › Design and development of residential and commercial properties and structures › 3D-architectural-design software
Computer-Integrated Manufacturing	› Designed for 11th- or 12th-grade students › Major Focus: › History of manufacturing, robotics and automation, manufacturing processes, computer modeling, manufacturing equipment, and flexible manufacturing systems
Digital Electronics	› Designed for 10th- or 11th-grade students › Major Focus: › Modern electronic devices › The process of combinational and sequential logic design, engineering standards, and technical documentation
	Capstone Course
Engineering Design and Development	› Designed for 12th-grade students › Major Focus: › Working in teams to design and develop an original solution to a valid open-ended technical problem by applying the engineering design process

Note: (Project Lead the Way, 2013)

While progressing through this engineering design process, students continually hone their organizational, communication, and interpersonal skills, their creative and problem-solving abilities, and their understanding of the design process (Project Lead the Way, 2013).

Technology and engineering education programs focus on preparing future workers who can integrate skill sets for solving ill-structured problems. These problems involve the ability to apply STEM concepts and use technological tools (Liao, 2011). Research on cognitive processes, however, can better inform the way in which technology and engineering education increases students' higher-order thinking skills to ensure that all future workers are provided with the curriculum and instruction that enables them to be effective problem solvers (Johnson & Thomas, 1994; Petrina, 2010; Zuga, 2004).

Cognition and Problem-solving

Cognitivism and Cognitive Research

Brown (2001) defined cognition as the coming to know, which includes the mental processes involved in learning, comprehension, perception, thinking, memorization, and attention. Additionally, cognition includes the higher-level mental functions of creative thinking, analyzing, reasoning, synthesizing, and problem-solving (Barak, 2011). A focus on cognition in the 1950s led to a revolutionary shift in psychology that offered additional theories of learning beyond behaviorism (Martinez, 2010). Up until this shift, behaviorism was the main theory for explaining how people think and learn (Brown & Green, 2011). Behaviorism included multiple theories based on

research conducted by behavioral psychologists, such as Pavlov (1927), which claimed that learning is only a result of negative or positive responses to stimuli. Psychological research began to show, however, that living organisms could adapt to unknown situations or environments, showing that there are additional cognitive processes happening in the mind. A focus on understanding these thought processes through representation and processing of knowledge in the mind has given birth to cognitivism and cognitive psychology (Neisser, 1967). Behaviorists argued against the idea of cognitivism because mental processes are invisible and therefore cannot be scientifically studied (Brown & Green, 2011). Cognitivists and their research, however, have created a new domain of scientific inquiry called cognitive science in 1956 (Simon, 1980). Cognitive science has a primary goal of providing an understanding of the nature of human intelligence, as well as intelligent systems (Johnson & Thomas, 1994). Developments in cognitive science led to several learning theories that today are employed through technology and engineering education (Barak, 2011), such as cognitive constructivism (Piaget, 1952), social constructivism (Vygotski, 1978), and activity theory (Leontiev, 1978).

Since the 1950s, much cognitive research in higher-level mental functioning and problem-solving has been conducted to provide a foundation of learning and competent performance development among learners (Donovan & Bransford, 2005). In the 1990s, however, Johnson and Thomas (1994) declared that cognitive research was of little interest to professionals working in the school subject of technology education. Johnson and Thomas thought this lack of interest as unfortunate. They believe cognitive science and research could promote the discovery of innovative instructional strategies. Cognitive

research gained popularity in technology education during the beginning of the 21st century (Brown, 2001; Petrina, 2010). Yet, there has been a lack of coherent research that focuses on how students cognitively process solutions to open-ended and ill-defined engineering design problems (Kelley & Rayala, 2011; National Research Council, 2010; Zuga, 2004).

Cognitive research can help provide an understanding of human capacity for complex thought in solving ill-structured problems, which has enabled societies and cultures to propagate from one generation to the next (Martinez, 2010). Now, in the 21st century, complex cognition in problem-solving is indispensable because of the workforce changes in the innovation-driven economy (Quellmalz et al., 2011).

Martinez (2010) stressed that people must now work more with their minds than ever before. Hence, he concluded that understanding the complex cognition involved in problem-solving, as an educational goal has never been greater. Education, and especially technology and engineering education, has an overall goal of advancing society and preparing citizens for an economically viable future (International Technology Education Association, 2002). Furthermore, technology and engineering education is largely focused on nurturing students' ability to solve problems so as to modify the natural world to meet society's need and desires (Warner, 2011). Although there is no set procedure for solving problems, understanding how a student's mind processes these problems can provide more applicable heuristics for guiding success in teaching and learning through technology and engineering education programs (Bjorklund, 2008; Kelley & Rayala, 2011; Martinez, 2010; Petrina, 2010).

Cognitive Development

As students increase their abilities for higher-order thinking, they are developing cognitively. Cognitive theories have suggested that a student's thinking and problem-solving abilities are different at each stage of his or her cognitive development. These abilities are thought to become more complex and sophisticated as students move through these stages of development (Stonewater & Stonewater, 1984). The relation between cognitive development and problem-solving skills has been documented and explored throughout cognitive research. The work of psychologist Jean Piaget dominated cognitive-development research throughout the 20th century. Piaget (1952) provided a theory of cognitive stages of humans from birth to late adolescence. He also claimed that the emergence of intellectual competence is not a linear progression from child to adult stages and that a child thinks in different ways than adults do.

Piaget's cognitive development theory asserts that a student can cognitively process only information that is at or below his or her own stage of cognitive development, but not above. Therefore, the ability to learn to solve problems at any stage in life is determined by the developmental state of the person. Curriculum and instruction are generally organized according to this idea of student cognitive development (Stonewater & Stonewater, 1984). For instance, there are different expectations for students in sixth grade and students in twelfth grade, which are adjusted to the student's normal capabilities for learning. After Piaget, Vygotski (1978) went further to describe what is known as a zone of proximal development for learning. He explained that students who are being introduced to a new skill or concept must work within their defined zone of proximal development. Defining a learner's zone of proximal

development can provide the pedagogical space for potential learning. It is recognized that individuals can perform a higher level of skills within this zone through the assistance, encouragement, and coaching from other people. This creates a definition of the zone of proximal development as the difference between the competence of a person developing knowledge on his or her own and the learning capability the student can achieve with the help of others (Martinez, 2010). Consequently, improving student problem-solving requires the understanding of cognitive development and human growth to create instructional strategies for moving students to higher cognitive development stages that are more capable of complex problem-solving.

The ideas in Piaget's theory of cognitive development have been challenged by psychologists who believe people can engage in more sophisticated thinking beyond their stage of development (Gelman & Markman, 1986). To counteract the weakness of this theory, Neo-Piagetian theorists have integrated all forms of cognitive research and recognized the functioning of the mind. Analyzing cognitive development and exploring these cognitive-development theories can provide information for improving curriculum and instruction (Martinez, 2010).

At higher levels of cognitive development, it is accepted that students are better able to conceptualize the world around them and perform the necessary tasks to assist their problem-solving abilities. Instructional strategies are often used to attempt to aid this cognitive development. There are generally two main strategies for facilitating cognitive development related to problem-solving. The first category of strategies is to challenge a student's cognitive structure to create disequilibrium of understanding. The second category involves providing student support to engage them in a manner of

learning that eliminates the disequilibrium of understanding. Using these strategies together can test a student's current ability to solve problems and help him or her move on toward a higher stage of cognitive development (Stonewater & Stonewater, 1984).

The development of the human cognitive system can facilitate an understanding of how people process technological problems. However, biological factors in human development are directly related to cognitive changes in humans. Human maturation and brain science provide insights on how people think, develop skills, and grow intellectually. The human brain is what makes cognition possible. Analyzing the association between mind and brain can extend the understanding of cognition. The brain's role in cognition can help advance the improvement of learning essential skills and the cognitive processing of complex problems.

The mind and brain are different from one another. The brain is a real material organ located within the skull, and it enables real biological functions. Conversely, the mind is an abstraction that is attributed to human consciousness. The mind cannot be observed and it is only made apparent by the effects of its functions. A very simplistic way to view the mind-brain association is that mind is what the brain does. Additionally, the mind and brain are interdependent when it comes to biological development and cognitive development. Understanding how the brain and mind works together relies on research determining correspondences between the brain anatomy and human functions.

Cognitive Architecture and Basic Processes

In order to conduct cognitive research as it pertains to technology and engineering education, it is necessary to review the architecture of the human mind. The mind is a complex thing to study, but years of research have yielded ideas of how it works. The

work of Neisser (1967) led people to begin describing cognitive architecture through the computational metaphor, which compares basic cognition to the programming of a computer. A computer and the mind work in a similar manner to store, transform, and transfer information (Casey & Moran, 1989).

The first similarity in this metaphor is memory. The mind and computer both have different types of memory for different reasons (Schunn & Silk, 2011). Martinez (2010) explained that in a computer there is random-access memory (RAM), which is temporary volatile information that the computer is processing at a given moment. This is similar to the short-term memory of the mind. Additionally, a computer has read-only memory (ROM), which is non-volatile information that is stored on its hard drive. This type of memory is also similar to a human's long-term memory. Furthermore, the mind and computer do more than just store information; both transform the information they store. A computer can compute tasks that are assigned to it, and the mind continuously extends what is known by processing information to make inferences and draw new conclusions. Moreover, the mind and computer act as an open system that takes input from the external environment, processes that information, and produces output that relates to the environment (Martinez, 2010; Schunn & Silk, 2011). Although this metaphor can help us begin to understand the structure of the mind, it does have limitations that must be examined for us to fully understand complex cognition in problem-solving.

The way in which the mind processes information is vital to the procedure used to solve complex technological problems. The human cognitive system often processes information as it flows from the exterior environment to inner consciousness. There are different types of memory in the human cognition system. The flow of information in

cognition can be traced through three human memory structures. Like computers, humans have short-term and long-term memory. However, humans also have a sensory registry. The sensory registry is extremely important. It is the first step in human cognition. This enables humans to process the information that reaches the sensory organs. The sensory registry provides approximately two seconds of memory to begin to cognitively process surroundings (Martinez, 2010).

Beyond the sensory registry is a human's short-term memory. This memory only holds a small amount of information for a short amount of time. Without short-term memory, however, people would not be able to conduct complex cognition. The short-term memory is often referred to as working memory, and rightfully so (Schunn & Silk, 2011). Working memory provides the cognitive workspace to conduct mental work in processing information to develop ideas and solutions (Van Merrienboer & Sweller, 2005). Although it provides the mental workspace for human cognition, the human mind can process only about seven pieces of information at once (Martinez, 2010). Psychologist George Miller (1956) made this clear by analyzing many psychological studies and noticing a pattern of approximately seven items that could be processed by the human mind at once. This may show why technological problem-solving can be a more complex task for people to do. When solving multifaceted problems in technology and engineering, one must consider multiple forms of information at once. The working memory may limit the way that people process information to develop viable solutions to real-life problems (Wickens, 2008). Furthermore, students in technology and engineering courses should approach technological problems with the nature of the working memory in mind, so they are not overwhelmed.

If the working memory provides only a small space for working through technological problems, then one may question how humans can effectively complete complex tasks (Van Merrienboer & Sweller, 2005). This is where long-term memory takes over. Humans know a lot and can retain a vast amount of information in their long-term memories (Martinez, 2010). This information is all the knowledge that a person has about people, places, or things. Most importantly to technological problem-solving, the long-term memory includes the way in which people do things (Wickens, 2008). This means that the long-term memory is responsible for holding the skills that one has developed through patterns of learned behaviors in everyday actions (Martinez, 2010). Subsequently, a student's skills must be stored and accessed from his or her long-term memory.

Additionally, the long-term memory holds different kinds of knowledge that can be responsible for one becoming a technological problem solver. Based on the dual-coding theory of psychologist Allan Paivio, the mind uses language and imagery as forms of knowledge to create a mental picture of a way to think through a task. This being said, long-term memory permits simple words or sights to create visualizations in the mind of specific items. The long-term memory can also allow a person to visualize the manipulation of an object without actually doing it (Clark & Paivio, 1991). Along these terms, *Standards for Technological Literacy* (International Technology Education Association, 2002) reports that an engineer must have the ability to visualize abstractly in solving technological problems. The long-term memory enables people to plan out processes and visualize proper ways to complete complex tasks, thus helping one be able to visualize abstractly like an engineer.

As a review of how information is transmitted through the cognitive architecture, Van Someren, van de Velde, and Sandberg (1994) have provided five processes of information transformation. The first type of processing has to do with perception, which takes information from the sensory registry and moves it to the working memory. The next process, retrieval, activates the necessary long-term memory into the cognitive workspace. The third process of construction generates new information from the working memory. An example would be a student solving a problem in designing a bridge truss. The student may note that a structure in a certain direction may be under more compression. This results in a new association between concepts that are stored as a new object in the working memory. The fourth process of storage moves information from working memory into long-term memory. Lastly, the verbalization process takes information that is active in the working memory and puts it into words. The output of this process is the verbal content of the working memory, which can be studied to help describe and explain the cognitive processes involved in solving technological problems.

The human mind cannot be limited to the computer metaphor and to the basic processing of information. There are many qualities of the mind that do not relate to current computers and go beyond processing information. The qualities of purpose, value, emotion, personality, and consciousness are the ones that inherently make humans human (Martinez, 2010). These qualities can affect the ways in which humans act in solving multifaceted problems. This was made evident by the research that Tolman (1932) conducted in his laboratory. Tolman placed rats in a maze and studied how they reached the cheese at the end of the maze. The rats developed a behavior to efficiently reach the end of the maze. Tolman went further and studied what the rats did when he placed

obstructions in the pathway they normally took. What he observed was that the rats overcame the obstructions to the purpose, using other efficient methods to reach the food at the end of the maze. Tolman then posited that the rats were able to use a mental map of the maze based on previous knowledge to complete a task with a sense of purpose. This study showed that there are more internal qualities and characteristics that the mind uses to complete different tasks. These characteristics relate to the complex cognitive functions of the mind.

Complex Cognition and Problem-Solving

Solving engineering design problems requires more complex cognitive skills than those involved in the basic processing of information. Problem solvers employ different forms of complex cognition to create viable solutions to everyday problems (Jonassen, Strobel, & Lee, 2006). Complex cognition is very different from straightforward and linear thinking. It involves the thinking strategies that enable people to live successfully in a multifaceted world (Finke, Ward, & Smith, 1992). Additionally, complex cognition is responsible for enacting and developing the 21st century skills required in today's globalized world (Liao, 2011). As Martinez (2010) describes, complex cognition can be categorized into problem-solving, critical thinking, inferential reasoning, creative thinking, and meta-cognition.

As depicted throughout this discussion, complex cognition in problem-solving is a major focus of technology and engineering education (Waetjen, 1989). However, engineering design problem-solving also requires features of all of the other subdivisions of complex cognition. To create the most viable solution to a problem, one should be able to be creative, think critically, and reason logically. Additionally, metacognitive abilities

are the complex mental processes that support all of the other forms of complex cognition. This being said, problem-solving cannot be described without an investigation of meta-cognition.

Metacognition refers to someone's ability to think about the way in which he or she thinks (Martinez, 2010). It is a cognitive process that binds all complex cognition together by allowing a person to be aware of his or her own knowledge and how he or she controls his or her own cognitive processes (Osman & Hannafin, 1992). Metacognition facilitates problem-solving by monitoring and manipulating thoughts as one employs problem-solving strategies. Moreover, metacognition creates metamemory, which allows a person to evaluate what he or she knows or does not know. Throughout problem-solving, a person must evaluate what he or she knows so as to determine what knowledge to remember or acquire in order to solve the problem at hand. An accurate metamemory is a desired quality of learners that contributes to better learning outcomes (Castel, McGillivray, & Friedman, 2012). Additionally, research has shown that successful performance in activities, such as engineering design challenges, requires skills in thinking metacognitively (Osman & Hannafin, 1992).

Metacognition does not only apply to the concept of thinking about monitoring what it is that one knows, but it also involves the monitoring and controlling of one's actions. For example, if a person is attempting to solve a problem and realizes that his or her strategy is not working, metacognition allows that person to pursue a different solution pathway. However, everyone does not easily do this. It is common for people to have trouble changing from their original approach for solving a problem or to admit that the problem is above their skill level. In technology and engineering education,

metacognitive skills enable a student to assess the quality of his or her method of solving a problem, as well as the steps to make that process more effective and efficient (Flavell, 1979). Without the ability to metacognitively process information, students cannot enact complex cognition for successful engineering design problem-solving.

Metacognition is a complex cognitive process that enables success in the complex cognitive process of problem-solving (Petrina, Feng, & Kim, 2008). To be able to solve a problem, a person must be able to assess his or her own knowledge and skills so as to be able to enact a productive process in arriving at a viable solution. Complex cognitive skills in metacognition and problem-solving are often thought of as the defining characteristics of humans. Since these skills make humans human, it is important to consider how students cognitively process problems in order to consider how technology and engineering education can improve a student's ability to solve problems.

Problem-solving is considered to be the pursuit of a goal when the path to that goal is uncertain (Mayer & Wittrock, 2006). Whenever a person is trying to accomplish something without knowing exactly how to do it, then he or she must employ complex cognitive processes. Additionally, when people are cognitively processing a problem, they are doing something that is new to them. Since they are attempting something new, they are not guaranteed to successfully solve the problem. This being said, a problem is unlike an algorithm, in that there is no set of rules that will produce success every time. Nevertheless, problem-solving is necessary because most life goals cannot be reached through following a set of rules. For example, during the Apollo 13 mission, NASA engineers and astronauts had to solve a problem that was a matter of life or death. A serious mechanical issue presented an ill-structured problem that needed to be solved for

the astronauts to land back on Earth safely. The ill-structured problem had never been faced by anyone before and required many people to employ complex cognitive skills to meet their goal. The NASA engineers used their experience to cognitively process ill-structured problems and were able to create a successful solution that saved the astronauts' lives (Martinez, 2010).

Although people may not always face such life threatening problems, people do face complex problems every day. These problems require higher cognitive skills that are essential for a student to be successful in the multifaceted 21st century. Examples of everyday problems that require higher-order thinking skills can be fixing a leaky faucet, selecting what clothes to wear, successfully completing a job interview, traveling to a new destination safely, and so on. Everyday problems can also be more technological as well. Everyday engineering problem-solving in this manner also requires more complex cognition from students, forcing them to reason logically to make critical decisions for developing creative solutions (Jonassen, Strobel, & Lee, 2006).

Cognitive Operations in Problem-solving

Anderson (1980) describes problem-solving as any goal-directed sequence of cognitive operations. Newell and Simon (1972) propose that those operations are composed of two critical elements. The first is that people develop a mental model of the problem, called the problem space. Jonassen (2000) declares that the mental construction of the problem space is the most crucial step for problem-solving. The second critical element is the mental manipulation of the problem space. The manipulation of the problem space involves internal mental representations, as well as external physical representations generated through the cognitive operations for solving the problem

(Jonassen, 2000). Middleton (2009) describes the problem space in technological problems as consisting of a problem zone, a search and construction space, and a satisficing zone. The problem zone is the meaning the problem solver has deduced of the issue at hand. The satisficing zone is the goal-driven meaning that the problem solver has made of a viable solution. The search and construction space is all of the information in memory and any newly formed ideas for solving the problem. To solve the problem, people must then perform the cognitive operations to navigate the search and construction space between the problem zone and satisficing zone. To better understand this navigation process, Middleton (2009) identifies ten cognitive procedures for solving problems. These procedures fit within the three categories of generation, exploration, and executive control. The cognitive procedures that belong to each category are described in Table 2.

Table 2

Cognitive Procedures in Solving Problems

Category of Cognitive Procedures		
Generation	**Exploration**	**Executive Control**
Retrieval Retrieving knowledge from the long-term memory Synthesis Formulating and articulating solutions to a problem Transformation Modifying an idea to solve a problem	Exploring Constraints Identifying the aspects of the problem related to its context Exploring Attributes Defining aspects of the problem that can facilitate its resolution	Goal Setting The process of establishing a goal for solving the problem Strategy Formulation Employing a general heuristic for approaching the problem Goal Switching Changing focus from one aspect of the problem to another Monitoring Checking the progress of achieving the problem-solving goals Evaluation Evaluating whether the problem-solving process and outcomes meet the established goals

Note: (Middleton, 2008)

Jonassen (2011) has also worked to identify seven general cognitive skills that support the mental navigation process of solving problems. The first skill involves developing a problem schema. Developing a problem schema is the cognitive operation of mentally categorizing the problem to enable its interpretation, as well as to connect the problem with prior knowledge. The second skill is analogical comparison, which is the cognitive operation of transferring knowledge from one problem schema to a new similar schema to assist in the formation of a problem-solving process for the new problem. The third cognitive skill is the understanding of causal relations in problems. Causal relations are a connected set of conditions and effects or consequences. The mental process of determining these relations allows problem solvers to make predictions, implications, inferences, and explanations in cogitating a solution to a problem. Next, Jonassen describes questioning as one of the most fundamental cognitive problem-solving skills. Formulating and answering questions enables a problem solver to determine the unknown and develop the necessary knowledge for solving the problem. The fifth cognitive skill is the construction of mental models of the problem and potential solutions. The sixth skill of arguing enables the rational resolution of problems. Lastly, the cognitive skill of metacognitive regulation allows the problem solver to self-control the development of essential knowledge and skills needed to successfully solve the problem. All seven of these cognitive skills are interconnected in such a manner as to enable any problem solver to cogitate a solution to a well-structured or ill-structured problem.

To understand cognitive operations involved specifically with technological problems, Halfin (1973) analyzed the work of prominent technological problem solvers. Through his analysis he identified 17 mental processes used by professional technologists

to solve a technological problem. These cognitive operations are defining problems, observing, analyzing, visualizing, computing, communicating, measuring, predicting, questioning, interpreting, constructing models, experimenting, testing, designing, modeling, creating, and managing. The operational definitions of these processes are listed in Table 3. Wicklein and Rojewski (1999) later re-validated these mental processes through a Delphi study that confirmed the continued relevance of all 17 processes. Wicklein and Rojewski's work also proposed an additional 10 mental processes which included contextualization, researching, searching for solutions, technology review, transfer/transformation, values, customer analysis, innovating, monitoring data, and establishing need. However, they made no attempt to remove any duplicative processes. The definition of these proposed mental processes are defined in Table 4. Understanding the cognitive operations involved in solving technological problems can help identify the way in which people think while they attempt to develop valid solutions for engineering design challenges.

How Problem Solvers Think

As Dewey (1910) explained over a century ago, thinking is the complex concept of the way in which people process, store, and retrieve information. However, thinking about solving ill-structured problems is no longer conceived as a single unitary complex cognitive process, as it once was (Finke, Ward, & Smith, 1992). Creating viable and innovative solutions to engineering design problems is considered to be a product of many types of complex mental processes (Petrina & Hill, 1998).

Table 3

17 Original Mental Processes for Solving Technological Problems

Cognitive Process	Definition
Analyzing	This is the process of identifying, isolating, taking apart, breaking down, or performing similar actions for the purpose of setting forth or clarifying the basic components of a phenomenon, problem, opportunity, object, system, or point of view.
Communicating	This is the process of conveying information (or ideas) from one source (sender) to another (receiver) through a media using various modes (The modes may be oral or written or pictures or symbols, or any combination of these.).
Computing	This is the process of selecting and applying mathematical symbols, operations, and processes to describe, estimate, calculate, quantify, relate, and/or evaluate in the real or abstract numerical sense.
Creating	This is the process of combining the basic components or ideas of phenomena, objects, events, systems, or points of view in a unique manner that will better satisfy a need, either for the individual or for the outside world.
Defining problem(s)	This is the process of stating or defining a problem, which will then enhance the investigation leading to an optimal solution. It is transforming one state of affairs to another desired state.
Designing	This is the process of conceiving, creating, inventing, contriving, sketching, or planning by which some practical ends may be affected, or proposing a goal to meet the societal needs, desires, problems, or opportunities and do things better. Design is a cyclic or iterative process of continuous refinement or improvement.
Experimenting	This is the process of determining the effects of something previously untried in order to test the validity of an hypothesis, to demonstrate a known (or unknown) truth, or to try out various factors relating to a particular phenomenon problem, opportunity element, object, event, system, or point of view.
Interpreting data	This is the process of clarifying, evaluating, explaining, and translating to provide (or communicate) the meaning of particular data.
Measuring	This is the process of describing characteristics (by the use of numbers) of a phenomenon, problem, opportunity, element, object, event, system, or point of view in terms that are transferable. Measurements are made by direct or indirect means, are on relative or absolute scales, and are continuous or discontinuous.
Modeling	This is the process of producing or reducing an act or condition to a generalized construct that may then be presented graphically in the form of a sketch, diagram, or equation; physically in the form of a scale model or prototype; or in the form of a written generalization.
Models/ prototypes	This is the process of forming, making, building, fabricating, creating, or combining parts to produce a scale model or prototype.
Observing	This is the process of interacting with the environment through one or more of the senses (seeing, hearing, touching, smelling, or tasting). The senses are utilized to determine the characteristics of a phenomenon, problem, opportunity, element, object, event, system, or point of view. The observer's experiences, values, and associations may influence the results.
Predicting	This is the process of prophesying or foretelling something in advance, anticipating the future based on special knowledge.
Questions/ hypotheses	Questioning is the process of asking, interrogating, challenging, or seeking answers related to a phenomenon, problem, opportunity, element, object, event, system, or point of view.
Testing	This is the process of determining the workability of a model, component, system, product, or point of view in a real or simulated environment to obtain information for clarifying or modifying design specifications.
Visualizing	This is the process of perceiving a phenomenon, problem, opportunity, element, object, event, or system in the form of a mental image based on the experience of the perceiver. It includes an exercise of all the senses in establishing a valid mental analogy for the phenomena involved in a problem or opportunity.

Note. (Halfin, 1973; Hill & Wicklein, 1999; Wicklein & Rojewski, 1999)

Table 4

10 Proposed Mental Processes for Solving Technological Problems

Cognitive Process	Definition
Contexts	This is the process of understanding the social, cultural, organizational, etc. contexts for the task.
Researching	This is the process of becoming familiar with the background information necessary to investigate the problem, as well as knowing what type of information to look for and where to locate it.
Searching for solutions	The process of examining multiple options when attempting to resolve technological problems.
Technology review	This is the process of evaluating the performance of a solution at an appropriate time in the future.
Transfer/ transformation	This is the process of transferring a process across areas or fields to new situations.
Values	This is the process of understanding the role of the technicians and others' values in deciding on courses of action.
Customer analysis	This is the process of evaluating inputs of the receiver or technology.
Innovating	This is the process of taking existing "know-how" and being able to implement it in new situations.
Monitoring data	This is the process of collecting and recording data and time conditions related to problem occurrence.
Establishing need	The process of determining the degree of need for the technological problem or solution.

Note. (Hill & Wicklein, 1999; Wicklein & Rojewski, 1999)

Designers and engineers rely on a variety of cognitive skills, such as creativity, critical thinking, analogical reasoning, and decision making, to develop and apply a problem-solving process (Hayes, 1989). Additionally, Lawson (2005) noted that creating solutions to these problems involves highly complex and sophisticated cognitive skills that must be learned and practiced to enable a successful engineer or designer to perform them unconsciously. This information might lead to a research agenda within the technology education profession that highlights an understanding of how people think in designing/problem-solving (Petrina, 2010; Petrina, Feng, & Kim, 2008).

Lawson (2005) was one of the first to begin studying how people think or process information when designing or engineering. His research focused specifically on the

ways that designers, architects, and engineers think in the process of solving problems. Lawson's findings might suggest that engineers solve problems through an analytic thinking approach rather than through a synthetic one. An engineer's analytic approach determines the optimum solution to a problem through maximizing his or her knowledge of the problem by breaking it down into its individual components. Conversely, designers and architects use a more creative process of combining separate elements to create an understanding of the solutions to their problems. Although there are differences in the way these individuals think, all tend to have similar values when problem-solving—adaptive thinking, creativity, focus on the end user, collaborative mentality, and intellectual curiosity.

Kelley (2008) conducted an observational protocol study of students in a *Project Lead the Way* pre-engineering high school program and a National Center for Engineering and Technology Education program. The purpose of the study was to determine the cognitive strategies students' use when solving engineering design problems. Kelley (2008) believed that examining students' cognition and metacognition as they worked through these problems could be used to evaluate the current curriculum. He provided high school students with an ill-defined problem and then placed them in isolation to solve it. The students were instructed to "think out loud" as they processed the ill-defined problem. The researcher found students from the different programs used very similar mental processes in the early stages of processing an ill-defined problem. However, the time spent on the different mental processes greatly varied between students. The results also supported that the more experienced problem solvers focused more on defining the problem than on generating solutions. The less experienced students

focused more on generating solutions, which led to their more creative but less viable solutions. Thus, research determined that students did not use the cognitive processes of measuring, computing, and mathematical thinking to predict the results of the design solution. Furthermore, the results showed that *Project Lead the Way* students were more problem focused, whereas the National Center for Engineering and Technology Education students were more solution driven. However, because the results did support the idea that students use similar mental processes at various experience levels, more research on cognition can be used in designing curricular changes to improve students' problem-solving skills.

Lammi and Becker (2013) employed an exploratory triangulation mixed methods research approach to examine high school students' cognitive issues, processes, and themes related to systems thinking while they engaged in a collaborative engineering design challenge. This research attempted to collect data in an environment close to the students' everyday classroom settings by observing them in a collaborative work environment. The researchers wanted to determine if high school students were actually able to perform complex systems thinking while in high school. The findings from this study have shown that students actually cognitively processed the anatomy and operation of their solution designs throughout the planning of the solution. Therefore, these findings have demonstrated that high school students are capable of highly complicated systems thinking at various experience levels.

As seen in the research conducted by Lawson (2005), Kelley (2008), and Lammi and Becker (2013), people of different experience levels vary in the way they think when it comes to solving problems. Although people are confronted with new problems every

day, they often solve the problems in a manner with which they are highly familiar. Engineers studied by Jonassen, Strobel, and Chwee Beng (2006) stated that drawing upon prior experiences is the most important factor in solving a problem with procedural fluency. Therefore, people who are able to draw upon a wealth of prior knowledge and experiences to solve a problem in a manner that is so automatic that they may not even recognize that they are solving a problem are considered to be expert thinkers (Anderson, 2009). However, a look at novice problem solvers can show how their lack of prior knowledge affects their ability to successfully solve problems. The idea of understanding the development of expert thinking when it comes to problem-solving can provide an overall goal for learners to achieve in education (Martinez, 2010).

Welch and Sook Lim (2000) provided insights into the strategic thinking of novice designers in ill-structured problem-solving in technology and engineering education. These researchers found that novice designers, in this case 7th grade students, sequence the sub-processes of a problem in a manner different from that which is prescribed by experts. These novice thinkers generally did not consider multiple possible solutions to a problem in order to make more successful and effective solution decisions. Additionally, these novice thinkers did not tend to practice metacognitive skills to enhance their proficiency as problem solvers. On the other hand, Jonassen's (2011) research showed that experts are able to employ different cognitive strategies that increase their use of prior experiences and knowledge, as well as, with more focused metacognition. Experts tend to focus on properly defining the problem first and then developing a problem schema to solve it. Next, they are able to make multiple analogical comparisons of the problem at hand with previous problems of a similar structure.

Novices tend to compare problems to previously solved ones, but only based on similar surface values, which offers a very limited transfer of knowledge. Furthermore, experts are able to focus on causal relationships when attempting to create and model a solution to a problem. Lastly, experts are not restrained to one initial idea or process for solving a problem. Experts are undaunted to meta-cognitively regulate what they are doing by questioning and arguing their own beliefs, values, ideas, and goals. All of this type of knowledge gained from examining different levels of thinkers can help educators with curriculum, instruction, and assessment activities and more efficiently move learners from novice thinkers to expert thinkers.

Development of Problem-solving Skills

Moving From Novice to Expert Thinking in Solving Problems

A recent trend in cognitive science related to design and problem-solving is the interest in expert thinking (Bjorklund, 2008). Expertise was defined by Stevenson (2003) as the ability to do something better than others who are new to the situation. People who are considered experts have different habits of the mind or behaviors in solving problems. Middleton (2002) noticed in his research that expert designers seemed to be able to direct their concentration on the most important features of a problem, act in a quick and proficient manner, and control their thought processes while employing a problem-solving procedure. Additionally, Dreyfus and Dreyfus (1986) stated that when studying novice thinkers who were transitioning to expert thinkers, a change in behaviors in solving problems could be recognized. Throughout their observations, they categorized the problem solvers into different stages of development: novice, advanced beginner, competent, proficient, and expert. Experts retain high levels of domain knowledge and

well developed cognitive structures in the form of schemas to enable their abilities to employ in depth metacognition in solving problems (Bjorklund, 2008). However, Petrina (2010) recognized that the distinctions between the stages of expertise are often blurred.

To describe the transition from novice to expert thinking, Anderson (2009) described three general stages for the development of expertise in a skill, such as technological problem-solving. The first stage he described is the cognitive stage. In the cognitive stage, learners encode specific facts related to skills that they are enacting to solve the problem at hand. The learner also tends to rehearse these skills as means to memorize the information needed to solve a similar problem. However, at this stage, the knowledge related to the skill of problem-solving is still declarative and not procedural. Declarative knowledge is harder to transform and apply to other circumstances, which would enable one to be considered more skilled in solving a variety of problems. The second stage of expert development begins when one makes declarative knowledge more procedural. This is done by making a variety of associations of the declarative knowledge with new situations and clearing up the misconceptions in its different applications. The autonomous stage is when the learner develops the ability to solve a problem without occupying as much cognitive space. The learner at this stage can now free more of his or her working memory by "chunking" information in a manner that can allow for more complex cognition, which is a process often referred to as developing automaticity (Miller, 1956). Just as learning to drive a car becomes more automatic and rapidly applied, so can thinking about problem-solving which results in expert thinking.

Learning to Solve Problems

As Starkweather (1997) stated concerning technology and engineering education:

We must focus on the end result, which is quality thinking. We must combine thinking with doing in a style that produces the next generation of technological problem solvers. Each country depends upon its educators to develop thinkers that will progress their civilization. The key to progress is fundamental in one way; "How can we best design learning that will result in creative, functional, and open-ended technological thinkers?" When technology educators are able to do that, we will be thinking to achieve! (p. 5)

As Starkweather described, the technology and engineering education profession must continue to involve the understanding of cognition in the development of curriculum, instruction, and assessment for the purpose of developing students who are more prepared to solve the complex problems of the future. Brown and Green (2011) described the importance in understanding how people think to better comprehend how people learn because thinking and learning are very much interconnected. As stated in Starkweather's quote, learning needs to be planned in a way to positively change the way in which students think. Therefore, Ormrod (2009) defined learning as a change in mental representations or behavior, which then affects the way that a person acts and thinks. These changes occur as an outcome of an individual's experiences (Brown & Green, 2011). Research on human learning has exploded over the last 50 years and many learning theories have been generated to explain what type of experiences lead to enhanced learning (Bransford, Vye, & Bateman, 2002). In addition, research has begun to show how learners process information in regards to solving problems (National Research Council, 2000).

Problem-solving is often regarded as one of the most important everyday cognitive activities (Jonassen, 2000). However, Jonassen (2004) declared that learning to

solve problems is too seldom required in formal education settings, which is attributed to the fact that the process of problem-solving is limitless. He also claimed that problem-solving skills are the most difficult to teach because educators do not understand the thought processes involved well enough to support them. Macklin (2003) examined the theories that Jonassen developed and put them into educational practice. Macklin decided that in order for students to learn how to solve problems, they must be afforded an unknown within a situation and a desire or need to solve the problem. If learners do not see some type of social, cultural, or intellectual value in determining the unknown, then they will determine that the problem is not worth solving, resulting in minimal learning. If learners determine a value in solving the problem, they can then develop a mental model of the problem based upon their prior experiences. This development will lead to the formation of new problem schema, which can then be applied to new problems, indicating that learning has taken place.

Donovan and Bransford (2005) also provided three well-established fundamental principles that can be incorporated into learning to solve problems. The first principle is that students enter the learning environment with preconceptions about how the world works. To learn to solve problems, these preconceptions must be engaged to enable students to learn new skills and concepts, as well as to enable them to apply their knowledge and skills to various problem scenarios. The second principle is that students must have a deep foundation of factual knowledge, understand contextual facts or ideas, and organize knowledge in ways that facilitate basic cognitive processes in order to develop competence in inquiry and problem-solving. The last principle involves taking a

metacognitive approach to instruction, which will help students learn to control their own learning as is necessary for solving problems.

Incorporating the knowledge of how students learn with a problem-based learning approach can help support students in the development of problem-solving skills. Furthermore, training learners to employ metacognitive processes while developing a solution can provide them with the self-directed practice needed to develop their problem-solving skills (Macklin, 2003). Johnson and Thomas (1994) supported these ideas by stating that an effective technology and engineering education program is one that increases students' procedural and declarative knowledge by providing them with opportunities to develop technological skills that can be transferred to a variety of contexts through practicing solving relevant engineering design problems.

Assessing Students' Problem-solving Skill Development

The effort to equip students with the abilities to think analytically and creatively in solving problems has become an integral part of technology and engineering education (Hill, 1997). However, Jonassen (2011) asserted that teachers do not know how to design and implement quality assessments of problem-solving. Hill (1997) also noted that systematic methods of defining and measuring student outcomes related to successfully solving problems have not been sufficiently developed. Yet, students in the midst of the STEM education phenomenon are being required more and more to apply complex skills across a range of problems in real world contexts (Quellmalz, Timms, Buckley, Davenport, Loveland, & Silberglitt, 2011). Therefore, assessments of technology and engineering literacy must provide students with opportunities to demonstrate competencies for acquiring, applying, and transferring knowledge as they design

innovative solutions to technological problems. To be able to assess the problem-solving process, one needs to know about the cognitive strategies, skills, abilities, and habits that both novices and experts use in solving problems (Bjorklund, 2008).

Cognitive research and innovative technologies are leading to new developments in educational assessment. The National Research Council (2001) report, *Knowing What Students Know*, provided new ideas for integrating cognitive research findings into assessment design. Moreover, Quellmalz et al. (2011) provided methods for designing assessments of cognitive learning related to problem-solving, utilizing the latest instructional technologies. They capitalized on technology to create dynamic assessments that focus on complex, integrated knowledge structures and strategies that provide rich, authentic task environments that represent significant, recurring problems that offer interactive, immediate, customized, and graduated scaffolding and that also analyze evidence of learning trajectories and proficiency. They have also synthesized research related to identifying significant 21^{st} century knowledge and skills to develop interactive assessment tasks that provide evidence of the development of those skills and inform instruction. Therefore, determining cognitive capabilities in engineering design can provide educators with information on designing innovative, dynamic assessments for improving the way students develop their problem-solving skills.

Creating appropriate assessment strategies and establishing effective technological literacy efforts should be the primary goals of the technology and engineering education profession (International Technology Education Association, 1996). Hill (1997) pointed out that a key element in the development of technological literacy is the task of solving problems. Therefore, it is imperative that professionals in

the field develop and implement curriculum, instruction, and assessments that facilitate the development of cognitive problem-solving skills and strategies. As a result of the effort to increase student skill development in the areas of technological and engineering literacy, the National Assessment Governing Board (2012) released the framework for creating a Technology and Engineering Literacy Assessment for the 2014 National Assessment of Education Progress. This computer-based assessment is focused on providing a cognitive roadmap for evaluating student processes in competent technology and engineering abilities of problem-solving. As technology and engineering education continues to evolve, the Technology and Engineering Literacy Assessment will play an important role in determining the effectiveness and existence of problem-based technology and engineering education.

Summary

Chapter II covered topics on the history of technology and engineering education and how the subject can promote the development of higher-order thinking skills through problem-solving activities. The chapter also examined research in cognitive science and presented a summary of cognitive research specific to technology and engineering education. Chapter II noted that cognitive science, in the early in the 20th century, was limited to only the observable succession of reinforcement and punishment consequences. However, this view did not address the fact that people have complex thoughts related to plans, goals, and beliefs (Martinez, 2010). As psychology has advanced into the complex study of human cognition, educators of technology and engineering need to understand such vital concepts as reasoning, understanding, mental

models, problem-solving, and critical thinking and how these each apply to solving real engineering problems.

The information presented in Chapter II portrayed how imparting cognitive concepts and processes can be beneficial in enriching education (Martinez, 2010). Technology and engineering educators should understand that students' minds have been shaped by a combination of nature and nurturing and these students must be taught how to complete complex tasks, such as engineering design problem-solving. With new demands in design and engineering cognition, it is important to study the cognitive processes of novice problem solvers, as well as experts. Understanding the cognitive processes among these different groups is important for teaching innovative practices in technology and engineering education (De Miranda, 2004; Kelley & Rayala, 2011; Petrina, 2010; Zuga, 2004). A model of the cognitive processes involved in the practice of utilizing the engineering design process to solve problems may be powerful to have at the center of developing effective curriculum, instruction, and assessments that will develop students who are literate in technology and engineering (Petrina, 2010). As described throughout this chapter, the current STEM era of education that is focused on creative problem-solving can benefit from combining the study of human cognition with educational practices to prepare students to become successful contributors in the 21st century (De Miranda, 2004; Kelley & Rayala, 2011; Petrina, 2010).

Chapter III explains the methods and procedures used to conduct this study. The chapter identifies and explains the participants of the study, the data to be collected, the methods of data collection, the analysis of data, and the validity and reliability of the

study. Chapter III also introduces the engineering design challenge used to conduct this study.

CHAPTER III

METHODS AND PROCEDURES

The methods and procedures used in this study are described in this chapter. This study employed an exploratory triangulation mixed-methods case study approach to identify the cognitive processes used by advanced pre-engineering students to solve complex engineering design challenges. The relevant literature was used to design the research approach for this study and to develop a process for analyzing the collected data. In this chapter, the selection of participants, data, setting, engineering design challenge, methods of data collection, data analysis, and research validity and reliability will be discussed.

Selection of Participants

The aim of this study was to examine the ways advanced pre-engineering high school students cognitively navigate an engineering design problem to create a viable solution. The purpose of the research was to identify the cognitive processes advanced pre-engineering students use to design, construct, and evaluate operational solutions to engineering design problems, as well as develop a conceptual engineering design process model for informing the design of technology and engineering curriculum, instruction, and assessments. Petrina (2010) recognized that when conducting research of this nature, the proper selection of participants is a vital component. Selecting the proper participants is vital because if one is to create an example on which to base teaching and learning in secondary education, then it makes sense to study students at the desired development levels. Petrina supported this idea because constructivists warn that children do not think in the same manner as adults. Therefore, the selection of participants was based on those

who could provide data on identifying the cognitive processes employed at a desirable experience level in engineering.

The participants selected for this study were junior and senior high school students enrolled in the capstone course of the *Project Lead the Way* pre-engineering program. Students enrolled in this course were composed of 11 males and 3 females. These participants were selected because the *Project Lead the Way* program is a standardized national model designed to prepare students for post-secondary engineering programs. Schools that implement *Project Lead the Way* must complete a rigorous certification process to ensure that all students enrolled in the program receive similar experiences (Project Lead the Way, 2013). To be enrolled in the capstone course, students must have successfully completed a series of three courses covering topics in engineering and problem-solving. Therefore, participants selected were experienced at solving engineering design problems with a similar background and have developed skills in using technological tools and materials but were still at an adolescent level of development, not one as an adult.

Essentially, the participants and the selected high schools were identified through criterion purposeful sampling. This study included eight student participants drawn from two high schools in the southeast region of the United States. The high schools were selected because they had a reputation for having model *Project Lead the Way* pre-engineering programs in the region. The high school recommendations were derived from high school teachers, state administrators, and the region's *Project Lead the Way* affiliate university director. Middleton (2008) provided some considerations for the selection of participants. First, the participants needed to be at the appropriate stage of expertise for

the proposed research objectives. In this case, the appropriate level was advanced pre-engineering students. The second consideration was to select participants who would normally be exposed to the type of problem that is under investigation in their everyday learning environment. The *Project Lead the Way* students are typically exposed to various forms of engineering problems throughout their program of study. These experiences include designing automated manufacturing systems, solving robotic challenges, and developing various consumer products. Lastly, the participants were selected with the consideration that they had the verbal abilities to successfully "think aloud" and were comfortable in doing so.

Data

Various forms of data were collected through this study to enable the proper triangulation of the findings. The first form of data collected provided the background knowledge and experience of the participants related to technology and engineering design. These data were used to describe the population under investigation. Next, verbal think-aloud protocols were collected to capture the thoughts that emerged from the participants' minds as they engaged in engineering design problem-solving (Ericsson & Simon, 1993). The third data types were visual protocols collected through point-of-view video-recording equipment. As Lammi and Becker (2013) state, the verbal and visual protocols complement each other to provide richer information about the thoughts and actions in the engineering design process. In addition, the combined protocols enabled the coding and recording of the number of times each cognitive process was employed and the amount of time taken for each process using Hill's (1997) computer analysis tool titled, the Observation Procedure for Technology Education Mental Processes

(OPTEMP). The resulting data were then used to address the research objective of identifying the fundamental cognitive processes that participants use to design, construct, and evaluate a valid solution to an engineering design problem. To supplement these data, the participant-generated non-verbal artifacts were collected and examined to assist with triangulating the findings. These artifacts consisted of both design journals and the solution end product. Furthermore, teacher evaluations of the participant solutions were collected to achieve the research objective of determining trends in the cognitive processes that relate to student aptitude in solving engineering design problems. Quantitative data on the solution's effectiveness of solving the problem were also collected to determine which solutions were the best performing. These data enabled the researcher to compare and contrast the cognitive processes used by participants who developed the top-performing solutions to the participants who developed the least effective solutions with a purpose of determining potential cognitive indicators for creating more effective solutions. Lastly, all of the data were used to meet the third research objective of creating a conceptual model of student engineering design cognition.

The Setting

Student problem-solving data were collected in a setting where technological and engineering design activity regularly occurred and was naturally performed by the participants. The study location consisted of two large rooms in the area's career and technical center where the participants traveled to attend their capstone pre-engineering course. The two rooms accommodated four participants at a time solving the engineering design problem with limited interference and interaction with one another. The

participant data were collected during the normal time scheduled for their capstone *Project Lead the Way* course. This was done to provide a level of comfort to the participants as they conducted their activities. Each participant wore a point-of-view camera to collect and record their process as they thought aloud. The participants were isolated from their classmates at individual laboratory tables to encourage the verbalization of their thoughts without distraction from peers. A full description of the setting can be found in Appendix A.

The Engineering Design Challenge

Petrina (2010) noted that the proper analysis of engineering cognition requires data to be collected from a person-in-interaction-with design and engineering problems, solutions, and strategies. Therefore, a carefully developed engineering design challenge that meets a number of product specifications needed to be provided to the participants (Middleton, 2008). This study was designed to examine the cognitive processes students employed throughout each stage of the design process as participants defined their problem and navigated to their solution. To achieve this task, the researcher utilized a modified engineering design project from the *Project Lead the Way* curriculum for the capstone *Engineering Design and Development* course. This modified engineering design challenge did not provide participants with a list of objectives or materials for the problem as to not interfere with the natural process the participant would take to solve the problem without researcher or teacher intervention. The participants were only provided with a situation where a solution was necessary and therefore, they needed to identify their own criteria and constraints for the solution, as well as determine what materials would be best for their solution prototype. In addition, this challenge was designed in a

way that enabled the researcher to collect quantitative data to determine solution effectiveness.

The participants completing the engineering design challenge were tasked with designing and constructing an inexpensive, durable, and easy-to-use water purification system. The participants were permitted to utilize any materials or tools necessary for creating a solution to quickly remove contaminants from a water sample. Therefore, participants were required to design, build, and evaluate a water purification system to decrease the turbidity of a contaminated water source and to do so as if no one was observing them. Additionally, participants were reminded to do what they felt necessary to solve the problem and not to do what they believed the researcher or classroom instructor wanted them to do. Lastly, participants evaluated the effectiveness of their solutions by testing the turbidity of their water samples using a computer based data collection turbidity sensor interface. The complete engineering design challenge is provided in Appendix B.

Data Collection

To establish a descriptive analysis of how students cognitively process solutions to complex engineering design challenges, various data were collected through the use of an exploratory case study (Zuga, 2004). A mixture of qualitative and quantitative data collection and analysis is necessary to study engineering design problem-solving because it involves a series of complex interactions between many variables (Middleton, 2008). Case studies have become important in technology and engineering education research because of their effectiveness in capturing the pedagogy of the classroom and in understanding cognitive processes used in interactions among students and teachers in the

completion of design activities (McCormick, 2008). In this study, the researcher collected various forms of verbal and non-verbal data to analyze each case where each participant was given an engineering design problem to solve.

The participants were first given a demographics survey to determine their individual experience in engineering design. This information was important to establish the consistency of their skill levels in regards to technology and engineering. The participants selected were students in the capstone *Project Lead the Way* course, which should have allowed them to be at similar experience levels in pre-engineering. *Project Lead the Way* requires a number of courses in technology and engineering content, as well as mathematics and science. The participants were asked the following questions to determine their similarities and differences in education, as well as their qualification for being considered advanced pre-engineering students:

1. What grade are you enrolled?
2. What is your gender?
3. What is your age?
4. What is your mother's occupation?
5. What is your father's occupation?
6. What is your grade point average?
7. What high school and middle school technology and engineering courses have you taken?
8. What high school mathematics courses have you taken?
9. What high school science courses have you taken?
10. What type of afterschool STEM programs or contests have you participated?

11. What are your career interests?

12. In your own words, please describe the engineering design problem-solving process.

See Appendix C for the complete demographics survey.

Once the participants' background information was collected, they were prepared to complete an engineering design challenge while using the point-of-view cameras and following the "think aloud" procedure. The procedure for the engineering design challenge can be found in Appendix D. Next, the participants were presented with the engineering design challenge found in Appendix B and were given an estimated timeline of approximately three hours to solve the problem. They were also not constrained by using any materials or tools. Participants were allowed to use any of the materials or equipment in the career and technical center's laboratories. After the participants were given the engineering design problem, they were then instructed to "think aloud" as they worked alone to solve the challenge. The participants were provided an engineering design journal to use when solving the challenge. They were also given access to a computer based data collection turbidity sensor interface to test and record the turbidity of the water samples as a way to evaluate their solution effectiveness.

The "think aloud" procedure allows a researcher to study a participant's thought processes and provides insight to what is going on in their mind from moment to moment. "Thinking aloud" is a verbal method that allows the participant to continuously speak their thoughts as they come to mind while performing the task at hand (Van Someren, van de Velde, & Sandberg, 1994). Atman and Bursic (1998) proposed that using a verbal protocol analysis for assessing the cognitive processes of engineering

students is a formidable method for understanding the processes they use when developing a design solution. This verbal protocol for recording one's thoughts was combined with observational protocols of capturing video of each participant's processes used in solving the engineering design challenge. The participant's processes for solving the design problem were recorded in a method unique to this study. The camera technology was attached to the participant's ear and adjusted so that what was being recorded was exactly the manual processes the participant was seeing. The camera also captured the verbalizations of the participants' thoughts, as well as what they were looking at as they solved the problem. The observation protocol was extremely important (Laeser, Moskal, Knecht, & Lasich, 2003), because the "think aloud" method can be weak in capturing the non-verbal processes involved in problem-solving (Cross, 2004).

Upon completing the challenge, participants were asked to complete a series of reflection questions in their design journals. These participant-produced design journals were then collected for analysis. The participants were also asked to create a mind map of their processes for solving the problem to aid in the development of the study's conceptual engineering design model. Lastly, the classroom teacher and the researcher evaluated the participant solutions using the engineering design project rubric to assist in determining which solution outcomes were the most effective. This rubric can be found in Appendix E.

Data Analysis

Data were analyzed to identify the fundamental cognitive processes students employed to successfully design, build, and evaluate effective solutions to an engineering design challenge. One data source consisted of audio/video recordings of the problem-

solving activity of each participant, which included continuous verbalizations of the thought processes employed. Additionally, the design documentation used throughout the problem-solving process was collected. To prepare for the analysis of these data, the audio/video recording of the problem-solving sessions were segmented into a solution design, solution construction, and solution evaluation phase. Ericsson and Simon (1993) provided cues for segmenting the protocol, such as pauses and changes in intonation and syntax in phrases or sentences. Segmenting the data in this manner enabled the researcher to analyze the coded results at certain intervals of the engineering design process.

As participants progressed through the problem-solving sessions, the researcher identified and coded their cognitive processes using a list of 17 universal mental processes for technological problem solving defined and validated by Halfin (1973) and re-validated by Wicklein and Rojewski (1999). The mental processes were also organized under five constructs developed by Hill and Wicklein (1999) using factor analysis to help facilitate the identification of the correct code. These mental process codes are listed in Table 5. The researcher coded the cognitive processes used by each participant while observing the video recordings using an updated version of Hill's (1997) OPTEMP computer analysis tool. This tool enables a researcher to view the recordings while capturing, documenting, and systematizing the cognitive process codes from each problem-solving session (Kelley, Brenner, & Pieper, 2010). In addition, the OPTEMP program output provides the number of times each participant employed each cognitive process, as well as the duration of each of those processes. The researcher divided the coded data into units of time, time on each code, total time on each code, percentage of code time of the overall design process, and total time of the problem-solving experience.

Table 5

Cognitive Process Codebook

Cognitive Process	Code	Definition
		Researching the Problem
Cognitive Process	**Code**	**Definition**
Questions/ Hypotheses	QH	The process of asking, interrogating, challenging, or seeking answers related to a phenomenon, problem, opportunity, element, object, event, system, or point of view.
		Searching for Solutions
Cognitive Process	**Code**	**Definition**
Managing	MA	The process of planning, organizing, directing, coordinating, and controlling the inputs and outputs of the system.
Measuring	ME	The process of describing characteristics (by the use of numbers) of a phenomenon, problem, opportunity, element, object, event, system, or point of view in terms, which are transferable. Measurements are made by direct or indirect means, are on relative or absolute scales, and are continuous or discontinuous.
Communicating	CM	The process of conveying information (or ideas) from one source (sender) to another (receiver) through a media using various modes. (The modes may be oral, written, picture, symbols, or any combination of these.)
		Innovation
Cognitive Process	**Code**	**Definition**
Creating	CR	The process of combining the basic components or ideas of phenomena, objects, events, systems, or points of view in a unique manner which will better satisfy a need, either for the individual or for the outside world.
Defining Problem(s)	DP	The process of stating or defining a problem, which will enhance investigation leading to an optimal solution. It is transforming one state of affairs to another desired state.
Designing	DE	The process of conceiving, creating, investing, contriving, sketching, or planning by which some practical ends may be effected, or proposing a goal to meet the societal needs, desires, problems, or opportunities to do things better. Design is a cyclic or iterative process of continuous refinement or improvement.
		Analyzing Data
Cognitive Process	**Code**	**Definition**
Analyzing	AN	The process of identifying, isolating, taking apart, or performing similar actions for the purpose of setting forth or clarifying the basic components of a phenomenon, problem, opportunity, object, system, or point of view.
Computing	CP	The process of selecting and applying mathematical symbols, operations, and processes to describe, estimate, calculate, quantify, relate, and/or evaluate in the real or abstract numerical sense.
Predicting	PR	The process of prophesying or foretelling something in advance, anticipating the future on the basis of special knowledge.
Visualizing	VI	The process of perceiving a phenomenon, problem, opportunity, element, object, event, or system in the form of a mental image based on the experience of the perceiver. It includes an exercise of all the senses in establishing a valid mental analogy for the phenomena involved in a problem or opportunity.
Modeling	MO	The process of producing or reducing an act or condition to a generalized construct, which may be presented graphically in the form of a sketch, diagram, or equation; presented physically in the form of a scale model or prototype; or described in the form of a written generalization.
Interpreting Data	ID	The process of clarifying, evaluating, explaining, and translating to provide (or communicate) the meaning of particular data.
		Evaluating Results
Cognitive Process	**Code**	**Definition**
Models/Prototypes	MP	The process of forming, making, building, fabricating, creating, or combining parts to produce a scale model or prototype.
Testing	TE	The process of determining the workability of a model, component, system, product, or point of view in a real or simulated environment to obtain information for clarifying or modifying design specifications.
Observing	OB	The process of interacting with the environment through one or more of the senses (seeing, hearing, touching, smelling, tasting). The senses are utilized to determine the characteristics of a phenomenon, problem, opportunity, element, object, event, system, or point of view. The observer's experiences, values, and associations may influence the results.
Experimenting	EX	The process of determining the effects of something previously untried in order to test the validity of an hypothesis, to demonstrate a known (or unknown) truth, or to try out various factors relating to a particular phenomenon, problem, opportunity element, object, event, system, or point of view.

Note. (Halfin, 1973; Hill & Wicklein, 1999; Wicklein & Rojewski, 1999)

The number of times and duration of each cognitive process were compiled and recorded in the output of the OPTEMP program. Basic statistical software products (SPSS and Microsoft Excel) were utilized to process the output of the OPTEMP program. The percentage of time taken on the various cognitive processes were analyzed to provide insight into the mental strategies used in successfully designing, constructing, and evaluating solutions to technological problems (Kelley & Hill, 2007). These data also enabled the comparison of the group means of time taken for each process, allowing the researcher to create a conceptual model of engineering design integrating the mental processes by comparing these processes to the participants design reflection responses.

To help determine potential cognitive identifiers for achieving successful solution results, the participant prototypes were evaluated by testing the turbidity of the water samples and assessed using the engineering design rubric provided in Appendix E. The participant results were then compared with the measures of central tendencies for the participant cognitive processes to determine how long each process was utilized by the top-performing and the bottom-performing participants. Comparing these results helped the researcher identify relationships and trends between the mental processes used and the effectiveness of the final solution.

Lastly, the study results were compiled to create a conceptual engineering design problem-solving model that integrated the student data for the purpose of informing teaching and learning in technology and engineering education. The cognitive processes used by each participant as he or she worked through the engineering design problem were utilized to develop graphical representation of the overall procedure each used to solve the engineering design problem. The researcher then paralleled the flow charts for

all 8 participants and compared them to the 12-step engineering design process and the participant generated mind maps of their own problem solving process to determine the general approaches in which they followed to complete the design challenge. These general approaches of engineering design were then linked with the solution effectiveness data to create the final authentic conceptual engineering design model. This final model was created to inform the design of technology and engineering curricula, instruction, and assessment. As Atman and Bursic (1998) explain, understanding the cognitive processes of engineering students is a powerful tool in evaluating a student's process for developing a solution in detail.

Validity and Reliability

This research design provided strength for reporting the findings for this study. The design ensured that rich data sources consisting of verbal protocols, observational protocols, and design artifacts were used to make accurate coding possible (Middleton, 2008). Accurate coding helped to ensure that the research was valid and that the study actually reported what it claimed to be reporting. However, the analysis of cognitive processes in real time is a difficult task (Middleton, 2008). This is especially true if there are cognitive processes operating in parallel (Olson, Duffy, & Mack, 1984). To address this threat to validity, the researcher used a "think aloud" procedure that Ericsson and Simon (1993) claim provides important information for drawing valid conclusions about cognitive processes. Furthermore, the collection of observational and "think aloud" protocols provided parallel data sources that enabled the capability of representing parallel cognitive processes. The multiple sources of data were also used to fill in the

gaps in the participants' verbalizations of their thought processes, thus enhancing the internal validity of the process (Middleton, 2008).

The external validity of the research was taken into consideration to ensure that the findings would be applicable to various populations and settings within the technology and engineering education school subject. This research was designed to address the four concerns of external validity expressed by Burns (1990). The first threat is the failure to describe the independent variables within the situation being studied. This threat was addressed by selecting participants with similar backgrounds in a nationally certified and monitored pre-engineering program. A more detailed background of each participant was collected through an initial survey and described in the findings. Additionally, the engineering design problem used in this study was modified from the national *Project Lead the Way* curriculum, which students across the United States are currently studying. These tasks allowed all of the independent variables of the study to be transparent and enabled the setting to be replicated. Next, Burns (1990) found that external validity is compromised if the participants used are not representative of the student population. The purpose of this study is to provide insight into the complex thinking of a specific level of student to help support theoretical ideas for improving teaching, learning, and assessment. Although, the participants selected were students at a designated level within the pre-engineering program, this is similar in schools across the United States.

Next, Burns (1990) cautioned that a participant's involvement in the research activity itself could influence the outcomes of the study. This threat was addressed by utilizing an engineering design problem that was assigned to the participants in a

classroom environment in which they were normally engaged. The final concern mentioned by Burns (1990) is the effect that participants can have on other participants being analyzed in the same setting. This was not seen as a threat in this study because the participants were acting in their normal environment and were not working in a group setting.

The research design was used to minimize threats to validity, both internal and external. However, as Firestone (1993) explained, it should always be understood that the extent to which findings from any one study could be applied across any other population or settings is problematic. Yet, as Simon (1975) described, understanding humans' problem-solving processes requires the knowledge of the strategies that underlie the diverse problem-solving behaviors of individuals, which is lost through the statistical and averaging processes.

The reliability of research is important to the credibility of any study (Middleton, 2008). In this case, the researcher ensured the reliability of the results by confirming that another researcher examining the same phenomena could replicate the findings. Although the problem-solving episodes of each participant could never be exactly replicated, the coding of the cognitive processes that each participant employed can be repeated. To achieve this task, the researcher utilized an independent coder to individually code all eight participant protocols. Intercoder reliability between the researcher and the independent coder was measured to reveal a level of consistency in coding the results. A Pearson's correlation coefficient between the amounts of time each code was used by each coder for every participant was calculated to illustrate the intercoder agreement of

the coding results. A Pearson's correlation coefficient above .70 indicates that the coders are in agreement, therefore implying that the researcher's coding results are reliable.

Summary

Chapter III outlined the methods and procedures used to complete this study. The participants and setting for this study were clarified and explained. This chapter elaborated upon the engineering design problem used and the data to be collected. The methods of data collection were described by explaining how the data were retrieved and from where the data came. Chapter III also explained how the data were recorded and organized for analysis. Additionally, details were provided as to how the data were coded and analyzed using the OPTEMP program and basic statistical software products. Lastly, the validity and reliability of the methods and procedures were addressed. Chapter III permitted the researcher to collect the data that are presented as findings in Chapter IV.

CHAPTER IV

FINDINGS

The purpose of this study was to identify the cognitive processes used by advanced pre-engineering students to solve complex engineering design problems. This information can assist in understanding the way advanced pre-engineering students cognitively navigate the engineering design process to develop viable solutions to authentic problems. The coded data retrieved through this study were analyzed to meet the research objective of identifying the fundamental cognitive processes students use to design, construct, and evaluate operational solutions to engineering design problems. Additionally, these data were analyzed to achieve the research objective of determining identifiers within student cognitive processes for monitoring student aptitude to successfully design, construct, and evaluate technological solutions. These findings were then used to create a conceptual technological and engineering problem-solving model derived from the participant's thoughts and actions. This chapter contains the collected and analyzed data to satisfy these objectives.

Demographics

Participant background data were collected through a demographics survey (Appendix C) to provide a description of the subjects being studied. This information was used to determine participant similarities and differences and provided their qualifications for being considered advanced pre-engineering students. The researcher collected background data from two female and six male participants with a cumulative high school grade point average at or above 3.6 who volunteered to participate in the study. This sample is representative of the class which was composed of 11 male and 3 female

students. In addition, the data revealed that all eight participants completed the *Introduction to Engineering Design*, *Principles of Engineering*, and *Digital Electronics Project Lead the Way* pre-engineering courses and were enrolled in the capstone *Engineering Design and Development* course. Furthermore, each of the participants completed Algebra I, Algebra II, Geometry, and Trigonometry/ Pre-Calculus mathematics courses. The participants each completed high school biology and physical science courses, and six participants completed one or two *Advanced Placement* science courses. Lastly, each of the participants partook in the *Skills USA* afterschool technical workforce competition program and each was interested in a future career in engineering. Therefore, these data indicated that the participants had a similar background and can be considered advanced pre-engineering students with expertise in these school subjects. A summary of these demographic data is reported in Tables 6 and 7.

In addition, the demographics survey asked the participants to provide their own description of the engineering design process. The participant responses provided insight into their prior experiences with engineering design, as well as preconceived notions of what it takes to solve an engineering design problem. A general consensus from the participant descriptions was that the engineering design process is a multistep approach to solving problems, which includes the actions of understanding the problem, researching, brainstorming multiple solutions, developing a solution design, constructing the solution, evaluating the solution's performance, making necessary improvements, and communicating the solution results. The individual participant descriptions of the engineering design process are reported in Table 8.

Table 6

Description of Participants 1 Through 4

Participant (Gender)	Grade	GPA	Math Courses	Science Courses	Technology/ Engineering Courses	After-school Activities	Career Goal
1 (M)	12	4.1 or Above	• Algebra I • Algebra II • Geometry • Trig/Pre-Calculus • Calculus I • AP Statistics	• Honors Physical Science • Honors Biology • Pre-AP Chemistry • Pre-AP Physics • AP Physics	• TE • IED • POE • DE • EDD	• Skills USA • Math Club • Student Council • Jazz Band • National Honors Society • Pep Band	Engineering, specifically in mechanical and aerospace fields.
2 (M)	11	3.6–4.0	• Algebra I • Algebra II • Geometry • Trig/Pre-Calculus	• Physical Science • Biology	• TE • IED • POE • DE • EDD	• Skills USA	Mechanical Engineer
3 (M)	11	3.6–4.0	• Algebra I • Algebra II • Geometry • Trig/Pre-Calculus	• Physical Science • Biology • AP Chemistry • Physics	• TE • IED • POE • DE • EDD	• Skills USA	Mechanical Engineer
4 (M)	12	3.6–4.0	• Algebra I • Algebra II • Geometry • Trig/Pre-Calculus	• Physical Science • Biology • AP Chemistry • Physics	• IED • POE • DE • EDD	• Skills USA	To become an electrical/ mechanical engineer. I have a passion for music and would love to become a sound engineer.

Note. Technology and Engineering Course Key: TE—General Technology Education Course; IED—Introduction to Engineering Design; POE—Principles of Engineering; DE—Digital Electronics; EDD—Engineering Design and Development.

Table 7

Description of Participants 5 Through 8

Participant (Gender)	Grade	GPA	Math Courses	Science Courses	Technology/ Engineering Courses	After-school Activities	Career Goal
5 (F)	12	4.1 or above	• Algebra I • Algebra II • Geometry • Trig/Pre-Calculus • Calculus I • Algebra III	• Physical Science • Biology AP • Physics AP • Chemistry	• IED • POE • DE • EDD • Computer Programming I	• Skills USA	I would like to major in Chemical Engineering.
6 (F)	12	4.1 or above	• Algebra I • Algebra II • Geometry • Trig/Pre-Calculus • Statistics	• Physical Science • Biology • Physics • Chemistry	• IED • POE • DE • EDD • Computer Programming I • Computer Programming II • Computer Systems Repair	• Skills USA	I would like to major in Computer Engineering/Computer Science in college.
7 (M)	12	3.6–4.0	• Algebra I • Algebra II • Algebra III • Geometry • Trig/Pre-Calculus • College Calculus	• Physical Science • Pre-AP Biology • AP Biology • Physics • Chemistry	• IED • POE • DE • EDD	• Skills USA • VEX Robotics	Engineer. Do not know what kind.
8 (M)	12	3.6–4.0	• Algebra I • Algebra II • Geometry • Trig/Pre-Calculus • Calculus I	• Physical Science • Biology • Physics AP	• IED • POE • DE • EDD	• Skills USA	Electrical Engineering

Note. Technology and Engineering Course Key: TE—General Technology Education Course; IED—Introduction to Engineering Design; POE—Principles of Engineering; DE—Digital Electronics; EDD—Engineering Design and Development.

Table 8

Participant Descriptions of the Engineering Design Process

Participant	Description of the Engineering Design Process
1	Identify the problem, brainstorm solutions, research and identify potential solutions, choose a solution, build a prototype, test the prototype, evaluate results of tests, redesign prototype if necessary, and present solution.
2	Begin by researching, then brainstorm ideas, choose which idea is the best, begin designing the idea, make a prototype, test it, make any changes necessary, then make a final product.
3	Identify the problem, research the problem, and brainstorm for solutions to the problem. Then design the idea you have chosen to solve the problem, make a prototype, and test the prototype. If needed, redesign and finalize the product.
4	You first must recognize the problem. After that, research, research, research! Once you have more than one possible solution, critique them and find the overall best. After you have decided which solution to pursue, then organize needed materials and start designing.
5	The design process is used to solve problems and innovate solutions. There are multiple steps to solving the processes.
6	Define problem, brainstorm solutions, decide on an idea, develop the idea, make a prototype, test the prototype, modify the design, and attain a final solution.
7	Identify the problem. Think about the problem. Come up with solutions for the problem. Pick a favorite solution. Build a prototype for the solution. Test the prototype. If it works, manufacture!
8	You must brainstorm all possible solutions then decide on which is the best using different methods. After you have decided on your solution, you must design it and come up with a prototype. Based on how the prototype performs, you then have to change and tweak your design to make it the best possible solution.

Research Objective 1

The first research objective for this study was to identify the fundamental cognitive processes students use to design, construct, and evaluate operational solutions to engineering design problems. To achieve this research objective, the eight participants were presented with an engineering design challenge that required them to solve the problem of accessing clean drinking water after an occurrence of a natural disaster in a developing nation. A detailed description of the engineering design problem is provided in Appendix B. This engineering design problem challenged the participants to

individually design, construct, and evaluate a water filtration device to reduce the turbidity of a contaminated water sample while verbalizing their thought process using the "think aloud" method. To collect the data necessary for Research Objective 1, the researcher fitted each participant with point-of-view camera technology to capture their verbalizations and actions as they worked to solve the problem.

The verbal and observational data, along with participant design journals gathered during the engineering design problem-solving sessions were independently coded by two coders using the 17 mental processes for technological problem-solving identified by Halfin (1973). A full list and description of these processes are presented in Table 9. The coding process was facilitated using an updated version of the Observational Procedure for Technology Education Mental Processes (OPTEMP) computer analysis tool. The outputs of this tool provided the number of times each mental process was used and how much time was taken for each process. The coders first utilized sample student engineering design sessions to become comfortable with the cognitive process codes and their operational definitions, as well as using the OPTEMP computer analysis tool. After each coder coded each of the participant engineering design sessions, a Pearson's correlation coefficient was used to determine the intercoder reliability of the results. This analysis indicated how consistent the coders were at identifying the cognitive processes and how well they agreed on the processes used by each participant. A Pearson correlation coefficient close to 1.00 indicates the highest level of coding consistency and agreement. Any correlation below .70 is considered to be not in agreement. Ideally, the correlation should be above .80.

Table 9

Halfin's Original 17 Mental Processes for Technological Problem-Solving

Cognitive Process	Code	Definition
Analyzing	AN	The process of identifying, isolating, taking apart, or performing similar actions for the purpose of setting forth or clarifying the basic components of a phenomenon, problem, opportunity, object, system, or point of view.
Communicating	CM	The process of conveying information (or ideas) from one source (sender) to another (receiver) through a media using various modes. (The modes may be oral, written, picture, symbols, or any combination of these.)
Computing	CP	The process of selecting and applying mathematical symbols, operations, and processes to describe, estimate, calculate, quantify, relate, and/or evaluate in the real or abstract numerical sense.
Creating	CR	The process of combining the basic components or ideas of phenomena, objects, events, systems, or points of view in a unique manner which will better satisfy a need, either for the individual or for the outside world.
Defining Problem(s)	DP	The process of stating or defining a problem, which will enhance investigation leading to an optimal solution. It is transforming one state of affairs to another desired state.
Designing	DE	The process of conceiving, creating, investing, contriving, sketching, or planning by which some practical ends may be effected, or proposing a goal to meet the societal needs, desires, problems, or opportunities to do things better. Design is a cyclic or iterative process of continuous refinement or improvement.
Experimenting	EX	The process of determining the effects of something previously untried in order to test the validity of an hypothesis, to demonstrate a known (or unknown) truth, or to try out various factors relating to a particular phenomenon, problem, opportunity element, object, event, system, or point of view.
Interpreting Data	ID	The process of clarifying, evaluating, explaining, and translating to provide (or communicate) the meaning of particular data.
Managing	MA	The process of planning, organizing, directing, coordinating, and controlling the inputs and outputs of the system.
Measuring	ME	The process of describing characteristics (by the use of numbers) of a phenomenon, problem, opportunity, element, object, event, system, or point of view in terms, which are transferable. Measurements are made by direct or indirect means, are on relative or absolute scales, and are continuous or discontinuous.
Modeling	MO	The process of producing or reducing an act or condition to a generalized construct, which may be presented graphically in the form of a sketch, diagram, or equation; presented physically in the form of a scale model or prototype; or described in the form of a written generalization.
Model/Prototype Constructing	MP	The process of forming, making, building, fabricating, creating, or combining parts to produce a scale model or prototype.
Observing	OB	The process of interacting with the environment through one or more of the senses (seeing, hearing, touching, smelling, tasting). The senses are utilized to determine the characteristics of a phenomenon, problem, opportunity, element, object, event, system, or point of view. The observer's experiences, values, and associations may influence the results.
Predicting	PR	The process of prophesying or foretelling something in advance, anticipating the future on the basis of special knowledge.
Questions/ Hypotheses	QH	The process of asking, interrogating, challenging, or seeking answers related to a phenomenon, problem, opportunity, element, object, event, system, or point of view.
Testing	TE	The process of determining the workability of a model, component, system, product, or point of view in a real or simulated environment to obtain information for clarifying or modifying design specifications.
Visualizing	VI	The process of perceiving a phenomenon, problem, opportunity, element, object, event, or system in the form of a mental image based on the experience of the perceiver. It includes an exercise of all the senses in establishing a valid mental analogy for the phenomena involved in a problem or opportunity.

Note. (Halfin, 1973; Hill & Wicklein, 1999; Wicklein & Rojewski, 1999)

The Pearson's correlation coefficient calculation for each participant during each phase of the design session indicated that 75% of the agreement results showed excellent reliability with a coefficient between .901 and .988 ($n = 17, p = 0.00$). The remaining agreement results were considered to be reliable with a correlation coefficient from .812 to .833 ($n = 17, p = 0.00$). These results indicated that both coders were consistent in using the codes and agreed on the results. The Pearson's correlation coefficients for each participant are reported in Table 10.

Table 10

Intercoder Reliability Agreement Results

Participant	Pearson R
1	0.833
2	0.942
3	0.969
4	0.988
5	0.812
6	0.968
7	0.901
8	0.908

Note. ($n = 17, p = 0.00$).

The coded data for each participant were analyzed to determine which cognitive processes the participants employed, the number of times they employed each process, and the total time taken for each process. This analysis enabled the researcher to determine the average time the participants took using each process and the average number of times each process was employed. The coded data were segmented into three distinct phases of developing a solution to an engineering design problem. These phases included solution design, solution construction, and solution evaluation. Through the

participant observations, the researcher determined where each of these phases began and ended. Participants were not given a set amount of time to complete each of these phases in working toward a solution to the problem. The coded data for each phase, however facilitated the identification of cognitive trends during the various segments in the overall engineering design problem-solving process.

One note to be made is that through the coding process, the two coders determined the mental processes of *Modeling* and *Modeling/Prototype Constructing* were too similar and were difficult to accurately differentiate between based on the given descriptions. Halfin (1973) also noted the inability to differentiate between these two processes in his original work to initially develop the 17 mental processes. Therefore, the results will be based on the assumption that these codes cannot be defined separately, and consequently the operations of the *Modeling* mental process have been assigned to either the codes of *Designing* or *Model/Prototype Constructing.*

The data analysis indicated that the solution design phase lasted an average of 29 minutes and 29 seconds for the participants. This phase consisted of framing the problem and developing an initial solution design. The solution design phase began at the start of the problem-solving process and ended when the participants initiated construction of their solution. During this phase, the participants employed 13 of the 17 mental processes. The processes not used were *Model/Prototype Constructing*, *Observing*, *Experimenting*, and *Testing*. The process of *Interpreting Data* was only identified as being used for less than one second, which was likely a result of a coding error. Therefore, it can be considered that this process was not used during this phase.

The individual participant data reported that some participants dedicated substantially more time to the solution design phase than others. This was particularly true for the female participants. The female participants each took over 41 minutes designing a solution to the problem (Participant 5, 45 minutes and 30.4 seconds; Participant 6, 41 minutes and 39.3 seconds), while their male peers took approximately 30 minutes or less time designing a solution. The female participants took more time employing the *Communicating* process, thus thoroughly documenting their research in their engineering design journals, employing the *Managing* process by planning out their problem-solving procedure, and employing the *Analyzing* process by conducting exhaustive research. It is also noticeable that some participants were more analytical than others by taking more time *Analyzing* the problem and the related research. Participants 2, 5, 6, and 8 took over 15 minutes employing the *Analyzing* process, while the other participants took under 10 minutes and 30 seconds. The individual participant cognitive process data for the solution design phase are reported in Table 11. A graphical representation of the percentage of time taken for each mental process by each participant during the solution design phase can be found in Appendix F.

Solution Design

The individual participant data were used to calculate the mean time each mental process was employed during the solution design phase and to determine the mean amount of time taken for each process. On average, the participants employed the 13 different mental processes approximately 114 times for a total of 29 minutes and 29 seconds during the solution design phase.

Table 11

Participant Cognitive Processes for Solution Design Phase

	Participant 1		Participant 2		Participant 3		Participant 4		Participant 5		Participant 6		Participant 7		Participant 8	
CODE	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time
AN	5	02:05.2	12	15:28.8	17	10:35.7	16	07:54.9	39	19:19.4	48	18:00.5	27	08:56.8	26	15:04.5
CM	7	01:18.2	3	00:35.1	4	00:48.1	4	00:48.8	31	06:25.6	42	04:47.4	2	00:04.9	16	02:16.3
CP	0	00:00.0	0	00:00.0	1	00:16.9	0	00:00.0	0	00:00.0	1	00:08.4	0	00:00.0	0	00:00.0
CR	4	00:34.7	3	00:39.6	15	03:24.6	9	01:53.9	7	01:49.5	17	03:05.1	18	02:34.6	8	01:39.9
DE	13	04:43.2	6	03:17.3	17	07:44.2	3	01:25.2	19	06:13.5	26	06:50.6	31	07:53.4	16	05:05.7
DP	7	02:55.3	4	04:37.2	3	01:10.5	5	01:52.0	7	01:06.3	6	01:44.3	9	01:12.2	3	00:12.9
EX	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0
ID	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	1	00:03.6	0	00:00.0	0	00:00.0
MA	4	01:52.9	6	01:15.9	1	00:12.6	5	00:48.2	27	07:09.3	16	02:32.2	9	01:22.5	5	00:44.3
ME	1	00:03.1	0	00:00.0	2	00:19.5	0	00:00.0	5	00:27.3	0	00:00.0	2	00:06.4	0	00:00.0
MO	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	5	00:47.5	0	00:00.0	0	00:00.0	0	00:00.0
MP	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0
OB	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0
PR	8	00:49.5	6	00:34.3	9	00:58.0	8	00:39.9	14	01:40.6	30	01:51.1	16	00:53.0	15	01:03.9
QH	5	00:46.8	7	01:15.4	9	02:22.0	9	01:11.4	8	01:02.0	16	01:46.5	19	01:45.5	6	01:02.1
TE	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0
VI	10	01:33.0	5	00:52.5	9	02:08.8	4	00:19.0	5	00:29.5	8	00:49.7	28	03:30.5	10	00:59.7
TOTAL TIME	64	16:42.2	52	28:36.3	87	30:00.8	63	16:53.4	167	45:30.4	211	41:39.3	161	28:20.1	105	28:09.3

Out of the processes employed, *Analyzing* ($\bar{x}$ = 11 minutes and 25.7 seconds) and *Designing* ($\bar{x}$ = 5 minutes and 13.1 seconds) took the most amount of time during this phase. The processes of *Computing* ($\bar{x}$ = 7.9 seconds) and *Measuring* ($\bar{x}$ = 7.0 seconds) were utilized the least by the participants. The mean number of times each cognitive process was used while designing a solution to the engineering design problem, as well as the mean amount of time taken for each process are reported in Table 12.

Table 12

Mean Total Cognitive Processes Used in the Solution Design Phase of the Engineering Design Activity

Solution Design Phase					
Code	**$\bar{x}$ Times Used**	**$\bar{x}$ Amount of Time**	**Code**	**$\bar{x}$ Times Used**	**$\bar{x}$ Amount of Time**
AN	23.750	11:25.7	ME	1.250	00:07.0
CM	13.625	02:16.4	MO	0.625	00:05.9
CP	0.250	00:07.9	MP	0.000	00:00.0
CR	10.125	02:18.4	OB	0.000	00:00.0
DE	16.375	05:13.1	PR	13.250	01:03.8
DP	5.500	01:43.7	QH	9.875	01:24.0
EX	0.000	00:00.0	TE	0.000	00:00.0
ID	0.125	00:00.2	VI	9.875	01:20.3
MA	9.125	02:10.3	**TOTAL**	113.750	29:29.0

Note. $\bar{x}$ represents the sample mean.

The mean participant data were then utilized to determine the average percentage of time taken for each process during the solution design phase of the engineering problem-solving session. On average, 41.4% of the participants' solution design time was dedicated to the process of *Analyzing* and 18.2% of their time was taken employing the *Designing* process. The mental processes of *Communicating*, *Creating*, *Defining Problems*, *Managing*, *Visualizing*, and *Questioning/Hypothesizing* were employed for the

majority of the remaining solution design time. Only 4.2% of the time was dedicated to employing the processes of *Predicting*, *Measuring*, and *Computing*. Figure 2 provides a graphical representation of the average percentage of time taken for each of the processes utilized during the solution design phase.

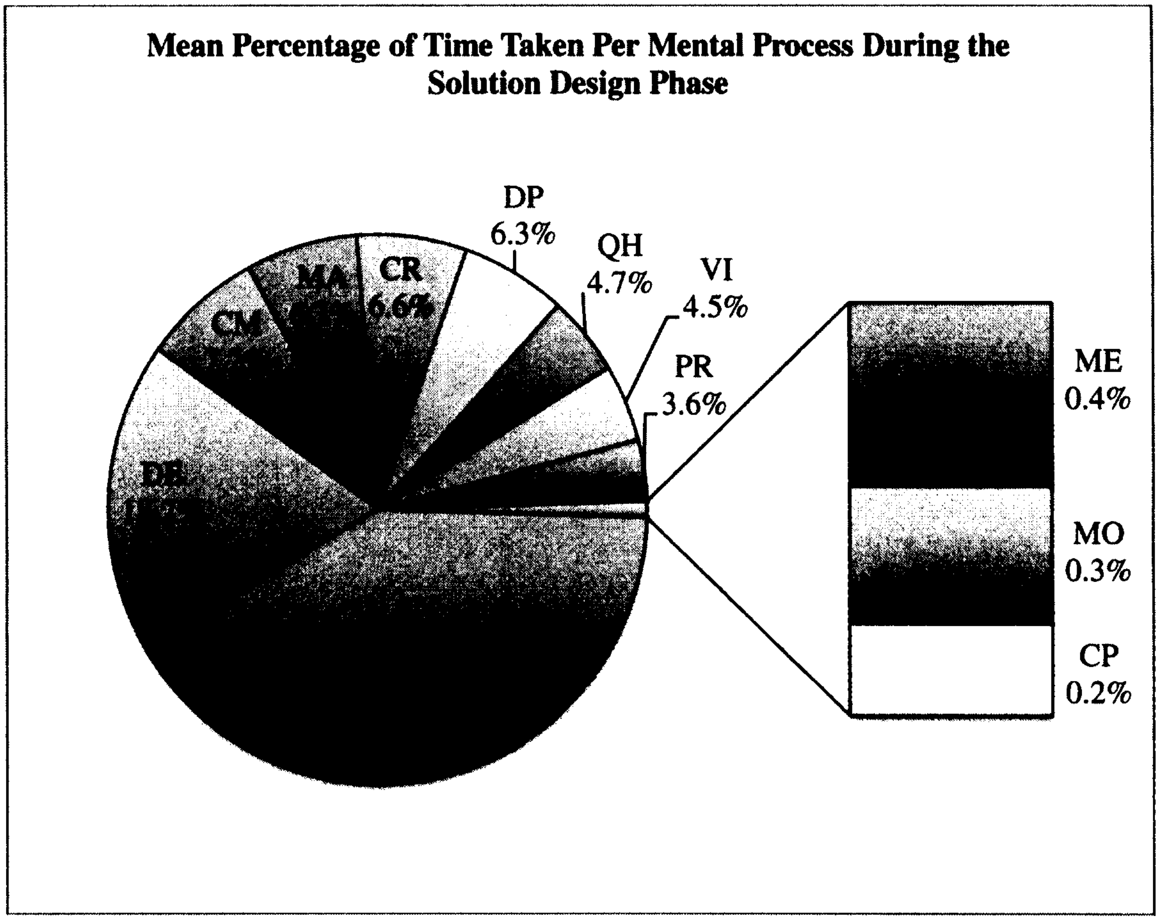


Figure 2. Mean percentage of time taken per mental process during the solution design phase.

Solution Construction

The data analysis indicated that the solution construction phase lasted an average of 39 minutes and 45.7 seconds for the participants. This phase began when participants moved away from planning their solution design to actually making it and consisted of

the physical construction of their solution model/prototype. The phase ended when the participants began testing their solution. During the solution construction phase, the participants employed all 17 mental processes. However, only two participants were observed employing the *Testing* process, each for less than five seconds. This may indicate that the process of *Testing* may have been mistakenly entered as a code for the process of *Experimenting* due to their similarity in definition. Therefore, it can be considered that the *Testing* process was not used during this phase.

The individual participant data reported a wide range of times taken to complete the solution construction phase. Some participants took less than 20 minutes completing this phase, while others took more than an hour. However, all eight participants were similar in the percentage of time taken employing each mental process in relation to their total amount of time taken to complete the solution construction phase. The only noticeable difference was seen in the amount of time taken employing the *Measuring* process. Participants 3 and 5 dedicated a larger amount of their time to the *Measuring* process, while they were constructing their solution. The complete list of the individual participant cognitive processes data for the solution construction phase is reported in Table 13. A graphical representation of the percentage of time taken for each mental process by each participant during the solution construction phase can be found in Appendix G.

Additionally, the individual participant data for the solution construction phase were used to calculate the mean time each mental process was employed and to determine the average amount of time taken for each process. On average, the participants employed the 17 mental processes 133 times for a total of 39 minutes and

Table 13

Participant Cognitive Processes for Solution Construction Phase

	Participant 1		Participant 2		Participant 3		Participant 4		Participant 5		Participant 6		Participant 7		Participant 8	
CODE	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time
AN	0	00:00.0	0	00:00.0	0	00:00.0	2	00:07.2	0	00:00.0	0	00:00.0	8	01:25.6	20	01:51.9
CM	0	00:00.0	1	00:07.2	2	00:32.8	0	00:00.0	6	00:35.3	2	00:20.7	0	00:00.0	0	00:00.0
CP	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	1	00:03.9	0	00:00.0
CR	2	00:20.9	2	00:13.6	8	01:03.9	12	01:32.7	1	00:09.7	2	00:12.1	8	01:02.2	1	00:04.6
DE	3	00:18.1	5	02:12.8	4	01:38.7	3	00:51.8	9	00:52.8	1	00:58.3	17	02:30.5	1	00:12.6
DP	0	00:00.0	0	00:00.0	2	00:12.7	0	00:00.0	0	00:00.0	0	00:00.0	1	00:15.2	0	00:00.0
EX	2	00:40.0	6	01:26.5	1	00:10.9	1	00:34.1	1	00:30.0	3	00:32.4	1	00:06.4	2	00:31.3
ID	11	00:47.9	1	00:02.3	1	00:03.3	2	00:05.6	0	00:00.0	1	00:02.4	0	00:00.0	1	00:02.6
MA	17	08:25.7	24	09:16.4	27	10:13.6	48	13:00.8	12	05:14.0	35	05:48.6	41	10:59.3	15	03:58.8
ME	10	01:20.5	1	00:04.9	20	06:42.7	5	00:45.1	9	02:53.3	7	00:31.9	9	01:41.0	9	00:44.3
MO	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	1	00:08.6	0	00:00.0	3	00:22.5	0	00:00.0
MP	35	20:33.6	34	24:20.2	42	38:33.3	46	26:30.4	20	06:41.1	38	18:21.4	58	29:52.5	30	07:44.9
OB	16	02:25.7	14	03:07.5	12	02:34.6	18	01:49.1	2	00:20.2	8	00:47.5	8	00:41.3	16	01:25.3
PR	6	00:33.7	11	01:01.7	14	00:51.1	12	00:43.5	2	00:19.5	8	00:17.6	14	00:53.3	7	00:24.9
QH	2	00:31.4	6	00:43.4	2	00:07.7	9	00:56.8	3	00:18.3	1	00:08.5	0	00:00.0	0	00:00.0
TE	0	00:00.0	0	00:00.0	0	00:00.0	1	00:03.8	1	00:04.6	0	00:00.0	0	00:00.0	0	00:00.0
VI	11	01:27.4	17	03:06.7	21	04:24.7	18	02:46.6	8	00:50.7	9	00:28.1	24	03:10.2	6	00:23.1
TOTAL TIME	115	37:25.3	122	45:43.6	156	1:07:10.2	177	49:47.7	75	18:58.0	115	28:32.3	193	53:03.9	108	17:24.4

45.7 seconds throughout the solution construction phase. During this phase, the *Model/Prototype Constructing* process was employed the most by each participant with an overall mean time of 21 minutes and 34.7 seconds.

Managing (*x*□ = 8 minutes and 22.2 seconds) was the second most-used process by each participant during this phase. These two processes were utilized the most since the participants were often observed managing the inputs of their solution as they worked to actually create it. Table 14 reports a complete list of the mean number of times the cognitive processes were used by the participants while constructing a solution to the engineering design problem, as well as the mean amount of time taken for each process.

Table 14

Mean Total Cognitive Processes Used in the Solution Construction Phase of the Engineering Design Activity

Solution Construction Phase					
Code	***x*□ Times Used**	***x*□ Amount of Time**	**Code**	***x*□ Times Used**	***x*□ Amount of Time**
AN	3.750	00:25.6	ME	8.750	01:50.5
CM	1.375	00:12.0	MO	0.500	00:03.9
CP	0.125	00:00.5	MP	37.875	21:34.7
CR	4.500	00:35.0	OB	11.750	01:38.9
DE	5.375	01:12.0	PR	9.250	00:38.2
DP	0.375	00:03.5	QH	2.875	00:20.8
EX	2.125	00:33.9	TE	0.250	00:01.1
ID	2.125	00:08.0	VI	14.250	02:04.7
MA	27.375	08:22.2	**TOTAL**	132.625	39:45.7

Note. *x*□ represents the sample mean.

The mean participant data for the solution construction phase were then utilized to determine the mean percentage of time taken for each process. On average, over 54% of the participants' solution construction time was dedicated to employing the process of

Model/Prototype Constructing, over 21% of their time was taken *Managing* their problem-solving process, 5.2% of their time was dedicated to *Visualizing* their solution, and 4.6% of their time was taken employing the mental process of *Measuring*. The processes of *Analyzing*, *Communicating*, *Creating*, *Defining Problems*, *Experimenting*, *Interpreting Data*, *Predicting*, and *Questioning/Hypothesizing* were each employed for an average of less than 1.6% of the participants' solution construction time. Figure 3 provides a complete graphical representation of the average percentage of time taken for each process during the solution construction phase.

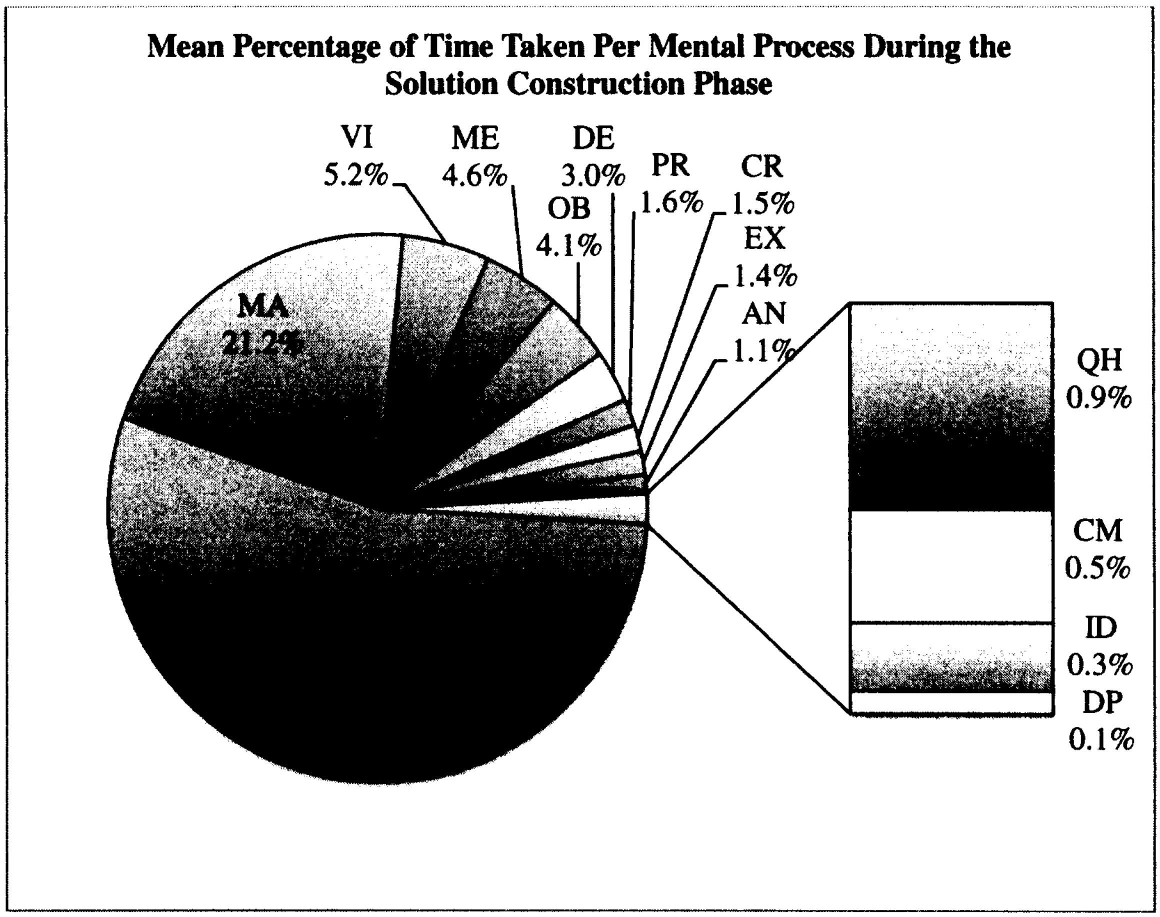


Figure 3. Mean percentage of time taken per mental process during the solution construction phase.

Solution Evaluation

Further, data analysis indicated that the solution evaluation phase lasted the longest of the three phases with an average time of 41 minutes and 21.1 seconds for the participants. The solution evaluation phase consisted of the actual testing and refinement of the solution. This phase began when the participants were satisfied with their prototype or model and began testing how well it solved the problem. This phase ended when the participants stopped making refinements to their design, achieved some level of success, and then communicated their results. During this phase, the participants employed all of the mental processes except *Modeling*. However, as indicated earlier the operations of the *Modeling* process were assigned to the processes of *Designing* and *Model/Prototype Constructing* by the coders.

The individual participant data reported that some participants employed the *Model/Prototype Constructing* process during the solution evaluation phase, while others did not. Participants 4 through 8 each employed the *Model/Prototype Constructing* process. Participants 6 through 8 even dedicated between 5 and 20 minutes to this process. It was observed that much of this *Model/Prototype Constructing* time was taken to revise and improve solution prototypes. Participants 1 through 3 did not employ the *Model/Prototype Constructing* process in any attempt to revise their solutions. Additionally, only three of the eight participants employed the *Experimenting* process during the phase. A full report of the individual participant cognitive processes used during the solution evaluation phase is provided in Table 15. A graphical representation of the percentage of time taken for each mental process by each participant during this phase can be found in Appendix H.

Table 15

Participant Cognitive Processes for Solution Evaluation Phase

	Participant 1		Participant 2		Participant 3		Participant 4		Participant 5		Participant 6		Participant 7		Participant 8	
CODE	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time	# of Times Used	Amount of Time
AN	19	07:35.7	16	04:34.9	11	02:46.3	6	01:31.7	14	04:34.4	27	05:09.0	47	08:11.1	37	04:26.8
CM	18	06:26.0	13	02:48.0	12	02:18.3	5	01:34.3	34	08:50.3	21	02:22.6	27	04:14.4	15	04:50.3
CP	8	01:27.9	3	00:25.3	3	00:12.1	3	00:09.6	11	03:12.5	5	00:19.2	5	00:16.5	8	00:27.6
CR	1	00:05.0	0	00:00.0	0	00:00.0	1	00:09.6	0	00:00.0	9	00:43.4	5	00:43.2	13	01:16.6
DE	4	01:50.5	6	02:48.2	0	00:00.0	0	00:00.0	17	03:14.2	6	00:34.4	3	00:10.7	12	02:39.6
DP	3	00:42.8	0	00:00.0	1	00:05.9	0	00:00.0	1	00:04.9	0	00:00.0	1	00:03.0	4	01:25.5
EX	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	3	00:55.2	2	00:39.1	0	00:00.0	3	00:29.0
ID	20	04:07.9	15	01:32.9	5	00:17.1	8	00:47.7	26	05:23.4	14	01:08.2	19	01:36.0	23	02:53.3
MA	9	02:47.6	8	04:11.3	4	01:34.1	15	03:19.3	28	09:25.4	34	06:03.3	20	04:47.2	42	08:15.3
ME	5	01:00.2	3	00:42.9	3	00:31.5	3	00:27.0	9	00:55.2	7	00:36.4	6	00:44.3	12	02:11.3
MO	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0	0	00:00.0
MP	0	00:00.0	0	00:00.0	0	00:00.0	2	00:16.6	1	00:07.3	44	20:57.8	15	05:23.1	18	07:15.8
OB	17	02:41.0	7	01:38.8	5	00:22.6	15	02:11.3	40	08:48.7	14	01:21.0	27	04:41.2	32	03:32.2
PR	6	00:59.8	0	00:00.0	0	00:00.0	7	00:15.1	18	03:20.7	11	00:37.7	7	00:22.4	13	00:50.2
QH	4	00:36.7	0	00:00.0	0	00:00.0	4	00:16.2	5	00:47.1	3	00:12.0	0	00:00.0	10	00:57.0
TE	23	13:31.4	13	07:37.1	9	04:54.7	24	07:54.3	50	25:02.8	30	13:08.3	27	10:08.3	50	16:14.0
VI	1	00:10.1	0	00:00.0	0	00:00.0	1	00:05.3	0	00:00.0	6	00:18.3	1	00:03.3	3	00:22.6
TOTAL TIME	138	44:02.6	84	26:19.5	53	13:02.6	94	18:58.0	257	14:42.0	233	54:10.7	210	41:24.8	295	58:08.4

The individual participant data for the solution evaluation phase were used to calculate the mean time each mental process was employed and to determine the mean amount of time taken for each process. On average, the participants employed the 17 mental processes 171 times for a total of 41 minutes and 21.1 seconds throughout the solution evaluation phase. During this phase, the participants employed the processes of *Testing* ($\bar{x}$ = 12 minutes and 18.9 seconds) and *Managing* ($\bar{x}$ = 5 minutes and 02.9 seconds) for the most amount of time. These two processes were employed the most for planning their procedure for testing their solution, coordinating what tools and materials were needed to test and revise their solutions, and conducting the testing of their solutions. The process of *Visualizing* had a very low occurrence during this phase and was only employed for less than 10 seconds on average. Additionally, only three participants were coded as employing the *Experimenting* process for less than a minute each, which is the reason why the average amount of time taken for this process was relatively short. However, as indicated earlier, the processes of *Testing* and *Experimenting* are very similar in their operation and may overlap in their definition. *Defining Problems*, *Creating*, and *Questioning/Hypothesizing* were also employed sparingly during the solution evaluation phase. Each of these processes had an average time of being employed for 21 seconds or less. The mean number of times the cognitive processes were used by the participants while constructing a solution to the engineering design problem, as well as the mean amount of time taken for each process, is reported in Table 16.

The mean participant data for the solution evaluation phase were utilized to determine the mean percentage of time taken employing each mental process. On

average, over 29.8% of the participant's solution evaluation time was dedicated to the process of *Testing*, 12.2% of their time was taken *Managing* their testing procedure and revision process, 11.7% of their time was dedicated to *Analyzing* the effectiveness of their solution, 10.3% of their time was taken employing the *Modeling/Prototype Constructing* process to improve their solutions, and 10.1% of their time was devoted to *Communicating* their testing results. The processes of *Visualizing*, *Creating*, *Defining Problems*, *Experimenting*, and *Questioning/Hypothesizing* were employed for less than 1% of the participants' solution evaluation time. Figure 4 provides a complete graphical representation of the average percentage of time taken for each process during the solution evaluation phase.

Table 16

Mean Total Cognitive Processes Used in the Solution Evaluation Phase of the Engineering Design Activity

Solution Evaluation Phase					
Code	**$\bar{x}$ Times Used**	**$\bar{x}$ Amount of Time**	**Code**	**$\bar{x}$ Times Used**	**$\bar{x}$ Amount of Time**
AN	22.125	04:51.2	ME	6.000	00:53.6
CM	18.125	04:10.5	MO	0.000	00:00.0
CP	5.750	00:48.8	MP	10.000	04:15.1
CR	3.625	00:22.2	OB	19.625	03:09.6
DE	6.000	01:24.7	PR	7.750	00:48.2
DP	1.250	00:17.8	QH	3.250	00:21.1
EX	1.000	00:15.4	TE	28.250	12:18.9
ID	16.250	02:13.3	VI	1.500	00:07.5
MA	20.000	05:02.9	**TOTAL**	170.500	41:21.1

Note. $\bar{x}$ represents the sample mean.

Overall Engineering Design Session

Data from the three phases of the engineering design process were utilized to

calculate the average number of times each cognitive process was used and the average amount of time that was taken employing each process by the participants during the entire engineering design session. These data reported that the average amount of time taken to complete the engineering design challenge was 1 hour, 50 minutes, and 35.8 seconds. *Model/Prototype Constructing* was employed the most during the entire engineering design session, followed by *Analyzing* and then *Managing*. The least-used processes were *Computing* and *Experimenting*. The mean numbers of times each cognitive process was used by the participants during the entire engineering design problem solution, as well as the mean amount of time taken for each process are reported in Table 17.

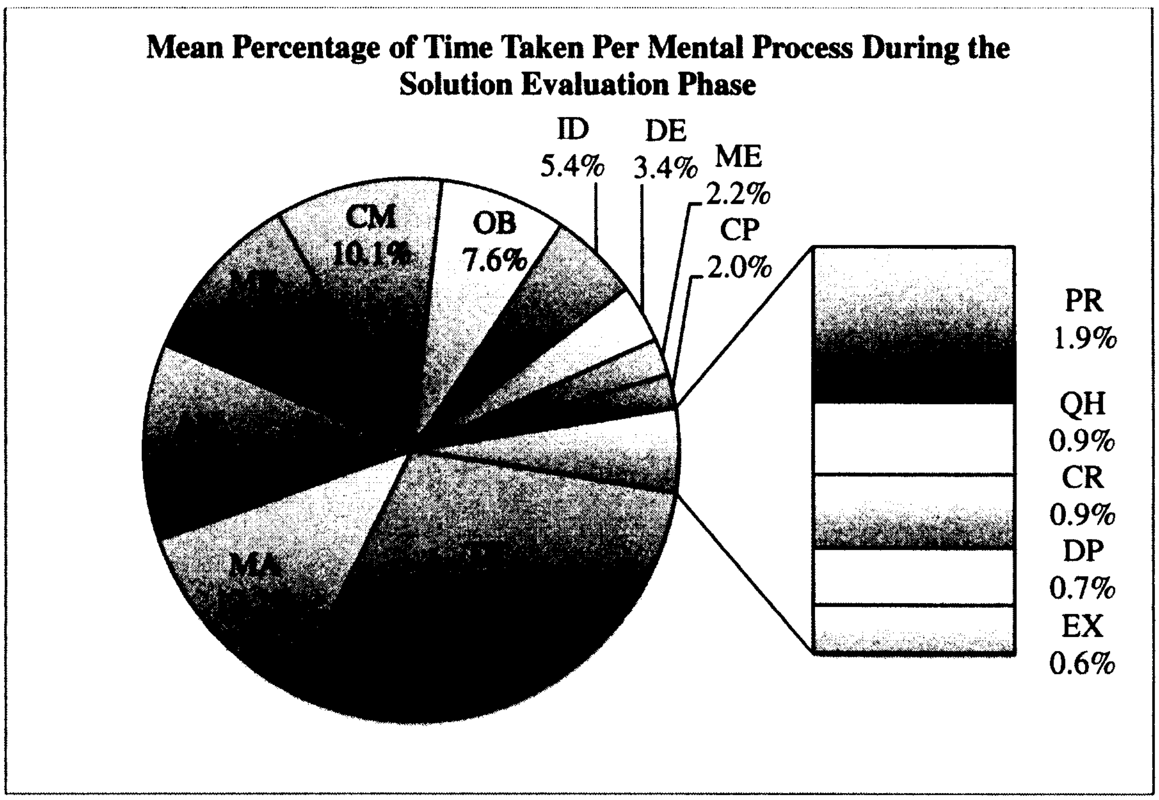


Figure 4. Mean percentage of time taken per mental process during the solution evaluation phase.

The data from the three phases of the engineering design process were also utilized to determine the mean percentage of time taken for each process during the complete engineering problem-solving session. On average, over 23.3% of the participants' time was devoted to employing the process of *Model/Prototype Constructing*; 15.8% of their time was used *Analyzing* their research and the effectiveness of their solution; 13.9% of their time was consumed by *Managing* their problem solving process and coordinating the necessary tools and materials for designing, constructing, testing, and revising their solution; and 11.1% of their time was employed in the *Testing* process. The processes of *Computing* and *Experimenting* were employed for less than 1% of the participants' time. A complete graphical representation of the average percentage of time used for each process during the entire engineering design session is reported in Figure 5.

Table 17

Mean Total Cognitive Processes Used Throughout the Engineering Design Activity

Entire Engineering Design Session					
Code	**$\bar{x}$ Times Used**	**$\bar{x}$ Amount of Time**	**Code**	**$\bar{x}$ Times Used**	**$\bar{x}$ Amount of Time**
AN	49.625	17:27.5	ME	16.000	02:51.1
CM	33.125	06:30.5	MO	1.125	00:09.8
CP	6.125	00:52.5	MP	47.875	25:49.8
CR	18.250	02:54.9	OB	31.375	04:48.5
DE	27.750	08:00.8	PR	30.250	02:30.2
DP	7.125	02:12.6	QH	16.000	02:05.9
EX	3.125	00:49.3	TE	28.500	12:20.0
ID	18.500	02:21.8	VI	25.625	03:32.5
MA	56.500	15:24.8	**TOTAL**	416.875	1:50:35.8

Note. $\bar{x}$ represents the sample mean.

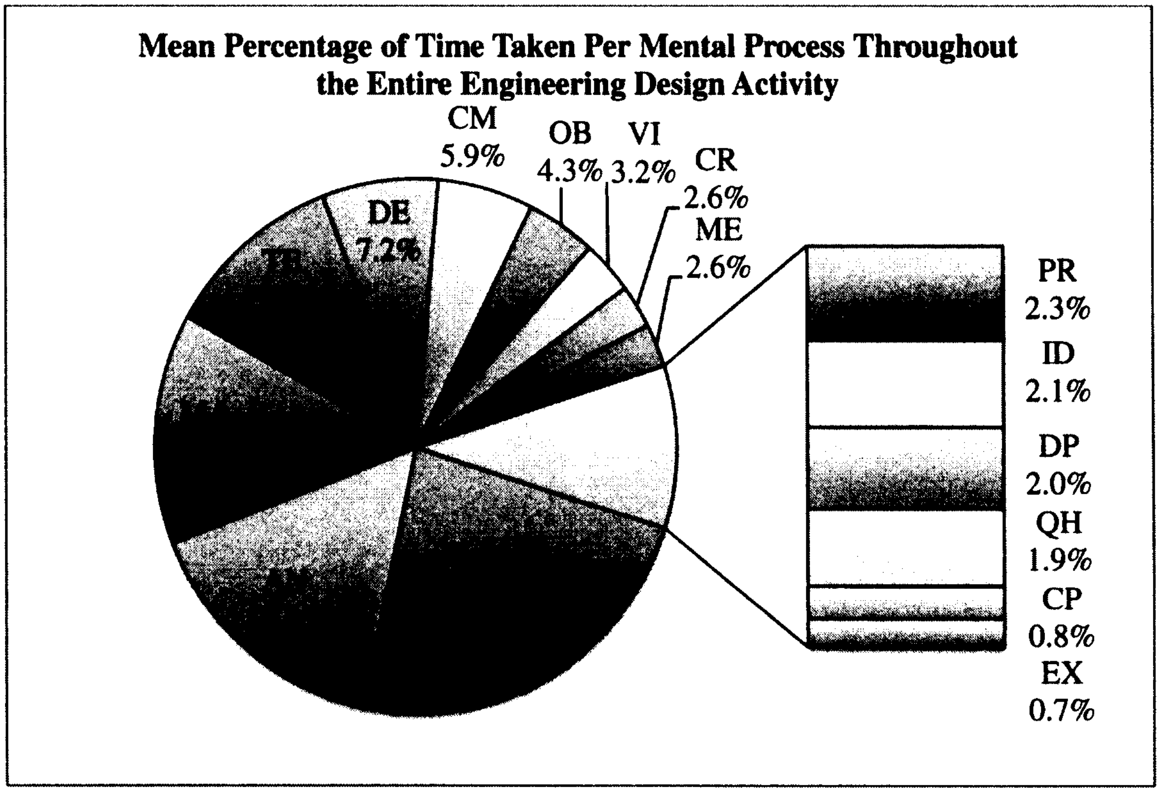


Figure 5. Mean percentage of time taken per mental process throughout the entire engineering design activity.

Research Objective 2

The second research objective for this study was to determine identifiers within student cognitive processes that can be possible indicators for successfully designing, constructing, and evaluating technological solutions. To achieve this research objective, the researcher gathered the results of the participants testing their designs. Each participant collected quantitative data on how well their solution to the clean drinking water problem reduced the turbidity of a contaminated water sample. This solution effectiveness information was used to determine participant ranking of success in solving the engineering design problem. The participant success ranking then enabled the researcher to compare the cognitive processes of the top two performing participants and

the bottom two performing participants.

Participant 5 created the top-performing solution, which reduced the turbidity of the water sample to 0.06 Nephelometric Turbidity Units (NTUs). Water is visibly turbid at levels above 5.0 NTUs and the standard for drinking water is 0.5 NTUs to 1.0 NTU. Participant 8 generated the second best performing solution, which reduced the turbidity of the water sample to 1.60 NTUs. Both of these participants reduced the turbidity of the water sample to a level considered suitable for drinking water. Participants 2 and 3 generated the least effective solutions, which resulted in a water sample with a turbidity level well above the level suitable for drinking water. These two participants were not observed taking time to revise and re-test their prototype, which seemed to limit their opportunity for improving the effectiveness of their solutions. A full report of the participant testing data used for determining their solution effectiveness ranking is reported in Table 18. Additionally, a design summary of each participant's solution can be found in Appendix I.

Using the participant solution effectiveness rankings, the researcher compared cognition data between the top two performing participants (Participant 5 and Participant 8) and the bottom two performing participants (Participant 2 and Participant 3). This comparison helped identify differences in the cognitive processes between these four participants, which may be potential indicators for creating better performing solutions. Additionally, the participants were evaluated on their use of the engineering design process by both the researcher and the classroom teacher using the engineering design process rubric in Appendix E. The rubric categories were aligned to the solution design, solution construction, and solution evaluation phases of the engineering design problem-

solving activity. The two top-performing participant scores and cognitive processes were averaged, as well as the scores and cognitive processes of the two bottom-performing participants. This information was used to determine differences between the cognitive processes used by the top-performing participants and the bottom-performing participants.

Table 18

Participant Water Turbidity Test Results

	Participant							
Test Iteration	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Initial	482.60	666.50	311.10	239.60	666.50	320.30	666.50	336.30
First Run	75.20	76.20	94.40	3.50	9.80	33.50	12.10	8.70
Second Run	60.80	56.60	73.90	5.10	5.50	92.60	8.50	7.30
Revision First Run	58.40	-	-	-	0.06	16.30	8.30	5.30
Revision Second Run	8.90	-	-	-	-	11.90	-	1.60
Revision Third Run	-	-	-	-	-	-	-	2.00

Note. Participant test results are reported in Nephelometric Turbidity Units (NTUs). Water is visibly turbid at levels above 5.0 NTUs and the standard for drinking water is 0.5 NTUs to 1.0 NTU.

The individual cognitive process data were used to calculate the mean time each mental process was employed and to determine the mean amount of time taken for each process by both the top- and bottom-performing participants. The top-performing participants employed the 17 mental processes an average of 504 times for a total of 1 hour, 1 minute, and 26.3 seconds throughout the whole engineering design session. The bottom-performing participants only employed the 17 mental processes 277 times for 45 minutes and 26.4 seconds. Throughout the engineering design session, the top

participants employed the processes of *Analyzing* ($\bar{x}$ = 22 minutes and 38.5 seconds) and *Testing* ($\bar{x}$ = 12 minutes and 18.9 seconds) for the most amount of time and employed *Experimenting* ($\bar{x}$ = 1 minute and 12.8 seconds) and *Defining Problems* ($\bar{x}$ = 1 minute and 24.8 seconds) the least. The bottom-performing participants employed the processes of *Modeling/Prototype Constructing* ($\bar{x}$ = 31 minutes and 26.7 seconds) and *Analyzing* ($\bar{x}$ = 16 minutes and 42.9 seconds) for the most amount of time and employed *Computing* ($\bar{x}$ = 27.1 seconds) and *Experimenting* ($\bar{x}$ = 48.7 seconds) for the least amount of time. A complete report of the mean number of times each cognitive process was used, as well as the mean amount of time taken for each process by both the top- and bottom-performing participants are provided in Table 19.

Table 19

Mean Cognitive Process Data for the Top- and Bottom-Performing Participants

	Top 2 Performing-Participants		**Bottom 2 Performing-Participants**	
Code	$\bar{x}$ **Times Used**	$\bar{x}$ **Amount of Time**	$\bar{x}$ **Times Used**	$\bar{x}$ **Amount of Time**
AN	68.00	22:38.5	28.00	16:42.9
CM	51.00	11:28.9	17.50	03:34.8
CP	9.50	01:50.1	3.50	00:27.1
CR	15.00	02:30.2	14.00	02:40.9
DE	37.00	09:09.2	19.00	08:50.6
DP	7.50	01:24.8	5.00	03:03.2
EX	4.50	01:12.8	3.50	00:48.7
ID	25.00	04:09.6	11.00	00:57.8
MA	64.50	17:23.6	35.00	13:22.0
ME	22.00	03:35.7	14.50	04:10.7
MO	3.00	00:28.1	0.00	00:00.0
MP	34.50	10:54.6	38.00	31:26.7
OB	45.00	07:03.2	19.00	03:51.7
PR	34.50	03:49.9	20.00	01:42.6
QH	16.00	02:03.3	12.00	02:14.2
TE	50.50	20:40.7	11.00	06:15.9
VI	16.00	01:32.8	26.00	05:16.3
Total	503.50	1:01:26.3	277.00	45:26.4

Note. $\bar{x}$ represents the sample mean.

The mean data from the top- and bottom-performing participants were utilized to determine the mean percentage of time taken for each process by both groups during the complete engineering design session. The top participants devoted the majority of their problem-solving time to employing the cognitive process of *Analyzing* (18.6%), to *Testing* (17.0%) their solutions, to *Managing* (14.3%) their problem-solving process, and to *Communicating* (9.4%) their designs/results. However, the bottom participants took the majority of their problem-solving time employing the processes of *Model/Prototype Constructing* (29.8%), *Analyzing* (15.9%), *Managing* (12.7%), and *Designing* (8.4%). The major differences between these two groups are the percentages of time taken employing the processes of *Testing* and *Model/Prototype Constructing*. The top participants took 17.0% of their time *Testing* and re-*Testing* their solutions, while the bottom participants took 5.9% of their time employing this mental process. This difference is a reflection of how the bottom-performing participants were not observed iteratively testing, improving, and re-testing their solutions. Additionally, the bottom participants were observed focusing more of their time on constructing their prototypes, while the top participants were observed taking 8.9% of their time for employing the process of *Model/Prototype Constructing*. A complete graphical comparison of the average percentage of time taken for each process used by the top- and bottom-performing participants during the entire engineering design session is reported in Figure 6.

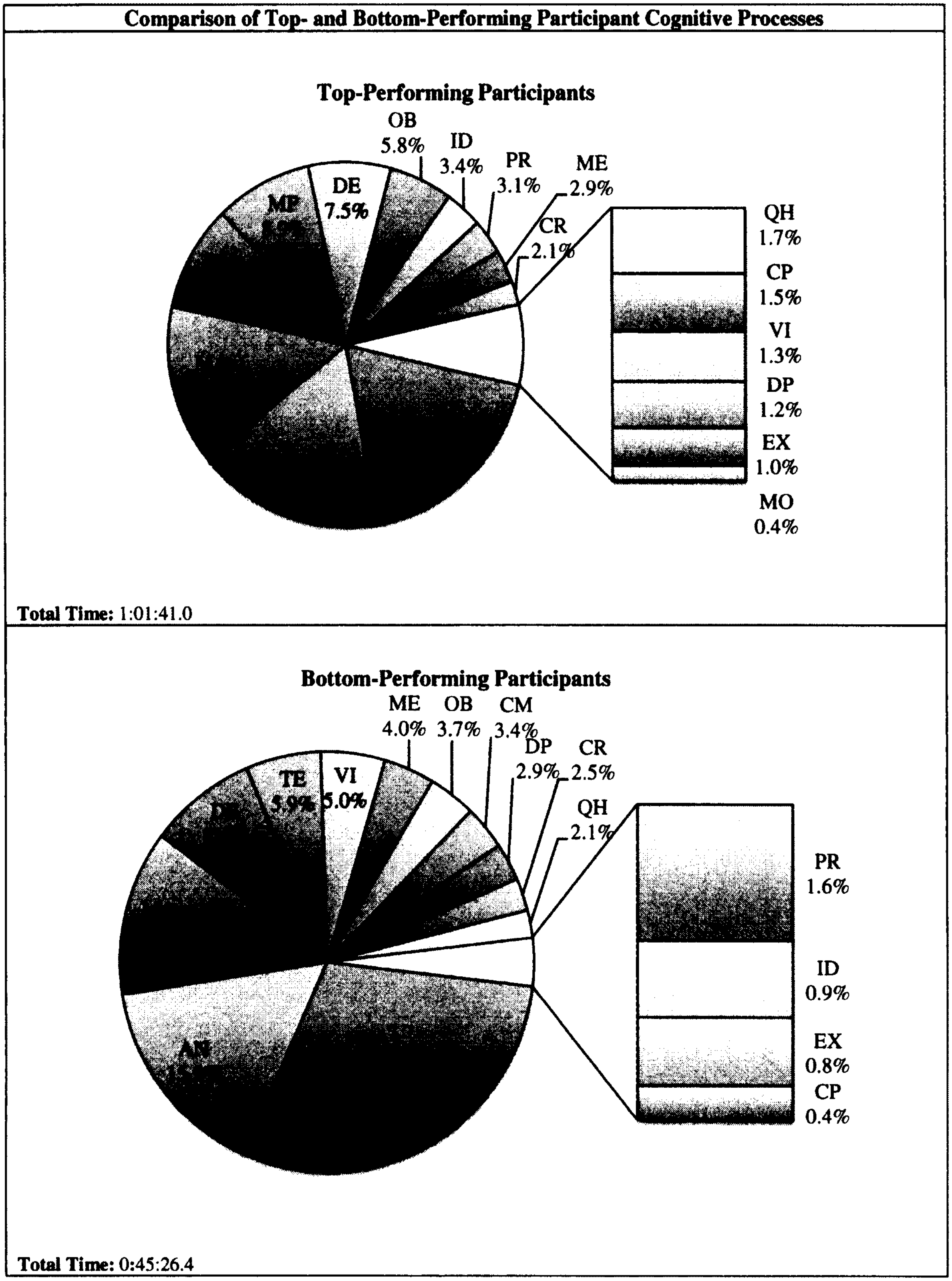


Figure 6. The comparison of top- and bottom-performing participant cognitive processes.

The data for the top- and bottom-performing participants were also analyzed and compared at the three different phases of the engineering design process. The data analysis indicated that the top-performing participants took 7 minutes and 31.2 seconds more than the bottom-performing participants during the solution design phase. During this phase, the top participants employed the different mental processes 66.5 more times than the bottom-performing participants. The top participants devoted 9.2% more of their time *Communicating* than the bottom participants. The top participants also took 8.1% more of their solution design time employing the *Managing* process than the bottom-performing participants. However, the bottom-performing participants dedicated 8.1% more of their solution design time to *Defining the Problem* and 3.4% more time *Questioning/Hypothesizing*. Furthermore, the participants' evaluations using the engineering design process rubric (see Appendix E for the full rubric) indicated that the top-performing participants scored the same as the bottom performing participants on the category of *Researching Current and Past Solutions*. However, the top-performing participants scored 55% higher in the category of *Multiple Solutions Considered* and 35% higher in the *Design Justification* category.

During the solution construction phase, the bottom-performing participants took 38 minutes and 15.6 seconds longer creating their solution than the top-performing participants. However, the percentage of time taken per mental process was very similar between both groups. Furthermore, the participant evaluations using the engineering design process rubric (see Appendix E for full rubric) indicated that the top- and bottom-performing participants received very similar scores during this phase. The top participants scored a total of 10% higher than the bottom participants on the three

categories of *Material Choice*, *Product Durability*, and *Product Ease of Setup* combined.

During the solution evaluation phase, the top-performing participants took 46 minutes and 44.2 seconds more time assessing and improving their solutions than the bottom-performing participants. The bottom-performing participants had 207.5 fewer total times employing the 17 different mental processes than the top-performing participants. The top participants expended a greater amount of time using the *Model/Prototype Constructing* process during this phase than the bottom-performing participants. Additionally, the participant evaluations using the engineering design process rubric (see Appendix E for full rubric) indicated that the top participants scored 50% higher in the *Filtration Performance* category, 20% lower in the *Time Performance* category, 15% higher in the *Prototype Testing* category, 50% higher in the *Prototype Revision* category, 25% higher in the *Engineering Documenting* category than the bottom-performing participants. A complete comparison between the top- and bottom-performing participants at each phase of the design process is provided in Figure 7.

Research Objective 3

The third research objective for this study was to create a conceptual engineering design problem-solving model based on the participants' actions and thoughts for the purpose of informing the teaching and learning of problem-solving skills. To achieve this research objective, the researcher created a graphical representation of each participant's overall process from the participant observations to show a spectrum of the different processes each employed while completing the engineering design problem.

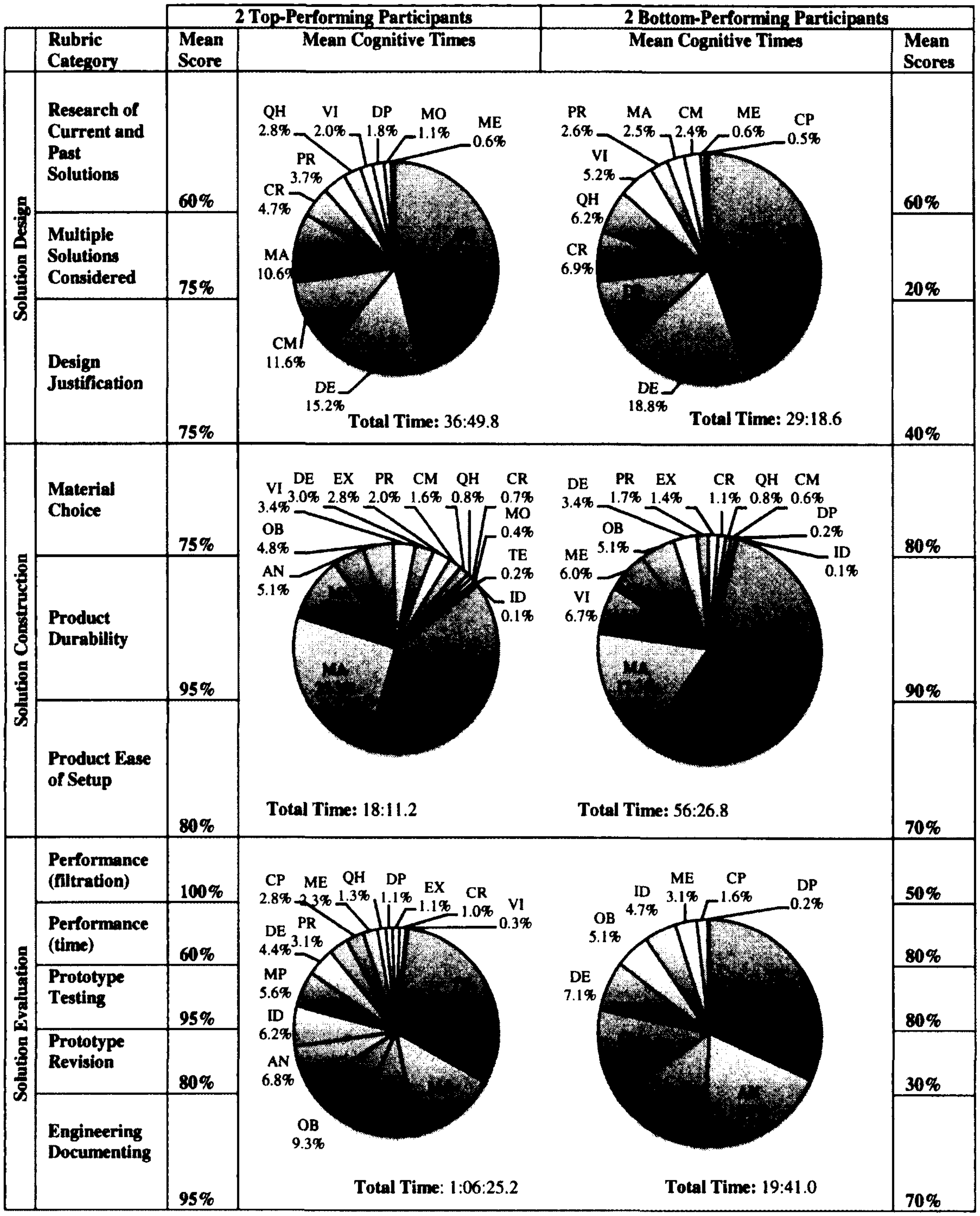


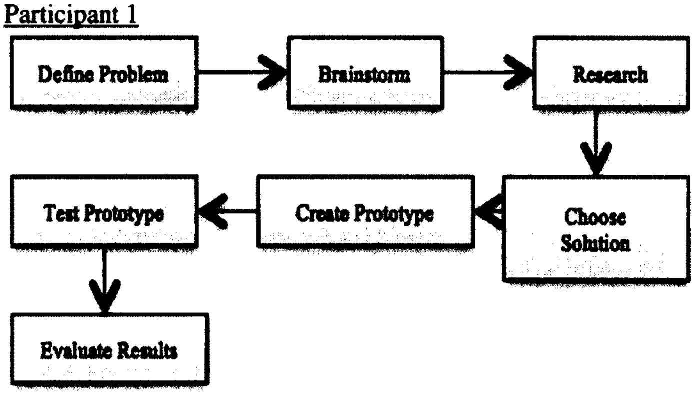
Figure 7. The comparison between participant scores and cognitive processes.

Additionally, the participants were tasked to create their own mind map of the processes they believed they used to solve the challenge. These mind maps were

collected to aid in the generation of the final conceptual model. The participant mind maps are presented in Figure 8 and 9. The participants mind maps combined with the researcher generated graphical representation of each participants' process, enabled the identification of trends in the various steps and cognitive processes used as the participants completed the problem-solving activity. These trends supported the determination of common themes related to the actual engineering design process that the participants used. This information, combined with the participant cognitive process data, allowed the researcher to develop a final conceptual model to use for improving the student problem solving abilities.

Participants 1 - 4 Reported Engineering Design Process

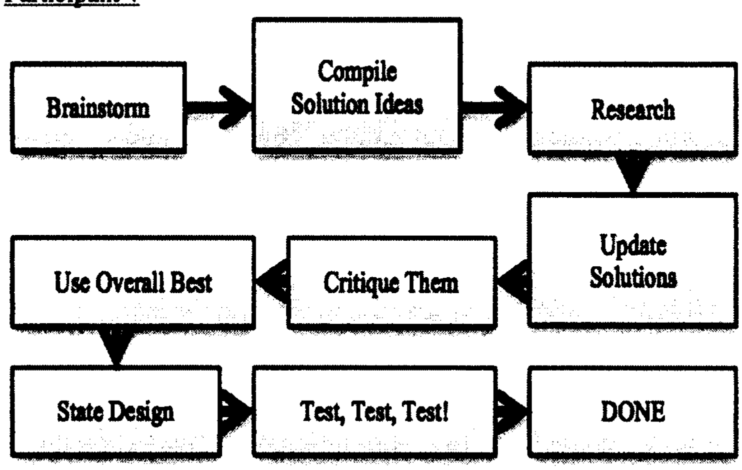
Participant 1



Participant 2

I began by researching on Google. I then sketched a few ideas in my notebook. Then I looked at my materials; I thought of my final solution and began building it. Once finished I began testing it. I filtered the water twice and checked the NTU each time. Afterwards I did my solution justification.

Participant 4



Participant 3

First research to see what has been done before and based my idea off of that. Then I designed and built my design.

Figure 8. Participant 1-4 reported engineering design process.

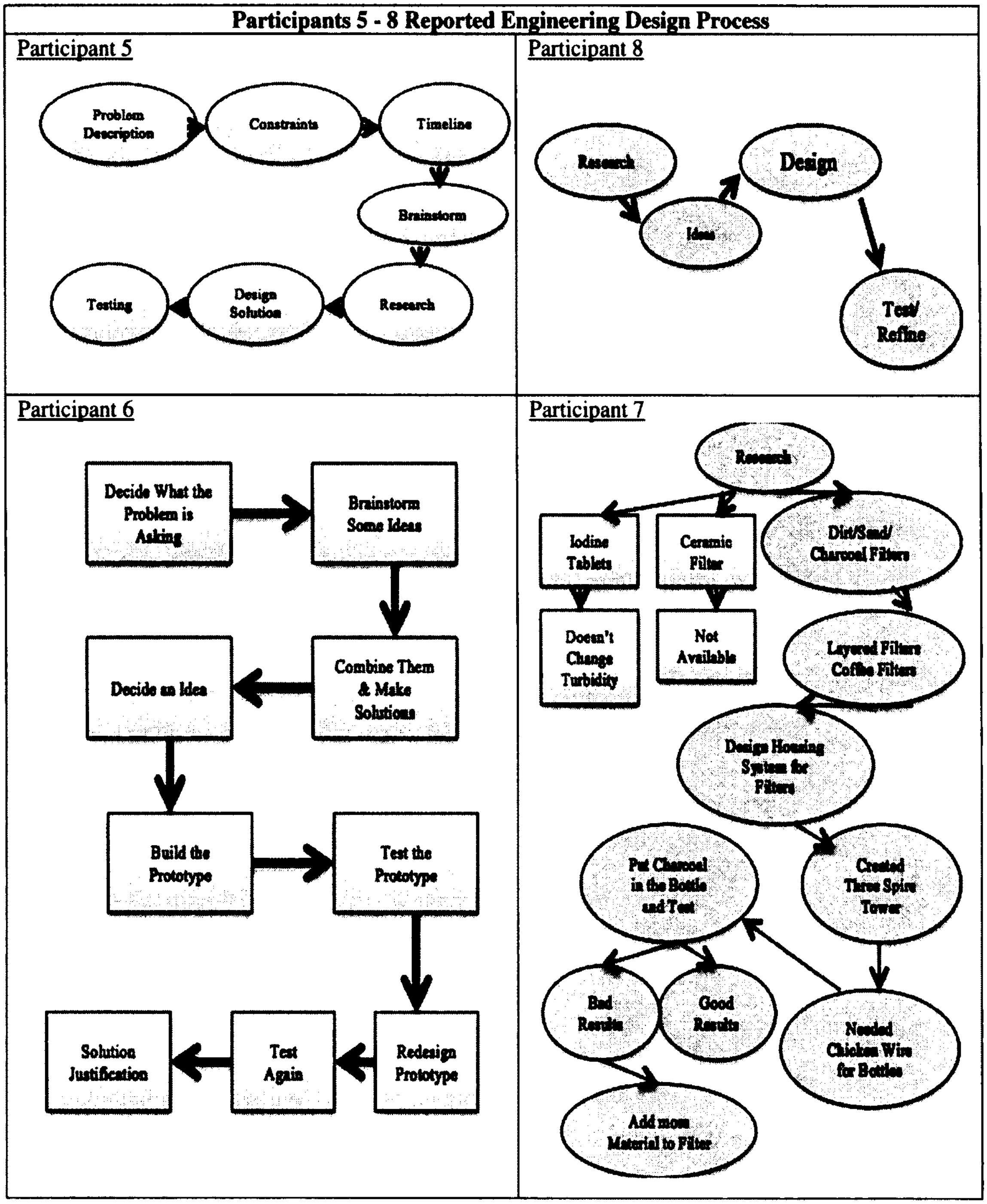


Figure 9. Participant 5-8 reported engineering design process.

The researcher first created generalized models of the approaches the participants took to solve the design problem by overlaying the graphical representations of each participant's engineering design process. Through this procedure the researcher identified

two distinctly different approaches enacted by the participants. One approach was more sequential, while the other process was more nebulous or nonsequential.

The researcher determined that Participants 1, 5, and 8 followed a sequential, logical, and systematic approach for solving the engineering design problem and Participants 2, 3, 4, 6, and 7 followed a more nebulous or nonsequential trial-and-error approach for solving the problem. The sequential participants developed a solution to the problem by carefully progressing from one step of the design process to the next step until a quality solution was reached. Furthermore, these participants utilized a proactive approach to solving the engineering design problem by planning for potential issues with their solutions and taking actions to address these issues before they happened.

The nonsequential participants were chaotic in their approach to solve the given problem, often moving back and forth between the various steps of the design process. Additionally, the nonsequential participants were more reactive in their approach to solve the design problem and attended to issues with their solutions when they occurred and did not plan to address these issues before building their solution prototype.

As Participants 1, 5, and 8 moved through the solution design, solution construction, and solution evaluation phases of the design process, they were observed as employing the cognitive processes of *Managing* and *Communicating* to control the inputs of their process, direct their actions, and document/share the necessary information. The participants then moved through six identified steps in the design process in a logical order. These steps included *Defining the Problem*, *Conducting Research*, *Developing a Solution*, *Constructing a Solution*, *Testing the Solution*, and *Communicating the Results.* These participants first defined the problem at hand and then determined a plan to solve

it. Next, they began to conduct research based on questions or hypothesizes they developed by using their own prior knowledge. The participants then employed the mental processes of *Questioning/Hypothesizing*, *Analyzing*, *Predicting*, *Visualizing*, and *Creating*, as learning attempts, to enable them to move from conducting research to creating a design for their solution. Afterward, they constructed their solutions by employing the mental processes of *Measuring*, *Experimentation*, *Visualization*, and *Predicting*. Once their solution was created, they began testing the effectiveness of their solution while employing the mental processes of *Testing*, *Observing*, *Measuring*, *Computing*, *Interpreting Data*, and *Analyzing*. These participants then went back to the design steps of the process to refine their design and then retested it. Once they were satisfied with the testing results, they communicated their outcomes.

Conversely, Participants 2, 3, 4, 6, and 7 were observed compartmentalizing each step of the design process and isolating each step from the next consecutive and logical step. Their approach was observed as being more centered on prototype development than the actual definition and solution of the problem. As these participants moved through their design process, they were observed employing the overarching mental processes of *Managing* and *Communicating* to control the inputs of their processes, directing their actions, and sharing necessary information. The participants then moved randomly between six identified and distinct steps of *Defining the Problem*, *Conducting Research*, *Developing a Solution*, *Constructing a Solution*, *Testing the Solution*, and *Communicating the Results* to design a solution to the problem, while utilizing four underlying mental processes of *Analyzing*, *Designing*, *Model/Prototype Constructing*, and *Testing*. These participants then went through a nonsequential and unstructured

process of moving through these steps, while enacting cognitive pathways of connecting mental processes to move from one underlying mental process to another. As these participants became satisfied with their design, they then communicated their results.

The researcher took participant observations and consolidated their processes into two approaches (sequential and nonsequential) used to solve the design problem. These approaches provide a general illustration of the two different styles the participants followed to solve the engineering design problem. These approaches are not identified as idealistic problem solving method but are actually the processes that participants followed when confronted with an engineering design problem. In both the sequential and nonsequential approaches, participants employed the mental processes of *Managing* and *Communicating* as overarching processes for facilitating and controlling their overall design procedure.

The problem solving approach in both models consisted of six distinct steps: *Defining the Problem*, *Conducting Research*, *Developing a Solution*, *Constructing a Solution*, *Testing the Solution*, and *Communicating the Results*. The sequential participants followed these steps in a logical and chronological manner to proceed to a desired end product. The nonsequential participants followed a varied approach centered on prototype construction. The nonsequential participants isolated the steps of the design process and moved between them in a random manner. The sequential participants enacted a direct progression of mental processes to move from one step to another, while the nonsequential participants used four underlying mental processes of *Analyzing*, *Designing*, *Model/Prototype Constructing*, and *Testing* to achieve an end product. The nonsequential participants also employed random networks of mental processes to move

back and forth between each step. The sequential participants followed a plan for their processes, while the nonsequential participants were reactive, which led to a more random approach to a solution. Additionally, the sequential participants followed logical steps to refine their solutions while the nonsequential participants did not complete multiple iterations of testing and redesigning. Figures 10 and 11 illustrate the two different approaches to engineering design followed by the participants. The researcher then combined these two approaches with the participant cognition and solution effectiveness data to generate a conceptual model of engineering design recommended for teaching and understanding student problem solving abilities. The conceptual model of engineering design can be found in Chapter Five.

Summary

Chapter IV collected and analyzed data from advanced pre-engineering students completing an engineering design challenge for the purposes of meeting the three research objectives of this study. The data analysis provided a report on the cognitive processes that the study participants employed throughout the engineering design problem-solving session, as well as, how much time was devoted to employing each design process. The reliability of these data were calculated and it was determined that the coding results achieved a high level of agreement and consistency between coders. The coded data were then utilized to compare and contrast the cognitive processes employed by the participants with the top-performing solution and the participants with the least effective solutions to identify possible mental process indicators for creating more successful solutions. Lastly, participant data were used to map the overall processes that each participant employed in attempting to solve the design problem. This

information led to the identification of two different approaches to solve engineering design problem, which has been used to create a conceptual model of engineering design to satisfy Research Objective 3.

Chapter V will provide a summary of the study and conclusions derived from the data provided in this chapter. Finally, Chapter V will conclude with recommendations based on the results of this study.

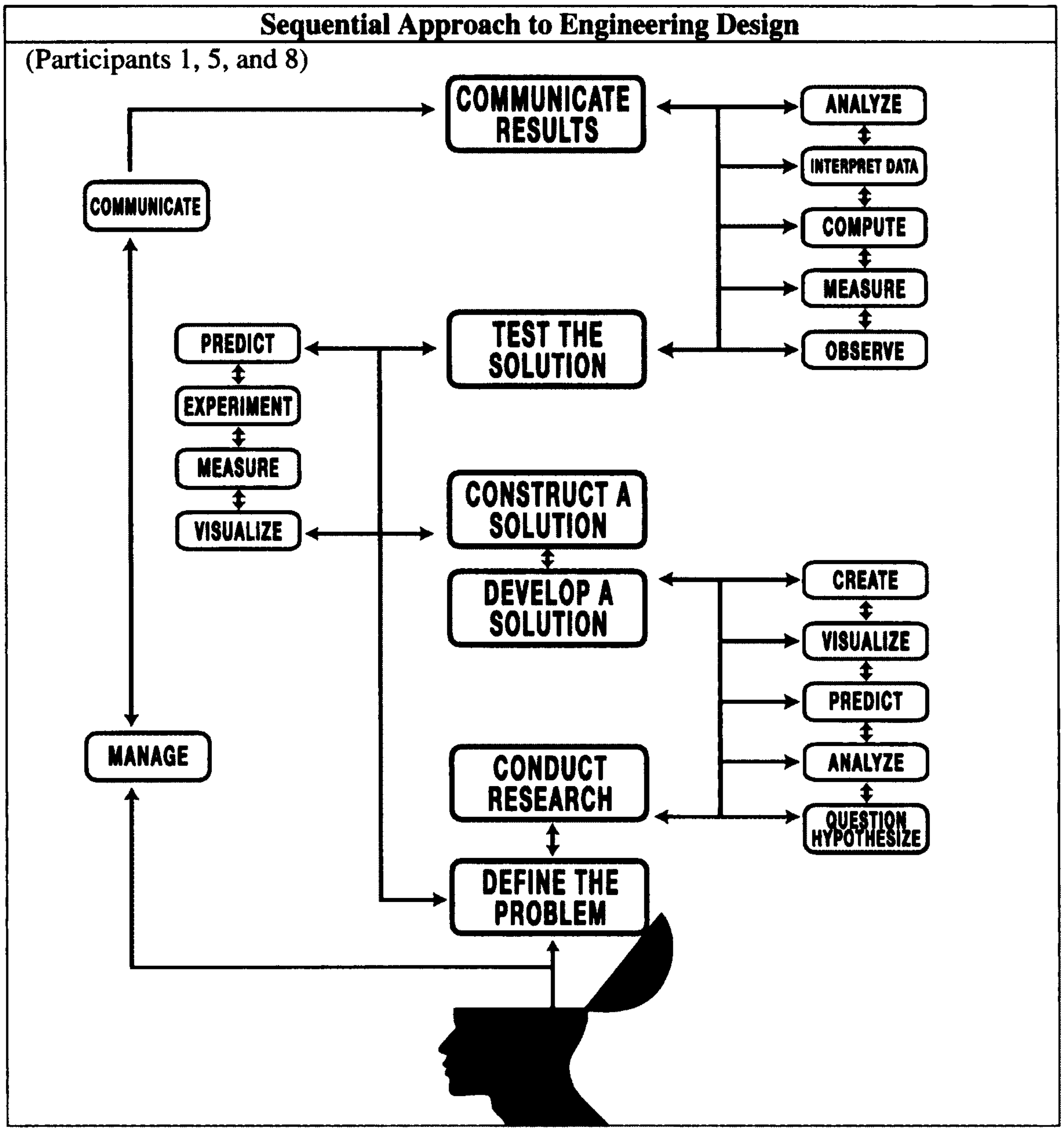


Figure 10. Sequential approach to solving engineering design problems.

Nonsequential Approach to Engineering Design

(Participants 2, 3, 4, 6, and 7)

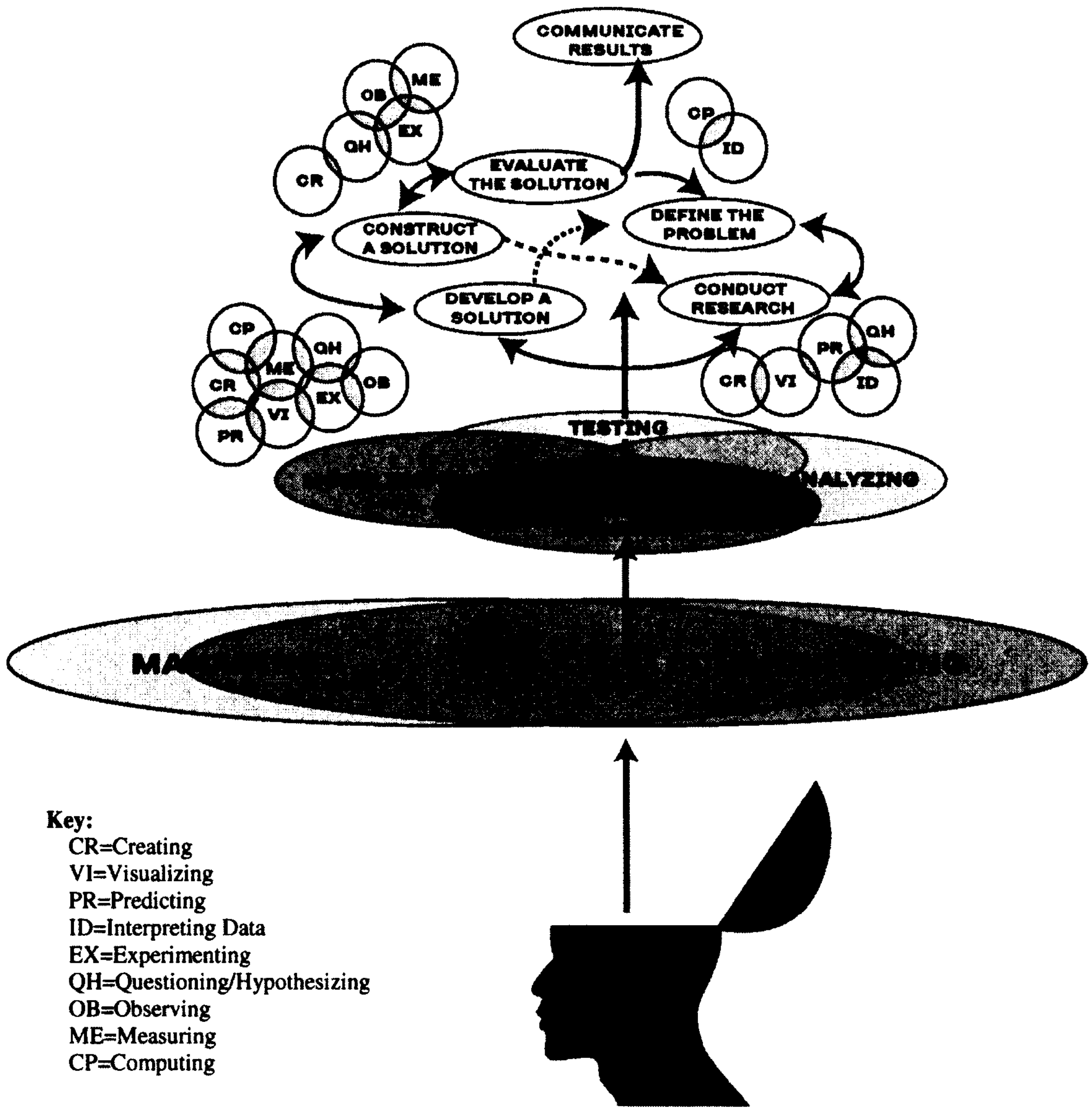


Figure 11. Nonsequential approach to solving engineering design problems.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The purpose of this chapter is to report the summary, conclusions, and recommendations of this study. This information was the result of a research study that collected data from eight advanced pre-engineering high school students from two schools in eastern West Virginia. These schools and students were chosen based on their high level of achievement in the *Project Lead the Way* pre-engineering program. The data collected included verbal and observational recordings, as well as design artifacts from participants engaged in solving an authentic engineering design challenge. Two coders independently coded these data to determine the cognitive processes students employed throughout the engineering design process and to achieve the study's research objectives.

Summary

The purpose of this study was to identify the cognitive processes used by advanced pre-engineering students to solve complex engineering design challenges. This research was undertaken to gain a better understanding of how pre-engineering high school students of an experienced level have learned to engineer viable solutions to problems from design conception to an end product for the purpose of improving student learning in technology and engineering education. Students in technology and engineering education classrooms are often taught to use an educator generated idealistic engineering design process to solve problems. However, the review of literature shows that it is unclear as to how people actually cognitively navigate solving a complex and multifaceted problem from beginning to end. Therefore, the first research objective for this study was to identify the fundamental cognitive processes students use to design,

construct, and evaluate operational solutions to engineering design problems. This objective was met by coding audio/video recordings of students' "thinking aloud" during a complete engineering design session lasting on average 1 hour, 50 minutes, and 35.8 seconds. The codes used in the data analysis were a set of 17 mental processes used in technological problem-solving, identified and validated by Halfin (1973) and revalidated by Wicklein and Rojewski (1998).

The second research objective was to determine identifiers within student cognitive processes for monitoring aptitude in successfully designing, constructing, and evaluating technological solutions. This research objective was achieved by comparing the cognitive processes used by the participants who created the most effective solutions to the cognitive processes used by the participants who created the least effective solutions. The purpose of this process was to highlight potential problem-solving cognition attributes used for producing more viable design solutions. Lastly, the third research objective was to create a conceptual technological and engineering problem-solving model integrating student cognitive processes for the improved development of student problem-solving abilities.

Research of this nature can be significant to the technology and engineering education profession because it can provide a better understanding of how pre-engineering high school students of a high experience level have learned to engineer viable solutions to complex problems from design conception through creating an end product. With greater understanding of student learning and cognition, educators can overcome the difficulty of planning and assessing students' abilities in solving authentic problems from start to finish.

According to Barak and Hacker (2011), the improvement of technology and engineering education depends heavily upon the role researchers and educators take in developing and utilizing an understanding of the mental strategies students use to solve technological problems. Kelley (2008) also states that enhancing the understanding of student engineering design cognitive processes is justified by the opportunity that it provides for improving the way technology and engineering curriculum and instruction are developed. Additionally, an understanding of student design cognition can help in the assessment of problem-solving abilities through technology and engineering coursework.

The United States education system has seen a growing emphasis on K-12 engineering education. This expanded attention can be attributed to the belief that engineering may help create a better educated populace and workforce to meet the need for high-demand careers in technology and engineering, as well as provide students with the skills necessary for economic success (National Research Council, 2009). According to the National Research Council (2014), there has been broad agreement among educational stakeholders that the teaching of science, technology, engineering, and mathematics (STEM) subjects in K–12 American schools must be improved to prepare students with the skills necessary for success in this century. Many of the concerns about STEM education tie to worries about the innovation capacity of the United States and its ability to compete in the global marketplace. Currently, engineering design education is seen as an approach to addressing these concerns because of its natural ability to tie mathematics and science together through solving authentic problems (National Research Council, 2009).

Engineering design problem-solving is now considered an essential component of

technology and engineering education curricula, much like scientific inquiry is to science education (NGSS Lead States, 2013). Therefore, problem-based learning is a necessity for technology and engineering education programs and can provide students with skills considered necessary for fostering innovation and economic success (NRC 2014). As a result, the *Next Generation Science Standards* have included engineering design standards; the *National Assessment of Educational Progress* has developed a *Technology and Engineering Literacy Assessment*; and the technology education profession has incorporated engineering design into its educational practices. However, the research base for cognitive sciences as they relate to engineering design is limited. In 2009, the National Research Council supported the idea that the development of K–12 engineering standards was not necessary due to the lack of cognitive research in the field. Additionally, Ritz and Martin (2012) highlighted research needs in the technology and engineering education profession determined by the world community, and the top need included increasing the understanding of student cognition. Therefore, the research objectives of this study have been developed to address these current research deficiencies.

The participants selected for this study were junior and senior high school students enrolled in the capstone course of the *Project Lead the Way* pre-engineering program. These participants were selected because the *Project Lead the Way* program is a standardized national model designed to prepare students for postsecondary engineering programs. Schools that implement this program must complete a rigorous certification process to ensure that all students enrolled in the program receive similar experiences (Project Lead the Way, 2013). To be enrolled in the capstone course, students must have

successfully completed a series of courses covering topics in engineering and problem-solving. Therefore, students selected were experienced in solving engineering design problems with a similar background but were still at an adolescent level of development. The selection of these participants was also based on three considerations provided by Middleton (2008). First, participants need to be at the appropriate stage of expertise for the proposed research objectives. In this case, the appropriate level was advanced pre-engineering students. The second consideration was to select participants who would normally be exposed to the type of problem that is under investigation in their everyday learning environment. The *Project Lead the Way* students are typically exposed to various forms of engineering problems throughout their program of study. Lastly, the participants were selected with the consideration that they had the verbal abilities to successfully "think aloud" and were comfortable in doing so.

The methodology used in this study included multiple forms of data collection. The participants were first given a survey to determine their prior experience with engineering and to develop a demographic description of the population. The participants were then presented an engineering design challenge to solve individually. While they completed the challenge, the participants verbalized their thoughts using an established "think aloud" method. These verbalizations were captured along with participant video recordings using point-of-view camera technology. Additionally, the participant design journals, design artifacts, solution effectiveness data sheets, and teacher evaluations were collected for analysis to help achieve the research objectives of this study. Two independent coders then evaluated the video/audio recordings using Halfin's (1973) 17 mental processes for technological problem-solving. The Observational Procedure for

Technology Education Mental Processes (OPTEMP) computer program created by Hill (1997) facilitated the coding process. The OPTEMP program enabled the coders to simultaneously view/listen to the video/audio recordings and code the data while automatically calculating the total number of times each mental process was employed, as well as the total amount of time used with each process. The coded data combined with the additional participant design data enabled the researchers to compare participants' actions and thoughts while building a conceptual model of engineering design.

There were limitations associated with this study. First, the data collected were limited to eight high school students in grades 11 and 12 who have completed at least three *Project Lead the Way* pre-engineering courses and were currently enrolled in the capstone pre-engineering course. The participants were purposefully selected from two high schools recommended by the state coordinator for engineering and technology education. Although the number of students studied was a limitation, the sample did allow for an analysis of the cognitive processes of experienced pre-engineering students. Another limitation of the study was that the collected data were regulated to student participants working alone to solve one specific engineering design challenge. These participants were tasked to work alone for the purpose of determining the way students individually managed the cognitive load in problem-solving. Lastly, the research was limited to the data coding and analysis by two coders using only the 17 mental processes for technological problem-solving identified by Halfin (1973). Therefore, the creation of the student engineering design model was limited to the observations of two coders and the researcher's findings.

Conclusions

Research Objective 1 was to identify the fundamental cognitive processes students use to design, construct, and evaluate operational solutions to engineering design problems. To achieve this objective, the participants were tasked to independently complete an engineering design challenge without assistance from an instructor. While completing this challenge, the participants employed all 17 of the mental processes identified by Halfin (1973). However, the mental process of *Modeling* was determined by the researchers to be too similar to the other codes of *Model/Prototype Constructing* and *Designing*. The inability to differentiate between these codes was also stated in the original work by Halfin (1973) to establish the 17 mental processes. As a result, the use of *Modeling* as a mental processing code was minimal and most of the actions that could be considered *Modeling* were coded as either *Designing* or *Model/Prototype Constructing*.

The average amount of time the participants took to complete this engineering design session was 1 hour, 50 minutes, and 35.8 seconds. The cognitive process of *Model/Prototype Constructing* consumed the most time during the design sessions, capturing an average of 23.3% of the participants' time. This information may illustrate how focused technology and engineering education students are on the actual building of their solution instead of completing an in-depth and well-thought-out solution design. This observation can also depict how technology and engineering curricula do not coincide with the practices of design and analytical modeling in the engineering profession. The next-most-used cognitive process was *Analyzing,* which consumed 15.8% of the participants' time on average. Researching and examining other solutions found on

various websites consumed much of the *Analyzing* mental processing time. *Managing* was the third-most-used process in engineering design with a mean of consuming 13.9% of the participants' problem-solving time. The majority of the *Managing* time was used directing participants' actions during the design session and organizing the inputs needed to build their solutions.

The least utilized processes during the design sessions were *Experimenting* (0.7%), *Computing* (0.8%), *Questioning/Hypothesizing* (1.9%), *Defining Problems* (2.0%), *Interpreting Data* (2.1%), *Predicting* (2.3%), and *Measuring* (2.6%). Of these minimally employed processes, *Computing, Measuring,* and *Interpreting Data* can be considered the most mathematical processes of all 17 as specified by Halfin (1973). The limited use of these mental processes may be a reflection of the curricula and instructional strategies utilized in technology and engineering education programs. Much like Kelley (2008) and Kelley, Brenner, and Pieper (2010) found in similar studies, students were limited in the use of mathematical thinking in designing, constructing, and evaluating their solutions. Although all of the participants completed Algebra I, Geometry, Algebra II, and Trigonometry/Pre-Calculus, and many completed college-level mathematics courses, they only devoted a small portion of time *Computing, Measuring,* and *Interpreting Data.* This information also coincides with a study conducted by Kelley and Wicklein (2009a), which found a low emphasis on mathematics and engineering sciences in technology education curricula. The time taken on these more mathematical mental processes still indicates a lack of emphasis on general mathematical practices, mathematical modeling, and mathematical analysis in technology

and engineering education, which was also noted by Kelley and Wicklein (2009b) in their examination on the content found in secondary technology education curricula.

The lack of *Measuring* observed during the participants design sessions can indicate another concern with technology and engineering programs. While designing and constructing solutions to the engineering design challenge, the participants took an average of 1 minute and 57.5 seconds *Measuring*. The minimal time spent *Measuring* may illustrate how little focus is placed on the quality of solution designs and the use of industry-quality materials found in technology and engineering education programs. Throughout the design process, participants frequently estimated the manipulation of materials used for their solutions and relied on the use of duct tape and hot glue to fix mistakes. Little attention was given to accuracy in measurements and to the quality of construction or aesthetics in the solution.

Experimenting was also a process used very sparingly among the participants. However, when it was utilized, it was observed that the participants developed new knowledge that they then applied to their solution designs. Most of the *Experimenting* time was used examining which materials worked better for different components of their solutions. Again, the minimal use of this process may indicate a low level of understanding of engineering and material sciences in their education.

When examining the participant data by the solution design, solution construction, and solution evaluation phases, participants used most of their time evaluating and refining their solution ($\bar{x}$ = 41 minutes and 21.1 seconds), followed by constructing the solution ($\bar{x}$=39 minutes and 45.7 seconds), and designing the solution ($\bar{x}$ = 29 minutes and 29 seconds). These data, coupled with the minimal use of the *Defining Problems*

process, could indicate students in these pre-engineering programs are more solution driven than problem driven. Participants took a limited amount of time planning their designs before beginning the construction of their solutions, which may be a reason why they needed more time to correct their solution to the design problem during the solution evaluation phase. This information can lead one to believe that technology and engineering education programs do not prepare students for the more analytical engineering careers but rather for hands-on "engineering technology" career pathways.

Each phase of the engineering design process required mental processes that were employed at a much greater rate than others. These processes could be considered underlying processes employed throughout the entire phase. During the solution design phase, *Analyzing*, which consisted of dissecting information to utilize in designing solutions, was employed the most in 41.1% during the participant's time on average. Additionally, *Designing* was utilized an average of 18.2% of the participant's solution design time, which may indicate that it is an underlying process used throughout this phase. *Model/Prototype Constructing* was utilized the most during the solution construction phase, as the participants took an average of 54.3% of their time building their solutions; and *Testing* was utilized the most during the solution evaluation phase. Therefore, it can be concluded that the processes of *Analyzing* and *Designing* are underlying mental processes for the solution design phase, *Model/Prototype Constructing* is an underlying mental process for the solution construction phase, and *Testing* is an underlying process for the solution evaluation phase. See Figures 12 through 14 for an illustration of the use of these mental processes during each phase of the design process.

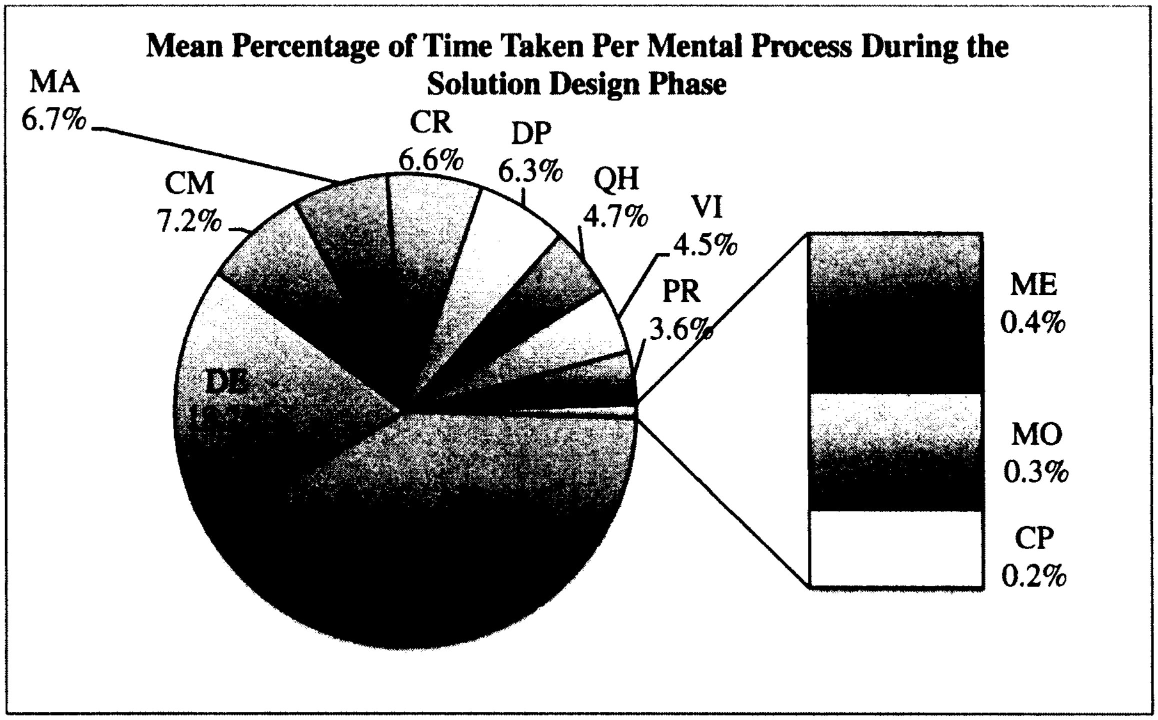


Figure 12. Mental process use during the solution design phase.

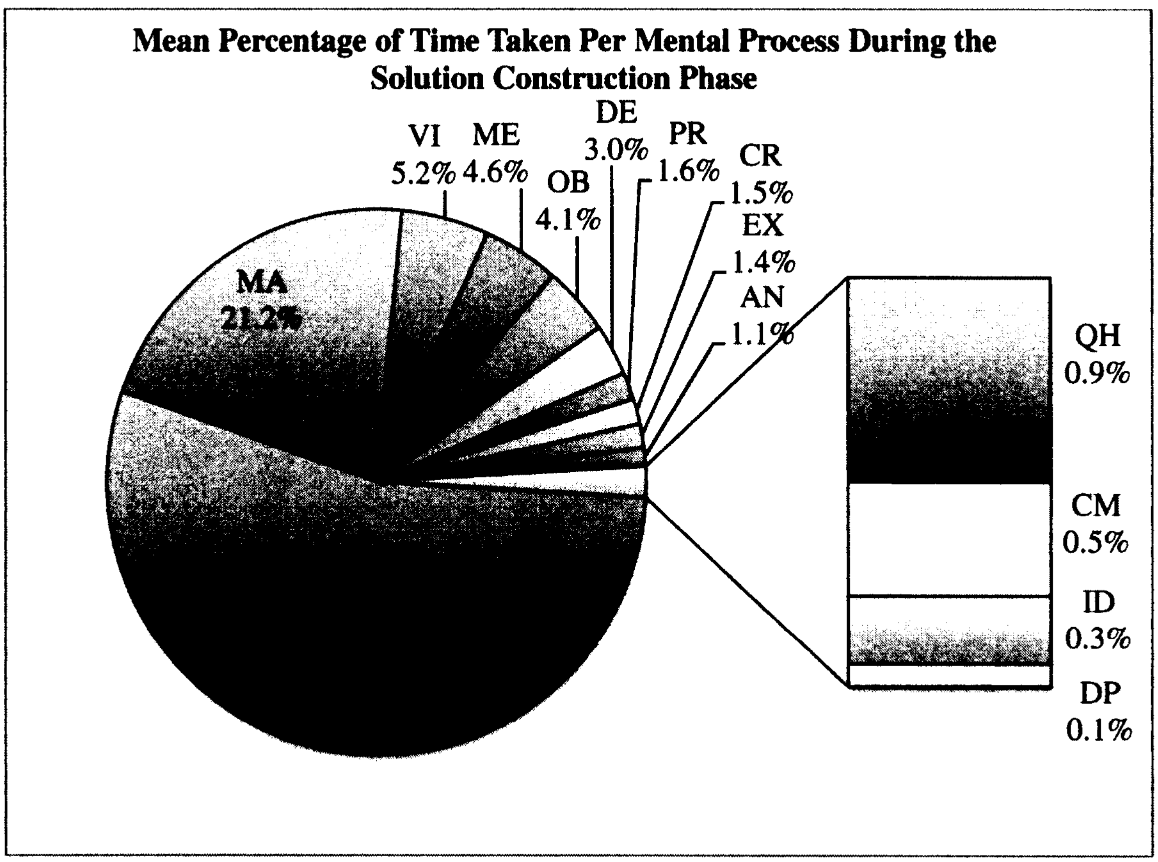


Figure 13. Mental process use during the solution construction phase.

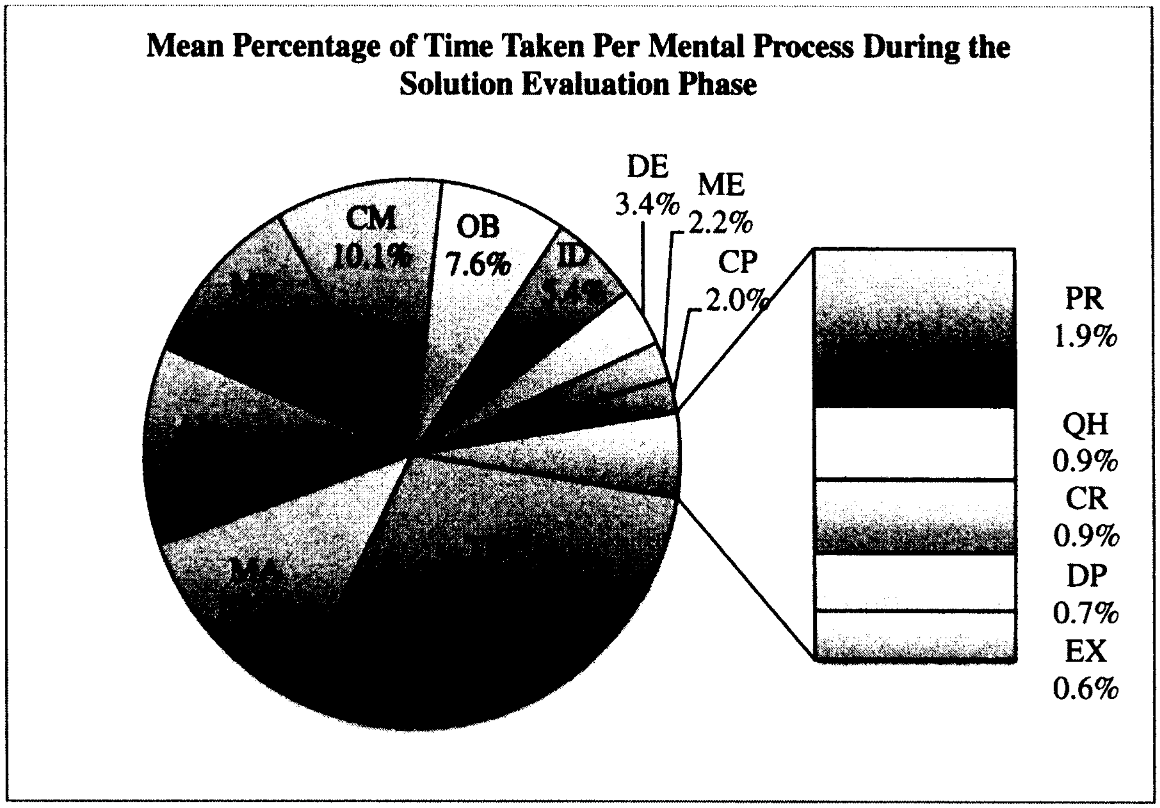


Figure 14. Mental process use during the solution evaluation phase.

During the solution evaluation phase, the majority of the participants did not employ the *Model/Prototype Constructing* process for a substantial amount of time. Most of the participants were satisfied with their initial design and did not use a significant amount of time interpreting their testing results for the purpose of refining their design. However, Participants 6, 7, and 8 did employ the *Model/Prototype Constructing* process during this phase a great amount more than the other participants. These participants took their time to test, improve their design, and retest multiple times and, therefore, enhanced their solution effectiveness. Because five out of eight participants did not take significant time to refine their designs, this may indicate a lack of emphasis in technology and engineering education curricula on utilizing testing data to improve solutions and

analytical modeling. See Appendix H for an illustration of the percentages of time used for each mental process by each participant during the solution evaluation phase.

When examining the coded data, one can observe a difference between the male and female participants. The female participants took more time during the solution design phase than the male participants. The females each took more than 41 minutes planning and designing their solutions, while the male participants took an average of 24 minutes and 47 seconds. Correspondingly, the female participants took a mere 23 minutes and 45.1 seconds, on average, constructing their solutions, while their male peers took an average of 45 minutes and 5.8 seconds. When examining the evaluation phase, the female participants took an average of 1 hour, 4 minutes, and 26.4 seconds, while the male participants took an average of 33 minutes and 39.3 seconds. Furthermore, the female participants took a much greater amount time *Communicating*, as they were more particular and thorough in documenting information in their engineering design journals.

Research Objective 2 was to determine identifiers within student cognitive processes for monitoring aptitude to successfully design, construct, and evaluate technological solutions. To achieve this objective, the participants' solution effectiveness was tested and the resulting data were used to rank which solution solved the problem most successfully. Next, an average of the data from the two participants with the top-performing solutions were compared to the averaged data from the participants with the bottom-performing solutions. Overall, the top-performing participants took more time solving the engineering design challenge than the bottom-performing participants and held a higher total frequency of employing the various mental processes. The top participants took 15 minutes and 59.9 seconds longer working to solve the problem and

employed 226 more total frequencies of the mental processes.

When examining the overall cognitive processes of the top- and bottom-performing participants, some noticeable differences can be seen. The top participants took 6.0% more of their time utilizing the *Communicating* process. Much of the additional *Communicating* time involved participants documenting their research and recording design alterations. This can be an indication that effective communication and documentation of the design process can enhance problem-solving capabilities. Additionally, the data suggests that the participants who were more thorough in planning, and directing their design processes by employing the *Managing* mental process were the ones who produced better solution results. As Wankat and Oreovicz (1993) state, novice problem solvers do not follow a specific plan and use a trail-and-error approach, while expert problem solvers formulate a specific strategy to solve the problem and closely monitors their solution progress. The novice strategy of trail-and-error is not considered to be an effective method and does not tend to help people become better problem solvers. Therefore, it is important to demonstrate the proper development and management of a consistent problem solving strategy (Wankat & Oreoicz, 1993).

Another noticeable difference can be seen among the processes of *Testing*, *Observing*, *Interpreting Data,* and *Experimenting*. These processes can be grouped together as more scientific actions within the design process, which can be used to improve the effectiveness of a solution. The top participants took 14 more minutes *Testing*, three minutes more *Observing*, three minutes more *Interpreting Data*, and almost a half a minute more of their time *Experimenting*. Conversely, the bottom participants utilized more of their time employing the *Model/Prototype Constructing* process as

opposed to the more scientific processes. The top participants enacted more iterations of testing their solutions, making observations, interpreting the outcome data, and then experimenting with design changes to improve their results. The bottom participants were focused on building the solution to the design problem and were satisfied after testing the solution once. This could show the need for technology and engineering curricula to reflect more professional engineering practices by emphasizing the importance of scientific methods of testing and analyzing the results for the purpose of optimizing solutions. A complete graphical comparison of the average percentage of time taken for each process used by the top- and bottom-performing participants during the entire engineering design session is reported in Figure 15.

When comparing the cognitive processes between the top two performing participants and the bottom two performing participants through the different phases of the design process, additional conclusions can be drawn. The top participants devoted more time to the solution design phase than the bottom participants. During this phase, the top participants expended more time *Analyzing*, *Communicating*, and *Managing,* while the bottom participants took more of their time *Defining Problems*, *Questioning/ Hypothesizing*, and *Creating*. The top participants devoted time to planning and managing their processes for solving the problem and were more direct in creating a design for a solution. The bottom participants needed more time to understand the problem and had many questions they needed answered in order to develop a solution idea. The top participants drew upon prior experiences with similar problems to develop a design, while the bottom participants needed more time to frame the problem and had to

be creative in developing solution ideas since they lacked prior knowledge and experience in these areas.

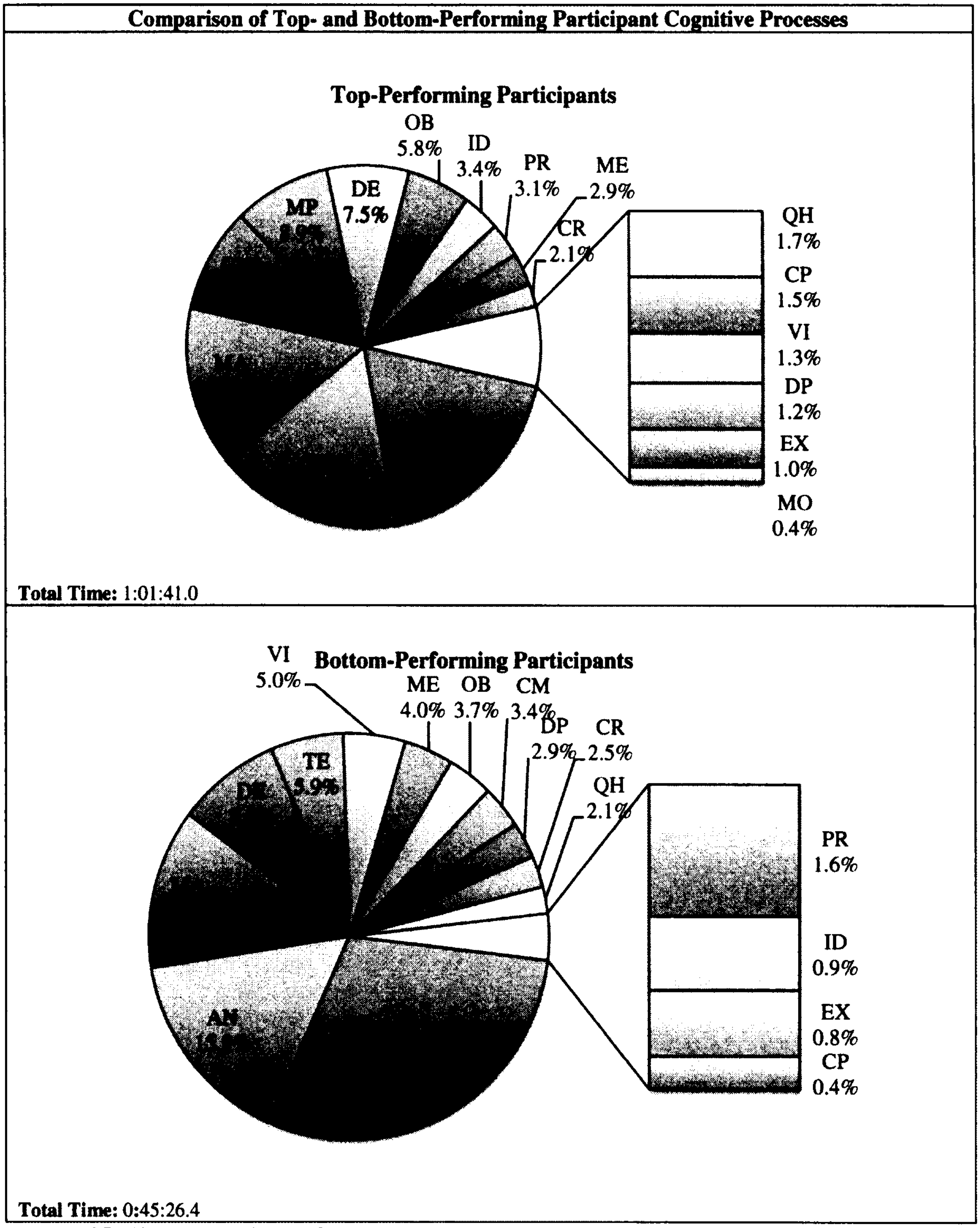


Figure 15. The comparison of top- and bottom-performing participant cognitive processes.

Additionally, the top participants were more purposeful in developing a design and the bottom participants were more creative in their design processes. These differences illustrate a need for emphasizing the importance of students establishing an initial plan for completing the problem-solving process, forming a concrete definition of the problem at hand, enacting more analytical ways of creating solution designs, and taking more time developing a solution.

During the solution construction phase, the comparison between the top- and bottom-performing participants did not indicate major differences in the percentages of time used while employing the different cognitive processes. However, there was a difference in the amount of time these two groups of participants expended during the construction phase in general. The top participants took over 38 minutes less time constructing their solution than the bottom participants. This could be an indication that, if more time were taken to plan and design the solution, then less time would be needed to actually construct the solution. The bottom participants were more focused on the hands-on aspect for the design process, while the top participants were focused on an analytical design for the solution. These differences may indicate which students are more adept for pursuing careers in theoretical engineering disciplines or engineering technology disciplines.

During the solution evaluation phase, the comparison between the top- and bottom-performing participants does indicate some differences. While the analysis of the percentages of time used for each cognitive process does not indicate major variances between these groups of participants, there are dissimilarities in the amount of time the two groups took to complete the evaluation phase in general. The top participants took

over 46 more minutes for the evaluation of their solutions. The data report that the top participants consumed over four minutes more *Communicating*, over one minute more *Designing*, almost one minute more *Experimenting*, over three minutes more *Interpreting Data*, over six minutes more *Managing*, almost four minutes more *Model/Prototype Constructing*, over five minutes more *Observing*, and approximately 14 minutes more *Testing*. Therefore, the evaluation phase would be an area of focus for improving a student's ability to create more viable solutions to an engineering problem. The data indicate that students need to employ a more significant amount of time testing their designs, observing the outcomes, interpreting the resulting data, experimenting with design modifications, retesting their solutions, and completing multiple iterations of this redesign cycle. Wankat and Oreovicz (1993) support the idea of focusing on in depth evaluation procedures through a comparison of novice and expert problem solvers. This comparison indicates that when novices fail at solving a problem or make mistakes, they often just ignore it and omit the evaluation of their results, while experts take the time to evaluate their results to learn what should have been done and then develop new methods for attempting to solve the problem again.

Lastly, the participant's classroom teacher and the researcher evaluated the participants using the engineering design rubric. The top-performing participants were the highest-scoring participants and the bottom-performing participants were also the lowest-scoring participants. The largest difference in the participants' scores were in the categories of considering multiple solutions, justifying their design, solution filtration performance, revising the prototype, and documenting the process. The bottom-performing participants received the same score as the top participants in the category of

researching current and past solutions. Furthermore, the bottom-performing participants scored higher than the top participants in the categories of choosing the best materials and solution time performance. These scores mirror the participants' cognition data that the better solutions were enabled through detailed documentation of the design process, taking more time to develop a well-thought-out design, and effectively conducting multiple tests and using the resulting data to optimize the solution.

A complete comparison between the top- and bottom-performing participants at each phase of the design process is provided in Figure 16. Additionally, Table 20 provides a list of the main identifiers determined through an analysis of the participant data for potentially creating more successful solutions to engineering design problems.

Research Objective 3 was to create a conceptual technological and engineering problem-solving model integrating student cognitive processes for the improved development of problem-solving abilities. This objective was achieved by examining the participant observations and the corresponding coded data to create graphical representations of the processes that each participant employed to solve the engineering design challenge. These individual processes were consolidated into two different approaches used to solve the design challenge. The researcher then utilized the models of these two approaches, combined with the participant cognition data related to solution effectiveness, to generate a conceptual engineering design model to be used for the improved development of problem solving abilities.

The examination of the participant observations led to the conclusion that they enacted two distinctly different approaches to solving the engineering design problem. Some participants followed a methodical, sequential process for solving the problem,

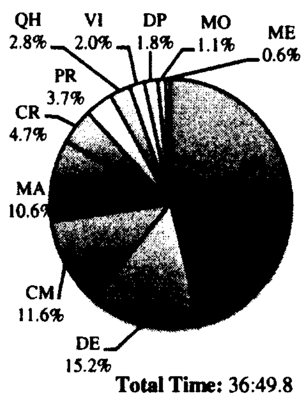
while other participants followed a more unformulated, nonsequential trial-and-error process. The sequential participants (Participants 1, 5, and 8) planned and followed a very logical step-by-step process for creating a solution to the problem and conducted multiple iterations of testing, redesigning, and retesting until they reached a desired outcome. These participants were more focused on the problem definition and meeting the established solution criteria versus physically building a solution. Additionally, these participants were very proactive when it came to addressing issues that arose when creating their solutions.

Conversely, the nonsequential participants (Participants 2, 3, 4, 6, and 7) followed a less structured trail-and-error approach, often moving around between steps of the design process to develop a solution without following a particular plan. These participants were more reactive in terms of confronting issues when creating their solutions. The nonsequential participants were focused more on the physical building of a solution rather than developing a complete design plan for creating and evaluating their solution. Most of these participants did not take the time to refine their designs and were satisfied even if their designs did not meet the desired criteria.

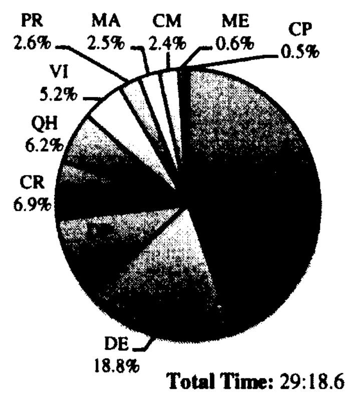
The participants who followed a sequential approach to solving the design problem were also the same participants who had the top-performing solutions and were evaluated higher using the engineering design rubric. A study by Ahmed et al. (2003) found similar differences between expert and novice engineers. Their findings indicated that novice engineers used an on-going trial-and-error technique of generating solutions, while experts made a preliminary evaluation of their tentative solutions before using integrated design strategies to create their final solutions.

	Rubric Category	2 Top-Performing Participants: Mean Score	2 Bottom-Performing Participants: Mean Scores
Solution Design	Research of Current and Past Solutions	60%	60%
Solution Design	Multiple Solutions Considered	75%	20%
Solution Design	Design Justification	75%	40%
Solution Construction	Material Choice	75%	80%
Solution Construction	Product Durability	95%	90%
Solution Construction	Product Ease of Setup	80%	70%
Solution Evaluation	Performance (filtration)	100%	50%
Solution Evaluation	Performance (time)	60%	80%
Solution Evaluation	Prototype Testing	95%	80%
Solution Evaluation	Prototype Revision	80%	30%
Solution Evaluation	Engineering Documenting	95%	70%

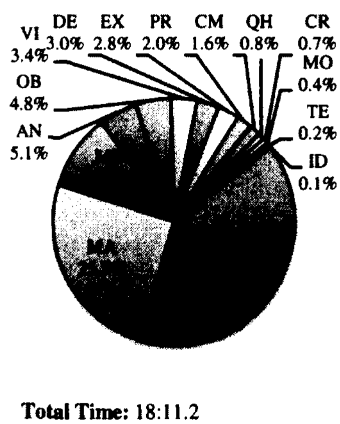
Solution Design — 2 Top-Performing Participants, Mean Cognitive Times:



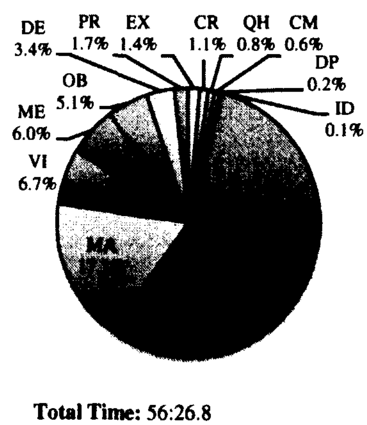
Solution Design — 2 Bottom-Performing Participants, Mean Cognitive Times:



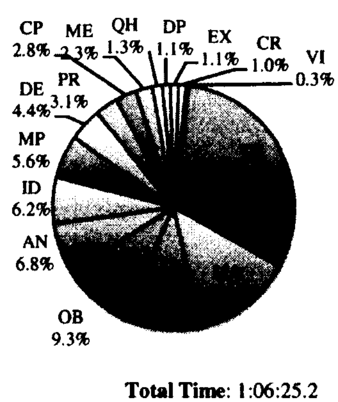
Solution Construction — 2 Top-Performing Participants, Mean Cognitive Times:



Solution Construction — 2 Bottom-Performing Participants, Mean Cognitive Times:



Solution Evaluation — 2 Top-Performing Participants, Mean Cognitive Times:



Solution Evaluation — 2 Bottom-Performing Participants, Mean Cognitive Times:

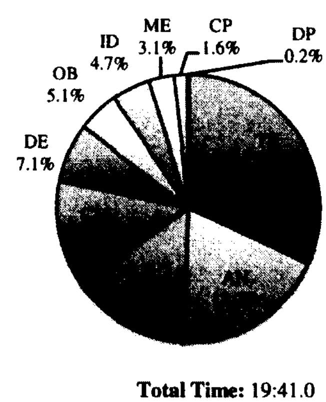


Figure 16. The comparison between participant scores and cognitive processes.

Table 20

Identifiers Within the Engineering Design Process for Creating More Effective Solutions

Identifiers	Supporting Data
Observations of individuals solving design problems suggest that:	
Additional time devoted to enacting the engineering design process leads to improved solution results.	The top-performing participants devoted more time solving the engineering design challenge than the bottom-performing participants. The top-participants dedicated 15 minutes and 59.9 seconds longer working to solve the problem than the bottom-performing participants.
Employing a greater frequency of the technological problem-solving mental processes leads to improved solution results.	The top-performing participants held a higher total frequency of employing the different mental processes. The top participants employed 226 more total mental processes than the bottom-performing participants.
More time dedicated to the solution design phase leads to improved solution results.	The top participants devoted over six minutes more of their time to the solution design phase of the engineering design process than the bottom-performing participants. However, the top participants took over 38 minutes less time constructing their solution than the bottom participants. This could be an indication that, if more time were taken to plan and design the solution, then less time would be needed to actually construct the solution.
Relating problems to prior experiences requires less time employing the mental processes of ***Defining Problems*** and ***Questioning/ Hypothesizing***, which resulted in improved solution results.	The bottom participants consumed more of their solution design time employing the mental processes of ***Defining Problems*** and ***Questioning/ Hypothesizing*** than the top-participants. These mental processes were employed by the bottom-performing participants to understand the nature of the problem because they lacked prior knowledge and experiences with the problem situation. The top-performing participants were able to quickly understand the problem due to their prior knowledge and devote more time to ***Managing*** their process to solve the problem.
More time devoted to employing the mental process of *Managing* throughout the design process, especially during the solution design phase, leads to improved solution results.	Throughout the engineering design process, the top-performing participants devoted six more minutes to employing the mental process of ***Managing*** than the bottom-performing participants. During the solution design phase, the top participants dedicated 8.1% more of their time to ***Managing*** than the bottom-performing participants. The top-performing participants utilized this process to plan and direct their processes for solving the problem. The participant observations suggest that those who are more thorough in managing, planning, and directing their design processes are those who create better solutions.
Extra time dedicated to employing the ***Communicating*** mental process throughout the design process, especially during the solution design phase, leads to improved solution results.	Throughout the engineering design process, the top participants took 6.0% more of their time employing the ***Communicating*** mental process than the bottom-performing participant. During the solution design phase, the top participants devoted 9.2% more of their time ***Communicating*** than the bottom-performing participants. The ***Communicating*** time involved participants documenting their research, design ideas, and recording design alterations. The participant observations suggest that effective communication and documentation of the design process enhances problem-solving capabilities.
Extensive time dedicated to the mental process of ***Model/Prototype Constructing*** was a result of a lack of design planning and therefore was an indicator of diminutive solution results.	Throughout the engineering design process, the top-performing participants dedicated 20.9% less of their time to employing the ***Model/Prototype Constructing*** mental process than the bottom-performing participant. The participant observations suggest that the bottom-performing participants took a greater amount of time employing this mental process because of their lack of developing a detailed design plan.
A minimal amount of time dedicated to employing the mental process of ***Measuring*** hindered solution results.	The participant observations suggest that a minimal amount of time devoted to employing the ***Measuring*** mental process caused design construction flaws.
Experimentation with solution materials during the solution construction phase leads to improved solution results.	The participant observations portrayed the top-performing participants conducting brief experiments with materials to use for creating their solution. These observations indicated that the material experiments assisted in producing a better-performing solution.

Table 20

Identifiers Within the Engineering Design Process for Creating More Effective Solutions (Continued)

Identifiers	Supporting Data
Observations of individuals solving design problems suggest that:	
More time dedicated to the solution evaluation phase of the design process leads to improved solution results.	The top-performing participants took over 46 more minutes for the evaluation of their solutions than the bottom-performing participants. The top participants enacted more iterations of testing their solutions, making observations, interpreting the outcome data, and then experimenting with design changes to improve their results. The participant observations suggest that the bottom-performing participants were satisfied with their solution result after testing the prototype just once.
Employing all of the mental processes for technological problem-solving during the solution evaluation phase leads to improved solution results.	The top-performing participants employed 16 of the mental processes for technological problem-solving during the solution evaluation phase, while the bottom-performing participants only employed nine different mental processes. The top-performing participants employed a greater variety of mental processes to enable themselves to completely evaluate and optimize their solutions. The data report that the top participants consumed over four minutes more ***Communicating***, over 1 minute more ***Designing***, almost 1 minute more ***Experimenting***, over three minutes more ***Interpreting Data***, over six minutes more ***Managing***, almost four minutes more ***Model/Prototype Constructing***, over five minutes more ***Observing***, and approximately 14 minutes more ***Testing***.
Additional time devoted to employing the scientific mental processes of ***Testing***, ***Experimenting***, ***Observing***, and ***Interpreting Data*** leads to improved solution results.	The top-performing participants devoted 14 more minutes employing the ***Testing*** mental process, three more minutes employing the ***Observing*** mental process, three minutes more employing the ***Interpreting Data*** mental process, and almost a half minute more of their time employing the ***Experimenting*** mental process than the bottom-performing participants. The participant observations suggest that these scientific mental processes were employed to collect and analyze valuable data essential for informing solution optimization.
More time dedicated to employing the mathematical mental processes of ***Computing*** and ***Interpreting Data*** leads to improved solution results.	The participant observations indicated that a minimal amount of time was dedicated by each participant to employing the mathematical mental processes of ***Computing*** and ***Interpreting Data***. However, during the solution evaluation phase, the top-performing participants devoted two more minutes to employing the process of ***Computing*** and three more minutes employing the process of ***Interpreting Data*** than the bottom-performing participants. The participant observations suggest that more mathematical thinking while evaluating a solution enables an individual to use quantitative and qualitative data to optimize their solution designs.

The top-performing participants also completed multiple iterations of testing and refining their solution, while the participants following a nonsequential approach did not. As Wankat and Oreovicz (1993) assert, checking the results should be an automatic part of the problem-solving strategy. However, they declare that novice problem solvers are not adept at evaluation and almost never do it unless explicitly told to do so. Therefore, students need to be strongly encouraged to study feedback and then resolve incorrect issues. Furthermore, Wankat and Oreovicz (1993) state that novice problem solvers follow an "uncompiled" solution procedure while experts follow a planned and

"compiled" single approach to solving a problem. Consequently, one possible conclusion can be that a logical and more sequential approach to the engineering design process, which can be developed when one gains more engineering design experience, is more effective in creating successful solutions.

The participants in this study were tasked to work alone to solve an engineering design challenge without the supervision of a teacher. Therefore, the data can provide an insight into how students actually solve problems in a more natural environment. As a result, the data indicate that students at an advanced pre-engineering level follow a simplified process for solving design problems than that prescribed by technology and engineering curricula. When the participants were left on their own to solve the engineering design problem, they did not follow a 12-step engineering design process (International Technology and Engineering Educators Association, 2013) fabricated by teachers and curricula specialists. Instead they followed what seems to be a more natural and organic problem-solving process. Based on the data observed in this study, the 12-steps of *Define a Problem, Brainstorm, Research & Generate Ideas, Identify Criteria & Specify Constraints, Explore Possibilities, Select an Approach, Develop a Design Proposal, Make a Model or Prototype, Test and Evaluate the Design, Refine the Design, Create or Make Solution*, and *Communicate Processes and Results* can be consolidated into the three phases of solution design, solution construction, and solution evaluation.

The 12-steps can be further simplified into 6-steps presented in the conceptual model generated through this study, which includes *Define the Problem, Conduct Research, Develop a Solution, Make a Solution, Assess the Solution*, and *Communicate the Results*. See Figure 17 for a simplified version of the 12-step engineering design

process. The mental processes identified by Halfin (1973) can then be utilized to express the underlying pathways for students to cognitively navigate between steps in either a sequential or a nonsequential manner. The remaining components of the 12-step engineering design process eliminated from the simplified version of the design process, such as exploring multiple solutions and selecting different approaches, can be thought of as design heuristics or strategies for solving problems, rather than specific steps. Ullman et al. (1988) supports this conclusion through the results of their study of experienced mechanical engineers. Their results indicate that many experts only pursue a single design proposal and in many cases where major problems had been identified in the original design proposal, the designer preferred to apply patches to it rather than reject the proposal outright and develop a better one. Therefore, it can be seen that some of the steps in the 12-step engineering design process may be thought to be beneficial to solving design problems but are not actually a general practice in most situations. These eliminated steps can then be considered heuristics for designers to use as tools for solving specific problems.

To achieve Research Objective 3, the researcher utilized the participant cognitive data, solution effectiveness data, the two identified approaches to solving a design challenge, and the study conclusions to generate a conceptual model of engineering design recommended for improved student problem solving abilities. Wankat and Oreovicz (1993) recommend that a distinct and consistent problem-solving strategy should be demonstrated and then required from engineering students. Woods et al. (1979) suggest that the strategy have between 4 and 15 steps. If shorter than 4 steps, the strategy is probably too short and not detailed enough to be useful; if longer than 15 steps it is too

long to remember and use. Therefore, the conceptual model is centered on the three phases of engineering design and the six coinciding steps to solve a design challenge. The model then describes the organization of Halfin's mental processes around the steps of the design process based on the participant observations. Lastly, the model depicts key attributes for engineering design that should be addressed throughout the design process to ensure proper engineering design capabilities. These attributes were identified through the student cognition data and their resulting solution effectiveness data. The attributes were identified as either actions that the participants took that helped improve their solutions or engineering design qualities that were identified as lacking throughout their design processes. The conceptual model for engineering design can be found in Figure 18.

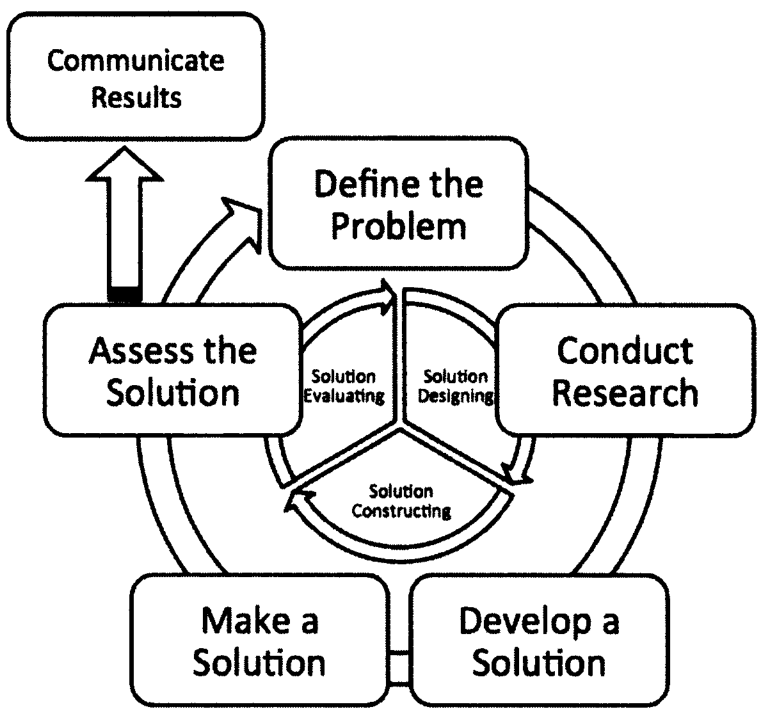


Figure 17. Simplified version of the 12-step engineering design process.

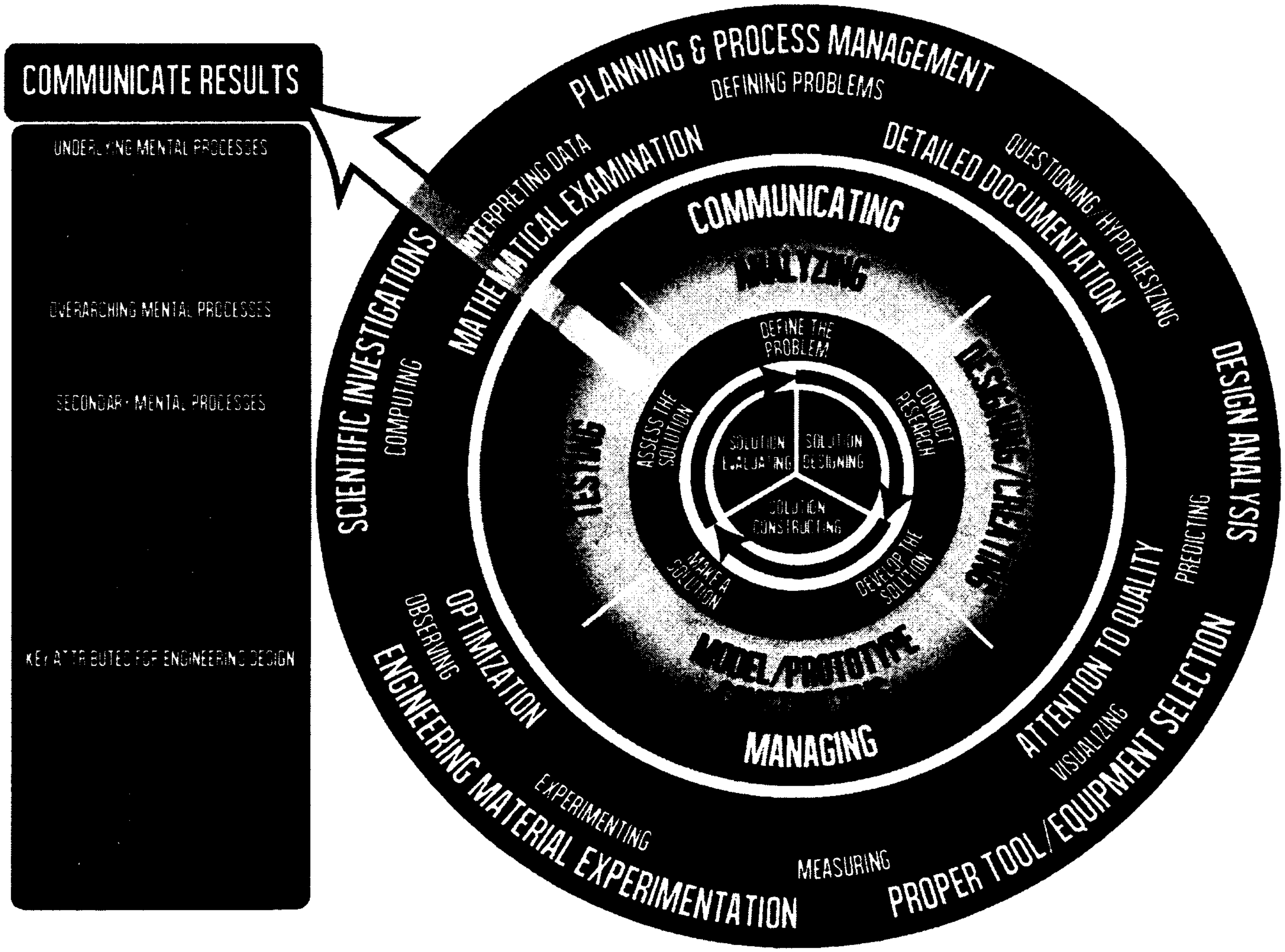


Figure 18. Conceptual engineering design model.

The engineering design model can be described starting in the center of the figure with the three phases of engineering design. The participant observations indicated that there were three distinct phases of engineering design (solution designing, solution constructing, and solution evaluating), and they progressed through these to solve the design challenge. These phases consisted of a blending of the six consolidated steps of engineering design.

The first phase, *Solution Designing*, consisted of the steps of *Defining the Problem, Conducting Research*, and *Developing a Solution*. The second phase, *Solution Constructing*, involved the continual *Development of a Solution* and the *Making of a Solution*. The third phase, *Solution Evaluating*, consisted of the steps of *Assessing the Solution, Defining any Additional Problems*, and *Communicating Results,* if the desired solution outcomes were met. Throughout these steps the participants employed the underlying mental processes of *Analyzing, Designing/Creating, Model/Prototype Constructing,* and *Testing* in four overlapping quadrants of the engineering design process. These four mental processes were the most employed mental processes during these sections of the design process. However, two overarching mental processes of *Communicating* and *Managing* were employed throughout the entire design process to control and converse the actions and outcomes of the problem-solving episode.

The outside ring of the model then contains the identified key attributes for engineering design and the supporting secondary mental processes. The participant data indicated that *Planning & Process Management* and *Detailed Documentation* were attributes that assisted the top-performing students in creating more effective solutions. Next, the data indicated that participants might have been hindered in solving the

problem by not conducting a thorough *Design Analysis* using technical drawings and 3-dimenisonal modeling, by not *Attending to Quality* when designing and making a solution, and by not *Selecting the Proper Tools/Equipment* necessary to construct a viable solution. Next, the data indicated that the top-performing participants conducted *Engineering Materials Experimentation* to determine what resources were best suited for their solution design and focused on *Optimization* through this material experimentation. Lastly, the attributes of conducting true *Scientific Investigations* in regards to evaluating a solution and enacting a *Mathematical Examination* of the resulting data for the purpose of improving the design was indicated to be lacking based on the limited amount of time the participants devoted to employing the mental processes of *Experimenting, Observing, Computing*, and *Interpreting Data*. To achieve these nine key attributes of engineering design, individuals must employ a blending of the secondary mental processes. These secondary processes are organized in the model based on when the students should be employing them the most. As a result, the nine key attributes for engineering design combined with the understanding of student cognition in relationship to the steps of the engineering design process can help teachers promote and students achieve true engineering design problem solving. A further description of the model is provided in Table 21.

Table 21

Conceptual Engineering Design Model Explanation

	Essential Tasks	Key Attributes for Engineering Design	Mental Processing	Design Heuristics/ Strategies
Define the Problem	**Problem Recognition/ Validation** • Determine if there is a true problem in need of a solution **Formulate a Problem Statement** • Re-describe the problem in a manner that has personal meaning **Understand/ Establish Criteria & Constraints** • Determine the guidelines and limitations for developing a successful solution	**Planning & Process Management** • Individuals who devote more time to planning and managing their design process tend to develop more effective solutions. • Novice designers tend to lack the self-discipline to develop a comprehensive plan for project completion. • Expert designers utilize a well-thought out strategy to solve problems, while novices use a trial and error approach. • Individuals should develop a detailed work plan to solve the problem based on the available resources before progressing in the engineering design process.	• The mental process of ***Managing***, which is the practice of planning, organizing, directing, coordinating, and controlling the inputs and outputs of the system, is an overarching mental process that is employed throughout the engineering design process. This mental process is essential for individuals to plan and direct their problem solving process. • ***Analyzing*** is a major underlying mental process for this step of the design process, which is the practice of identifying, isolating, taking apart, or performing similar actions for the purpose of setting forth or clarifying the basic components of a problem. This process enables individuals to understand the problem and relate it to their prior experiences and knowledge. • The secondary mental process of ***Defining Problems***, which is the process of formulating an understanding of a problem, is employed to help individuals restate the problem to include the desired solution evaluation criteria. This process is necessary to begin the engineering design problem solving process.	• Separate the project into manageable tasks • Establish benchmarks for project completion • Develop a timeline for solution development • Evaluate the resources available • Utilize project management tools (i.e., a Gantt Chart or project management software)
Conduct Research	**Research Current Solutions** • Evaluate what others are doing to solve the problem in order to generate ideas for new and/or better ways to solve the problem **Explore Concepts** • Develop the necessary knowledge base for designing a solution • Investigate possible concepts that can be applied to the problem in a novel way ***(Innovative Thinking)***	**Detailed Documentation** • Individuals who devote more time to documenting and revisiting their research and ideas tend to develop better preforming solutions. • Experts utilize their detailed documentation to analyze information and to look for patterns to draw inferences from. • Novices find it difficult to identify what is relevant information to their situation and tend to skip the documentation and analysis of information. • Individuals should plan to devote time for recording important aspects of their design process as they work to create a solution to the problem.	• The mental process of ***Communicating***, which is the conveying of information or ideas from one source to another through various modes of media, is an overarching mental process that is employed throughout the engineering design process. This mental process enables individuals to formulate their newly acquired knowledge into concise ideas to be documented and referred to throughout the problem solving process. • ***Analyzing*** is a major underlying mental process for this step of the design process, which is the practice of identifying, isolating, taking apart, or performing similar actions for the purpose of setting forth or clarifying the basic components of a problem. This process enables individuals to determine the most relevant information to be used for developing their solution. • The secondary mental processes of ***Questioning/ Hypothesizing*** (the process of asking questions, interrogating, challenging, or seeking answers related to a problem), ***Predicting***, (the process of prophesying or foretelling something in advance), and ***Visualizing*** (the process of perceiving a phenomenon in the form of a mental image) combined with the underlying process of ***Analyzing*** enables individuals to make attempts at learning new concepts and skills to aid in the development of ideas to be used in solving the problem.	• Categorize the fundaments for solving the problem and ignore superficial details • Recognize relevant information and organize it into "chunks" or patterns • Draw inferences to other potential ideas or concepts ***(Innovative Thinking)*** • Monitor solution progress

Table 21

Conceptual Engineering Design Model Explanation (Continued)

	Essential Tasks	Key Attributes for Engineering Design	Mental Processing	Design Heuristics/ Strategies
Develop the Solution	**Search for Solutions** • Combine ideas and concepts to generate unique solution ideas **Finalize Design Specifications** • Clearly delineate the features and performance expectations necessary for a design to successfully meet the criteria and constraints. **Create a Detailed Solution Representation** • Communicate the features and function of a solution design idea through detailed and well annotated visual representations **Develop a Design Strategy** • Outline the procedure for creating a model or prototype of the solution.	**Design Analysis** • Individuals who devoted considerable time to thoroughly analyzing their designs through detailed technical drawings, accurate measurements, and mathematical examinations tend to develop the more effective solutions. • Individuals should analyze their solutions with the recognition that all technologies are systems of interacting parts that are, in turn, embedded in larger systems. ***(Systems Thinking)*** • Individuals should conduct a thorough mathematical analysis of their design to ensure that it meets the desired design specifications. This can be accomplished using 3D modeling or digital prototyping software. **Proper Tool/ Equipment Selection** • Observations of individuals solving design problems indicate that the absence of selecting the proper tools and equipment when developing a solution hinders the ability to produce quality solutions. • Individuals should use industry-quality software and measurement tools to generate detailed technical visual representations of their solution. • Individuals should plan the use of industry quality tools/equipment for manipulating realistic materials for the construction of their solution.	• The mental processes of ***Designing*** (the process of conceiving, creating, investing, contriving, sketching, or planning to meet a determined goal) and ***Creating*** (the process of combining the basic components or ideas of phenomena in a unique manner to better satisfy a need) are major underlying mental processes for this stage of the engineering design process. These mental processes enable individuals to apply their prior knowledge and the information collected through research to conceptualize a solution design. • The secondary mental processes of ***Questioning/ Hypothesizing*** (the process of asking questions, interrogating, challenging, or seeking answers related to a problem), ***Predicting***, (the process of prophesying or foretelling something in advance), and ***Visualizing*** (the process of perceiving a phenomenon in the form of a mental image) combined with the underlying mental process of ***Analyzing*** enables individuals to make attempts at learning new concepts and skills to aid in ***Designing/Creating*** solutions ideas. • The mental process of ***Measuring*** (the process of describing characteristics of an object or event through the use of numbers in terms that are transferable) enables individuals to develop detailed technical visual representations of their solutions and fosters the analysis of the design through measuring the results of testing solution concepts. • The mental processes of ***Computing*** (the process of selecting and applying mathematical symbols, operations, and processes to describe, estimate, calculate, quantify, relate, and/or evaluate an object, event, or phenomena) and ***Interpreting Data*** (the process of clarifying, evaluating, explaining, and translating to provide the meaning of particular data) enable individuals to do the necessary calculations to understand the results of the design analysis and solution concept testing.	• Utilize creativity in the design process • Explore multiple solution possibilities • Select the best solution approach using a decision matrix • Employ design software to aid in design creation and concept analysis • Evaluate multiple industry quality tools when developing a plan to make a solution • Create a bill of materials for the proposed solution • Create a list of the necessary industry quality tools and equipment needed to make the solution • Monitor solution progress

Table 21

Conceptual Engineering Design Model Explanation (Continued)

	Essential Tasks	Key Attributes for Engineering Design	Mental Processing	Design Heuristics/ Strategies
Make the Solution	**Acquire the Appropriate Resources** • Collect the materials that will enable the construction of a well-built model or prototype to ensure that the testing of the solution and evaluation of the test data is realistic and valuable **Model/Prototype the Solution** • Utilize the design strategy to construct a quality model or prototype of the solution design **Modify the Solution Design as Necessary** • Continually make improvements to the model or prototype to optimize the solution's effectiveness at solving the problem	**Attention to Quality** • Observations of individuals solving design problems indicate that the lack of focusing on constructing a well-built solution through conducting accurate measurements and using the proper tools, equipment, and materials minimized the effectiveness of the solution. • Individuals should continually refer back to the design specifications to ensure the solution is of a quality that will enable the collection of the most realistic and valuable solution testing data. **Engineering Material Experimentation** • Observations of individuals solving design problems indicate that the iterative testing of the materials used in constructing the solution design led to improved solution results. • Individuals should continually evaluate a variety of materials used for the construction of their solution through scientific experiments. **Optimization** • Observations of individuals solving design problems indicate that the on-going process of evaluating whether the solution model or prototype meets the design specifications enhanced the quality of the final solution. • Individuals should continually evaluate the quality of the individual components of their solution as they work to construct the model or prototype.	• The mental process of ***Managing***, which is the process of planning, organizing, directing, coordinating, and controlling the inputs and outputs of the system, is an overarching mental process that is employed throughout the engineering design process. This mental process is essential for individuals to follow a procedure to make their solution and to acquire all the resources necessary to make their model or prototype. • ***Model/ Prototype Constructing*** is a major underlying mental process for this step of the engineering design process, which is the practice of forming, making, building, fabricating, creating, or combining parts to produce a scale model or prototype of the solution. This process enables individuals to direct their attention to physically manipulate tools, materials and equipment for constructing a developed solution idea. • The secondary mental processes of ***Visualizing*** (the process of perceiving an object, event, or system in the form of a mental image based on the experience of the perceiver) and ***Predicting*** (the process of foretelling something in advance on the basis of special knowledge) enables individuals to cognitively manipulate mental models of the solution design and to ponder the effects of altering the solution design. These processes allow an individual to understand how to manipulate their solution to better solve the problem. • The mental process of ***Measuring*** (the process of describing characteristics of an object or event through the use of numbers in terms that are transferable) enables individuals to accurately manipulate the tools, materials, and equipment needed to construct the solution. Cognitively processing precise measurements when constructing a solution is essential for producing high quality, well-built solution models or prototypes. • The secondary mental process of ***Experimenting*** (the process of determining the effects of something previously untried in order to test the validity of a hypothesis, to demonstrate a known or unknown truth, or to try out various factors relating to a particular phenomenon) is essential for individuals to determine the ability to make effective solution alterations.	• Follow your design strategy to ensure that the solution meets the design specification • Leverage the perspectives, knowledge, and capabilities of team members to address design challenges • Maintain an optimistic outlook to persist in creating the solution • Continue to look for improvements to the solution • Document any changes made to the solution design while constructing the model or prototype • Monitor solution progress

Table 21

Conceptual Engineering Design Model Explanation (Continued)

	Essential Tasks	Key Attributes for Engineering Design	Mental Processing	Design Heuristics/ Strategies
Assess the Solution	**Determine Test Criteria** • Clearly define what types of data needs to be collected to evaluate the solution based on design specification **Establish a Testing Procedure/ Experiment** • Develop a procedure for each test or experiment to be performed to collect the desired data **Collect the Data** • Conduct the designed tests/ experiments to evaluate how well the solution solves the problem **Analyze the Data** • Draw conclusions based on the test/experiment results **Continue to Refine the Solution** • Improve the design based on the conclusions drawn from the testing results to ensure the design specifications are met	**Scientific Investigation** • Observations of individuals solving design problems indicate that people who devote more time to iteratively testing and experimenting with their solution designs tended to create a more effective solution. • Individuals should test and evaluate their solution designs in a scientific manner to collect the proper data to inform their solution redesign. • Individuals should also investigate how their solutions impact people, systems, and the environment. Any designs or products can have unexpected and undesirable impacts on people, systems or the environment that need to be corrected. **Mathematical Examination** • Observations of individuals solving design problems indicated a lack of mathematical processing and analysis of testing/experiment data. Attempting to quantify, estimate, calculate, or describe how well a design solves a problem using the numerical information is a key feature of engineering design that enables the optimization of solution effectiveness. • Individuals should utilize statistical procedures to analyze the testing data to evaluate and improve their designs.	• ***Testing*** is a major underlying mental process for this step of engineering design, which is the practice of determining the workability of a model, component, system, product, or point of view in a real or simulated environment to obtain information for clarifying or modifying design specifications. This process enables individuals to focus on evaluating the effectiveness of their solution. • The secondary mental processes of ***Experimenting*** and ***Observing*** enables individuals to assess their solution models or prototypes and to collect the necessary data to evaluate its effectiveness at solving the problem. • The secondary mental processes of ***Computing*** and ***Interpreting Data*** enables individuals to analyze and draw conclusions from the data collected from the solution testing. These processes allow individuals to inform the improvement of their solution design. • ***Model/ Prototype Constructing*** is also an underlying mental process for this step of the design process, which involves the practice of forming, making, building, fabricating, creating, or combining parts to produce a scale model or prototype of the solution. This process enables individuals to physically manipulate tools, materials, and equipment to improve their solution model or prototype. • ***Defining Problems*** is a secondary mental process for this step of the design process, which involves the practice of stating or defining a problem. This process enables individuals to identify and define any unintended problems with the model or prototype that needs to be solved to develop an optimal solution design. This process is the link to restarting the design process to develop an improved solution design.	• Develop a detailed description of the testing procedure to ensure that data are collected in a controlled environment • Attend to ethics when collecting, analyzing, and sharing data related to the effectiveness and impact of the design. • Utilize statistical software to help analyze testing data (e.g. SPSS and Excel) • Document the modifications to be made to the solution • Conduct a critical design review with external members to evaluate the solution • Monitor solution progress

Table 21

Conceptual Engineering Design Model Explanation (Continued)

	Essential Tasks	Key Attributes for Engineering Design	Mental Processing	Design Heuristics/ Strategies
Communicate Results	**Study the Solution Results** • Draw conclusions about the solution to a problem from an analysis of the entire engineering design process **Share the Conclusions** • Present the conclusions and the solution design to the proper audience	**Communication of Engineering Design** • Individuals should communicate technical and scientific results as a means to explain and defend choices made in the design process and to add to the engineering/ scientific body of knowledge.	• ***Analyzing*** is a major underlying mental process for this step of the design process, which is the practice of identifying, isolating, taking apart, or performing similar actions for the purpose of setting forth or clarifying the basic components of a problem. This process enables individuals to determine the most relevant information about the solution design to share. • The mental process of ***Communicating***, which is the conveying of information or ideas from one source to another through various modes of media, is an overarching mental process that is employed throughout the engineering design process. This mental process enables individuals to formulate the gathered information in a manner to be shared with any potential audience.	• Examine all documentation of the design process to ensure all key elements of the problem solving process are shared • Utilize multiple forms of media to convey your information • Utilize presentation software to assist in communicating results • Attend to ethics when collecting, analyzing, and sharing data related to the effectiveness and impact of the design.

Recommendations

The researcher acknowledges this study was limited to a sample of eight participants; therefore, the results of the study may not be generalizable to all engineering design programs. However, stakeholders within the technology and engineering education community should consider the findings from this research when developing technology and engineering and integrative STEM education initiatives, projects, programs, and/or curricula.

Based upon this study's research findings and conclusions, the researcher developed recommendations for enhancing the teaching of engineering design and for continuing research in engineering design cognition. The first recommendation is to utilize the identified cognitive processes for directing the development of technology and engineering curricula and instruction. The mental processes employed, or the lack of these, can be used as indicators of voids in curricula, instruction, and student learning. As reported in the findings and conclusions for Research Objective 1, the following recommendations are proposed for improving technology and engineering curricula and teachers and instruction:

Include process management. The process of *Managing* was one of the most utilized by all participants throughout their engineering design process. Participants devoted the majority of their *Managing* time directing their actions during the design session and controlling the inputs of their solutions. However, some participants were more effective at planning their processes than others. The findings indicate that effective planning is a possible contributor towards a more successful solution. Therefore,

technology and engineering curricula should include effective management and planning techniques for implementing the engineering design problem-solving process.

Increase focus on mathematical thinking. Some of the least utilized mental processes by the participants during the engineering design session were *Computing, Measuring, and Interpreting Data*, which can be considered the more mathematical processes. The limited use of these mental processes may be a reflection of the curricula and instructional strategies utilized in technology and engineering education programs. Curriculum developers must emphasize the use of age-appropriate general mathematical practices, mathematical modeling, and mathematical analysis throughout engineering design challenges. Students should be exposed to explicit integrated examples of using mathematics while interacting with a design problem and its associated technologies. To ensure this recommendation is achieved, curriculum providers must deliver adequate teacher professional development to teach a more mathematically enriched curriculum. The teachers must learn how to demonstrate to students how mathematics can assist them with better solutions to design problems.

Attention to quality. The participant observations indicated that a minimal amount of time was used employing the cognitive process of *Measuring*. The participants paid little attention to accurately planning their designs and adding dimensions to their solution sketches. Additionally, they did not attempt to accurately measure the materials they used to build their solutions. As a result, participants wasted materials and time during the construction of their solution by only making estimations when manipulating the materials used to build their solutions. The participants relied on repair materials, such as hot glue and duct tape, to correct any construction errors they encountered due to

the lack of planning and measurement. It was observed that the participants placed little value on the quality of their making and the aesthetics of their solutions. These actions may indicate that current technology and engineering curricula place little importance on product quality and the use of tools and materials. It is recommended that curriculum developers highlight the importance of carefully and accurately creating solutions that are of quality and create challenges that require students to use industry quality materials to develop solution prototypes. Lombardi (2007) states that an authentic learning experience should culminate in the creation of a polished product, valuable in its own right, and students should know what it feels like to be held accountable for these products.

Emphasize scientific processes. The findings of this study indicated that participants with better performing solutions took more time employing the scientific mental processes of *Testing*, *Experimenting*, *Observing*, and *Interpreting Data*. The participants who created more effective solutions utilized these processes to iteratively refine their solutions by setting up mini-experiments to try different ideas, make observations of the tests, and interpret the data in a manner that informed their design modifications. The participant observations illustrated how these processes ultimately increased their solution's effectiveness. The evaluation phase, where the majority of these mental processes take place, seems to be an area of focus for improving a student's ability to create viable solutions to an engineering problem. The data indicate that students need to devote a significant more amount of time testing their designs, observing the outcomes, interpreting the resulting data, experimenting with design modifications, retesting their solutions, and completing multiple iterations of this redesign cycle.

It is recommended that technology and engineering curricula integrate the use of more scientific methods and procedures in their engineering design challenges. Students should be given the opportunity to establish engineering/scientific experiments as a means to test their designs and have the chance to interpret the resulting data as a means of making design improvements. Oftentimes, the testing and experimenting processes are missing from technology and engineering curricula. For example, designing a craft stick bridge is a common activity in technology and engineering classrooms. In this activity, students build a bridge out of unrealistic materials and then break the bridge by adding weight to it. The student bridge that holds the most weight is considered to be the best bridge. However, this destructive testing is not a realistic and true engineering/scientific experiment. The data from destroying the bridge are not actually used by students as new knowledge for informing the redesign of their bridge. The student observations in this study reflect the behaviors promoted by these unrealistic and nonscientific activities. As a result, many learning opportunities may be missed by not reinforcing these engineering and scientific mental processes in technology and engineering curricula.

Enrich engineering material experimentation. As Kelley and Wicklein (2009a) noticed in their study of technology and engineering curricula content, engineering and material sciences are missing content components. The findings in this study support their conclusion because the process of *Experimenting* was used very sparingly among the participants and very few participants experimented with different materials to be used for their solutions. However, the participants who did experiment with the materials were able to make improvements to their designs based on the knowledge they gained in the process. Hence, it is recommended that technology and engineering curricula

integrate material sciences through promoting experimenting processes for determining which realistic materials would be better used in solving the engineering design problem. As Orr and Flowers (2014) state, emphasizing experimentation in the technology and engineering classroom can enable students to learn through inquiry and to use experiment results to refine their own learning by generating new knowledge. They also recommend that teachers include experimentation in their curriculum and instruction as much as possible through teacher-directed experiments, student-selected experiments, student-found topics, and student inquiry because it promotes students to use evidence to inform their problem solving process.

Align with the engineering profession. The data highlighted some potential disconnects between technology and engineering curricula and the engineering profession. The actions and thoughts of these student participants did not always coincide with what the engineering profession practices. The data indicated that the participants were more focused on building their solutions and took a relatively minimal amount of time thoroughly planning their designs before beginning the construction of their solution. Little time was used for analytical design and modeling, and many of the participants did not utilize testing data to optimize their designs. Additionally, most of the participants did not experiment with materials to determine what would be the best choice for their solution; instead they relied on repair materials. This may indicate that the engineering habits of mind, which involve design, analysis, modeling, and optimization, are not stressed or accurately practiced throughout technology and engineering curricula and teaching. Subsequently, one may conclude that technology and engineering education programs or instruction do not fully align with the

engineering profession. It seems that technology and engineering programs tend to align somewhere between the engineering profession and the engineering technology profession. Therefore, it is recommended that technology and engineering education programs clarify their aim and establish their program's purpose. If their purpose is to teach engineering, then they must be sure to align with the best practices of the engineering profession.

Identify with both genders. The results of this study indicated a possible difference in the processes male and female students use to solve problems. The female participants were more thorough in conducting and documenting research and more detailed in developing their solution designs. The female participants devoted a lesser amount of time in making their solutions than their male counterparts. However, the female participants were more meticulous in testing their solutions and extremely dedicated to improving their designs. As a result, the female participants dedicated a larger amount of time to evaluating their solutions. Therefore, it is recommended that educators utilize this knowledge to understand the way different genders act during the design process. Female students may need more time to design and evaluate their solutions and need additional support to become proficient in making their solutions. Conversely, male students may need to be taught to devote additional time in planning their design solutions before they begin making them. Additionally, male students may need to be motivated to improve their designs through multiple testing iterations. Most of the male students were not observed reflecting on their design processes with the intent to improve their solutions and therefore, they should be assisted in developing reflection skills.

Center on the experiences. The participants who created the best-performing solutions noted in their design journals and reflections that they related the challenge to some other experiences they have had. Whether it was experiences using certain materials/tools or experiences with a similar platform for making solutions, it seemed to help them direct their problem-solving process. This information is similar to the results of an analysis of practicing engineers conducted by Jonassen, Strobel, and Beng (2006). Their findings indicated that drawing upon prior experiences is the most important factor in solving an engineering workplace problem. Thus, people who are able to draw upon prior knowledge and experiences to solve a problem are those who can be considered expert problem solvers. Based on this finding, it is recommended that technology and engineering curricula be shifted to provide students with specific authentic tool, material, and design experiences that can be drawn upon to solve other problems in the future. In doing so, technology and engineering can distinguish itself from other school subjects by providing situations in which students can have experiences with realistic materials, advanced prototyping technologies, and appropriate resources to solve authentic engineering design problems. The benefit of not being a standards assessed school subject can be the flexibility for teaching the most up-to-date technologies and focusing on solving the most relevant authentic engineering challenges. Moving away from generic problem-solving skills to focusing on real technologies can provide students with the capability to solve authentic problems that are found in today's world.

As seen in the findings and conclusions for the Research Question 2, the following recommendations are proposed for improving instruction in technology and

engineering education as a means of promoting the development of more viable solutions to problems.

Practice planning. The researcher's findings indicate that students who are thorough in managing, planning, and directing their design processes are more likely to achieve enhanced solution results. Therefore, it is recommended that instructors demonstrate methods for properly planning the development of a solution to an engineering design challenge. Teachers should provide students with appropriate tools and materials to aid in the planning of their problem-solving processes. Portz (2014) recommends requiring students to practice breaking down and documenting large projects into smaller, more manageable tasks using a Gantt chart. This type of chart is intended to help students identify constraints within a project, enabling them to order each task, allowing for sequential tasks to occur in the most effective order. Practice planning and managing design projects can provide students with critical skills for authentic workplace settings (Portz, 2014).

Define the problem. Cross (2004) proclaims that the processes of structuring and formulating the problem are frequently identified as key features of design expertise. He concludes that successful designers are proactive in problem framing, dynamic in imposing their view of the problem, and directive in the search for solution speculations. Cross's conclusions seem to be found in the findings of this study. The findings indicated that the top-performing participants were observed as more proactive problem solvers and more direct in the problem-solving process. Conversely, the lower-performing participants were considered more unstructured in their problem-solving process and required more time to define and understand the challenge. Much like Atman et al. (1999)

identified in their study, less successful engineering students became fixated in defining the problem and did not progress satisfactorily into further stages of the design process.

The data from this study showed that the lower-performing participants needed more time to understand the problem and they had many questions they needed to answer in order to develop a solution idea. Therefore, a recommendation is for technology and engineering educators to practice defining ill-structured problems and identifying the most critical solution criteria/constraints for their potential solutions with their students, both as a class and individually. Teachers should utilize engineering design problems that are authentic, natural, and consist of multiple and conflicting goals. This is in opposition to providing students with a design brief that has a well-defined problem statement and a list of the essential solution criteria and constraints. As Strimel (2014) states, traditional technology education design briefs leave little room for students to practice defining problems and lessens the opportunity for students to develop the problem-solving skills necessary for creating viable and valuable solutions.

Stress the importance of documentation. The findings in this study can be an indication that effective communication and documentation of the design process can enhance problem-solving capabilities. The top-performing participants took 6.0% more time utilizing the *Communicating* mental process for documenting their research and recording their design alterations. Therefore, it is recommended that instructors stress the importance of utilizing documentation practices as tools for managing the design of more viable solutions.

Practice using iterative cycles for testing and redesigning. The top-performing participants in this study chose more iterations for testing their solutions, making

observations, interpreting the outcome data, and then experimenting with design changes to improve their solutions. The bottom-performing participants were focused on making the solution and were satisfied after testing their solutions only once. Therefore, it is recommended that instructors model the appropriate behaviors of iteratively testing solutions, properly analyzing data, and utilizing the resulting data to make design optimizations. Curriculum projects should include instruction of this nature. Additionally, instructors should initiate student investigations and scientific research on their solution's effectiveness, as well as allocate time for students to reflect upon their results. Strimel (2014) states that students can gather useful information from scientific investigations that can enable them to develop more viable solutions. Additionally, he emphasizes that reflecting on these investigations can extend a students' learning and enhance their problem-solving abilities.

Technology and engineering teacher preparation and professional development changes. To address any of these recommendations requires changes in teacher preparation and teacher professional development opportunities. Often times, technology and engineering teachers do not graduate from a teacher preparation program. Many instructors in this subject become licensed to teach through emergency certification programs or enter from other teaching areas. This can lead to a group of teachers unprepared to teach authentic engineering. It is important to include the proper teaching of engineering in teacher preparation programs and in required professional development offerings.

Research Objective 3 led the researcher to the development of a conceptual engineering design model based on this study's findings and recommendations. The data

used to generate this model indicates that students follow two different approaches to solving design problems. One approach is more sequential and methodical, while the other is a nonsequential approach of trial-and-error. However, the data indicates that students who enacted the more sequential and consolidated approach to solving an engineering design problem developed the most effective solutions to the problem. A study by Radcliffe and Lee (1989) also suggested that a more systematic approach might be helpful to students in completing design projects. Their analysis of mechanical engineering students denoted a positive correlation between the quality or effectiveness of a design and the degree the student followed a logical sequence of design processes. Consequently, the conceptual model promotes a logical sequence for solving problems. However, it is recommended that this model be tested to ensure that curriculum developers and teachers can utilize it to enhance the teaching and learning of engineering design. Cross (2001) notes that an aspect of concern in design and design research has been the many attempts at proposing systematic models of the design process and suggestions for approaches that should lead designers efficiently towards a good solution. He believes that designers remain wary of systematic procedures that still have to prove their value in design practice. Therefore, the model should be used with caution, as it is a consolidated model of how students should idealistically solve design problems.

The observations of the students also led to the conclusion that the actual process that students follow to solve design problems without the supervision of an instructor is more simplistic than the teacher fabricated 12-step engineering design process utilized by some curriculum designers and vendors. Students seem to have a more natural and inherent process for solving problems; therefore, it is recommended that current

engineering design process models be separated into design heuristics used for different problem-solving situations and not utilized as a requirement for students to solve problems. For example, some students in this study generated multiple solution ideas and then created a decision matrix to determine which solution to make. These actions, in this situation, did not lead to more viable solutions and many students did not take these actions. Thus, certain aspects of the idealistic processes may not be necessary or applicable to all situations; therefore, they can become design heuristics for students to add to their problem-solving toolbox.

Another recommendation is for the technology and engineering education profession is to rethink its purpose and to look at how it might integrate the teaching of germane technological tools, manipulating industry quality materials, and generating new knowledge through scientific investigations to solve authentic and relevant global or local design problems. As design expertise literature indicates, drawing on specific experiences is what enables the production of good solutions. Authentic engineering design using industry quality materials and tools can provide the prior knowledge students need for solving future issues. The purpose of the technology and engineering profession should then shift to focus on providing experiences with current technologies and advanced materials rather than teaching general concepts using popsicle sticks, cardboard, and hot glue. In doing so, technology and engineering education can establish a learning environment that is not replicable by other academic school subjects.

The results of this study support this recommended shift in purpose. The participants, who were experienced in utilizing the engineering design process, enacted a more natural and simplistic method for solving an engineering design challenge when

they were left on their own to do so. Therefore, it may be suggested that years of technology and engineering coursework does not actually change students' problem-solving behavior. The technology and engineering profession generally claims that it enhances the development of general problem-solving skills. However, the results may indicate that problem-solving skills could be natural; therefore, the profession should focus on providing students with authentic experiences versus requiring idealistic problem-solving processes. Jonassen, Strobel, and Lee (2006) studied practicing engineers and determined that prior experiences were the biggest factors for successfully solving problems. Additionally, Cross (2001) stated that experience in a specific problem domain enables designers to move quickly to identifying a problem frame and proposing a solution conjecture and the accumulation of experience is a vital part of transformation to becoming an expert.

This study has provided insights for developing engineering design curricula and instruction at the secondary level. From this study, practitioners and researchers in the technology and engineering and STEM education fields can better understand how students actually solve engineering design challenges and how engineering design curriculum and instruction can develop a student's problem-solving abilities. Additionally, the results provide information for enhancing engineering design teaching practices. However, more information is needed to properly inform the field about the engineering design concept. Consequently, the following recommendations, based upon the findings and conclusions of this study, are suggested for further research for informing the teaching of technology and engineering education in the K–12 environment.

Revisit the mental processes. The first recommendation is to revisit the 17 mental processes for technological problem-solving used in this study. Halfin (1973) originally identified the 17 mental processes by analyzing the works of well-known engineers, industrialist, designers, inventors, and innovators. Halfin then validated and defined these processes through a Delphi study consisting of educators, government employees, industrialists, and scholars considered to be experts in the field of technology. However, his findings also suggested that there was some confusion among the Delphi panel's members in differentiating some of the processes. Wicklein and Rojewski (1998) later revalidated the original 17 processes and potentially identified 10 additional mental processes. However, their work made no attempt to remove any processes that were repetitive or too similar to one another. Therefore, the additional processes were unable to be differentiated by the researchers in this study and could not be utilized. As a result, it is recommended that these mental processes be revised with a focus on engineering design and validated using professional engineers and cognitive scientists. The addition of cognitive scientists can help in the determination of underlying cognitive processes and aid in creating clear and distinct operational definitions of the processes themselves.

Larger sample size. The results of this study provided further insight into the way experienced technology and engineering students actually think and act throughout the problem-solving process. Additionally, comparing students who produce more successful solutions to students who produce less successful solutions can help identify possible ways to develop effective problem solvers. This information can aid in designing more authentic curricula, instruction, and assessments to develop and monitor student problem-solving skill growth. However, these findings are only based upon the actions of

eight participants in one area of the United States. This sample size is too small to generalize the results to all U.S. students. Therefore, it is recommended that more researchers employ the methodology for comparing the cognitive processes of more effective solution producers and less effective solution producers with a large sample size. This type of study can have a greater impact on educating students with better problem-solving abilities.

Various student levels. It is recommended that researchers replicate this study with participants at various educational levels. Studying various populations can enable the comparison of students' design processes at the novice, intermediate, and expert levels. These comparisons can be used to determine the differences between individuals and portray how well technology and engineering curricula foster the development of students' engineering design skills. For example, this study could be replicated with students just beginning the *Project Lead the Way* pre-engineering program and the results can be compared to those of students in the capstone course. This study could help determine whether or not the pre-engineering program actually changes students' problem-solving cognition and behaviors. Additionally, this could be compared to participants who are college engineering students and participants who are working engineers. These studies could also help determine whether problem-solving skills can be developed or if they are inherent.

Engineering design process steps. It is recommended that researchers replicate this study utilizing the 12-steps of the engineering design process as the codes. This study would enable one to see which steps the participants used, when the steps were used, how long they were used, and the frequency at which they were used. These findings can then

provide insight into which of the 12-steps can be eliminated or if there are any steps to be added. Based on the findings of this study, the engineering design process can be further refined.

Impact of materials. While observing the participants as they solved the given design challenge, it was noted that their solution designs were impacted by the materials they had available and by the materials they were familiar in their laboratory. The participants did not see any materials while they were designing their solution; but, when they saw some items available to use as they began construction, they changed their design instead of locating the proper materials to use. These participants consistently relied on using non-technical materials, such as duct tape and hot glue, and did not think about the construction quality of their solutions. Further research is recommended on determining the impact of materials during the engineering design problem-solving process and if students can make the mental transfer from using non-technical materials for models to using authentic materials for prototype construction and testing.

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APPENDIX A

Setting Description

Location: A West Virginia Career & Technical Center

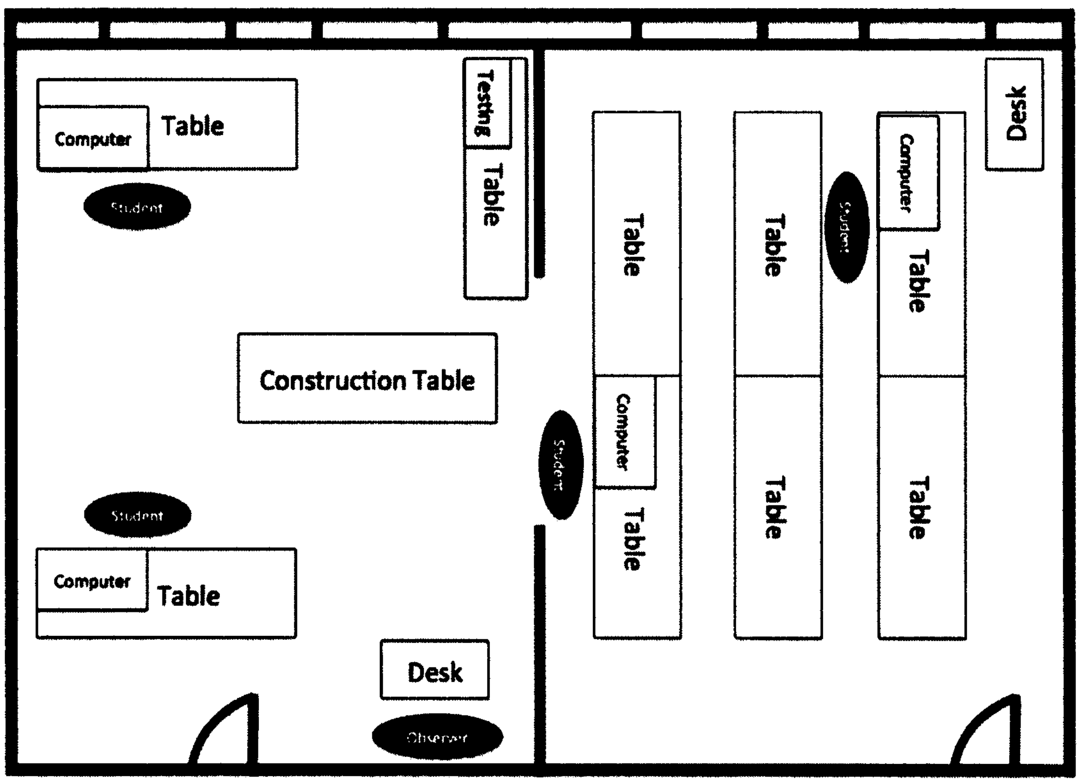
Participants: Junior and senior high school students enrolled in the capstone course of the *Project Lead the Way* pre-engineering program

Date: March 15-17, 2014 **Time Start:** 7:25am **Time End:** 11:15am

Student Materials: Notepad, pen, computer, testing equipment, construction materials

Goal: Observe students in interaction with an engineering design problem.

Room Layout:



Procedure: Students were individually placed at different locations in the production technology laboratory. Students completed the engineering design challenge at different lab tables to minimize student-to-student interactions. The researcher found a location to monitor the students from a distance while minimizing researcher and student interaction.

APPENDIX B

Engineering Design Challenge

(Adapted from *Project Lead the Way*)

Introduction:

Water is obviously an important resource. In some places water seems plentiful. However, in many places water is not plentiful, or the water that is available is not suitable to drink. Depending on where you live in the world, you may or may not have been exposed to this issue. In many developing countries, clean water is not readily accessible and therefore disease and illness is spread. This is especially true in the aftermath of natural disasters in these areas. While there are many challenges related to clean water, purification is an important part of many water treatment processes.

Problem Statement:

People in developing countries do not have continuous access to clean water, especially after the onset of a natural disaster. Water in these situations needs significant purification. However, water purification units are expensive and not easy to obtain. Therefore, you are tasked to design an inexpensive, easy to use, easy to assemble, durable, and low maintenance water purification system using low cost, readily available materials to quickly remove contaminants from water. You will focus on reducing the turbidity of a sample of water.

Testing Performance:

Turbidity is a measure of the lack of clarity (cloudiness) of water and is a key test of water quality. Turbidity is apparent when light reflects off of particles in the water. Sources of turbidity include soil erosion, waste discharge, urban runoff, events that stir up

sediments, humic acids and other organic compounds that result from decay of leaves and plants, and algal growth. In addition to creating an unappealing cloudiness in drinking water, turbidity can be a health concern. It can sustain or promote the regrowth of pathogens in the water distribution system, which can lead to the spread of waterborne diseases. Turbidity is measured in Nephelometric Turbidity Units, NTU. Water is visibly turbid at levels above 5 NTU. The standard for drinking water is 0.5 NTU to 1.0 NTU. In addition, some states have established water quality standards for water bodies that include turbidity standards.

Materials

- You are not limited to any specific materials.
- You can use any materials necessary to create the best solution.
- You should not be concerned with material availability.
- You should design your solution to best meet the specified criteria and constraints.
- You should create a list of materials, so that any materials that are not readily available in the production technology lab can be purchased for you in between design sessions. Your final solution should be of prototype quality.

Equipment

- Computer and Internet access
- Distilled water
- Contaminated water
- Sample bottle with lid
- Paper towels

- Bucket or other container to capture purified water
- Vernier Turbidity Sensor
- Turbidity Standard (included with Vernier Turbidity Sensor)
- Turbidity curvette (included with Vernier Turbidity Sensor)
- LabQuest Mini
- Logger Pro software

Procedure

1. Before beginning to design your solution for **the Mini Engineering Design Project**, consider a tentative plan that you should follow based on your knowledge of engineering.
2. As you work to solve this problem, be mindful of your processes.
3. Design, make, and evaluate a water purification system to decrease the turbidity of a water source. Document your process in your ***engineering journal*** using best practices.
4. As you progress toward your final design, refer to your plan and make appropriate adjustments
5. Build a ***functioning prototype*** of the water purification device. The prototype should be built showing quality workmanship.
6. Test your device to determine the turbidity of the water.
7. During the testing phase:

a. Calibrate the turbidity sensor using the instructions provided with the equipment.

b. Use the Turbidity Sensor, LabQuest Mini, and Logger Pro to measure, collect, and record the turbidity of contaminated sample and the purified water. You may want to investigate the advantages of running the water through your system more than once.

8. Create a ***Solution Justification***.

9. Once you have finalized your design and presented your solution, you will reflect on your process by answering the ***reflection questions***.

Deliverables:

- Functioning Prototype of Quality Construction
- Project Journal
- Solution Justification
    - A summary of the details of the design, its benefits, uses, and other important information that explains the design solution.
- Reflection Questions

Reflection Questions

Complete the following reflection items in your journal:

1. How would you define the problem you were asked to solve?
2. How well do you believe you solved the problem?
3. What information was needed for designing your solution?

4. How did you figure out the details for your possible solutions?
5. How many potential ideas did you consider?
6. Describe your methods of developing different design solutions or ideas.
7. What helped you decide which ideas would work and which ones would not?
8. Describe how you chose the best design solution.
9. Explain your testing results.
10. Would you drink the water that you filtered? Why or why not?
11. Based on this experience, what will you be sure to do differently when solving another engineering design problem?
12. Create a mind-map that reflects your process for solving the problem. Your mind map should clearly provide all the tasks and specific details that you undertook while creating your solution.
13. What materials would you use if you were to actually build your device?
14. How did the availability of materials influence your final solution design?

APPENDIX C

Participant Survey

***1. What is your student number?**

- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5
- ☐ 6
- ☐ 7
- ☐ 8

2. What grade are you enrolled?

- ○ Freshman
- ○ Sophomore
- ○ Junior
- ○ Senior
- ○ Fifth year / Other

3. What is your gender?

- ○ Female
- ○ Male

***4. What is your age?**

- ○ 14
- ○ 15
- ○ 16
- ○ 17
- ○ 18
- ○ 19
- ○ 20 or Older

Other (please specify)

____

***5. What high school do you attend?**

***6. What is your mother's current occupation?**

***7. What is your father's current occupation?**

***8. What is your GPA?**

- 4.1 or above
- 3.6 - 4.0
- 3.1 - 3.5
- 2.6 - 3.0
- 2.1 - 2.5
- 2.0 or below

***9. Please list the technology and engineering courses have you taken throughout middle and high school.**

***10. Please list the mathematics courses you have taken in high school.**

***11. Please list the high school science courses you have taken.**

12. Select the after school programs in which you have participated.

- [ ] FIRST Robotics
- [ ] FIRST Lego League
- [ ] VEX Robotics
- [ ] Math Club
- [ ] Science Olympiad
- [ ] Skills USA
- [ ] Technology Student Association

Other (please specify)

***13. Please describe your career interests.**

***14. In your own words, please describe the engineering design problem solving process.**

APPENDIX D

Procedure for the Challenge

This research is being conducted today because I am interesting in the way that you actually think as you solve engineering design problems. There are no other hidden motives. You have been selected as participants in this study because you are considered pre-engineering experts. Each of you has taken multiple *Project Lead the Way* courses and should have had experiences with using the engineering design process to solve problems. Today, you are going to work through an engineering design problem while recording what you do and say using a point-of-view camera. Do not worry, the videos will be confidential and your face will never actually been seen on the footage. There is no need to be nervous; everyone in this class will be doing the same thing.

As I said, you are an expert here, so solve the problem in the manner that you see best. Do not do what you think I want you to do or what your teacher wants you to do. You are the experts. Engineers use a variety of problem-solving methods. Reasons for using a specific method vary from preference, to addressing a specific problem, to requirements set by a corporate entity.

As you work to solve this problem, you will need to do the following:

- You must work alone to solve the challenge
- You must not talk to other students
- You will have two full class periods to solve the challenge
- You will need to budget your time between designing, building, and testing. You will have approximately 3 hours to complete the engineering design challenge.
    - The Design phase will consist of understanding the problem and developing a solution idea.
    - The Construction phase will consist of locating materials, constructing the solution, and troubleshooting your solution.
    - The Testing phase will consist of evaluating and refining your solution to the problem.

    a. You must not talk about the challenge outside of the class with other students.

b. At the start of each class you will be asked about your thoughts on the challenge while you were outside of class.

Thinking Aloud

Now we need to discuss the thinking aloud process that you will be doing. While you are working on the challenge, you will wear a point-of-view camera over your ear. This will capture what you are doing, saying, and viewing. Remember the camera will not capture your face. The unique thing that we will be doing is the thinking aloud. As you complete the challenge you will be required to talk through your thoughts. This means that you must verbalize what you are thinking as you are working to solve the problem. Thinking Aloud is a method that allows researchers to understand, at least in part, the thought processes of a person as they perform some type of task. As you are completing the challenge, the only time I will talk to you is when I need to remind you to keep talking or thinking aloud.

Getting Ready

Now let's get ready to begin. Remember the goal of this activity is to capture your thoughts as you act to solve a problem. We are investigating the process that you go through, yet do not focus too much on saying the right thing, focus more on the thoughts you are having for design ideas and solving the challenge.

1. So let's practice! I am going to give you a simple task. "*Tell me the number of windows in your house*." As you are thinking, you need to speak what is going on in your mind to explain the process.
2. *One more example: A bottle of soda costs $1.25. The soda costs $0.55 more than the bottle. How much does the bottle cost?*

Presenting the Problem

Now let's discuss the design challenge (Present the Engineering Design Challenge found in Appendix B). You must complete this challenge in the manner that you would if no one were watching. It is important that you say aloud everything that you think as you work to complete the challenge. To test the functioning of your device you will use the

turbidity sensor found at the testing station. Once you complete your solution, the teacher and the researcher will evaluate you on how well your solution solves the problem.

Beginning the Task

You are ready to begin the task. You need to remember that:

- You will only have approximately 3 hours to design, build, and test your solution.
- You need to make sure your camera is turned on. The camera will begin beeping in your ear if the battery is dying.
- You need to be talking at all times and when you are talking you are explaining what you are thinking not just saying what you are doing.
- You cannot talk to other students.
- You may not discuss your solution outside of class.
- Once you are done testing, please let me know and then begin answering your reflection questions.
- You may ask questions at any point in the process, but you may not receive an answer to them.
- You can use a computer.
- You should not be nervous or embarrassed. It is okay if you have trouble solving the problem.

Now just relax and perform the task and say out loud what comes to your mind. Our focus is on the thought process that you go through. With that in mind, please speak loud and clear.

APPENDIX E

Engineering Design Rubric

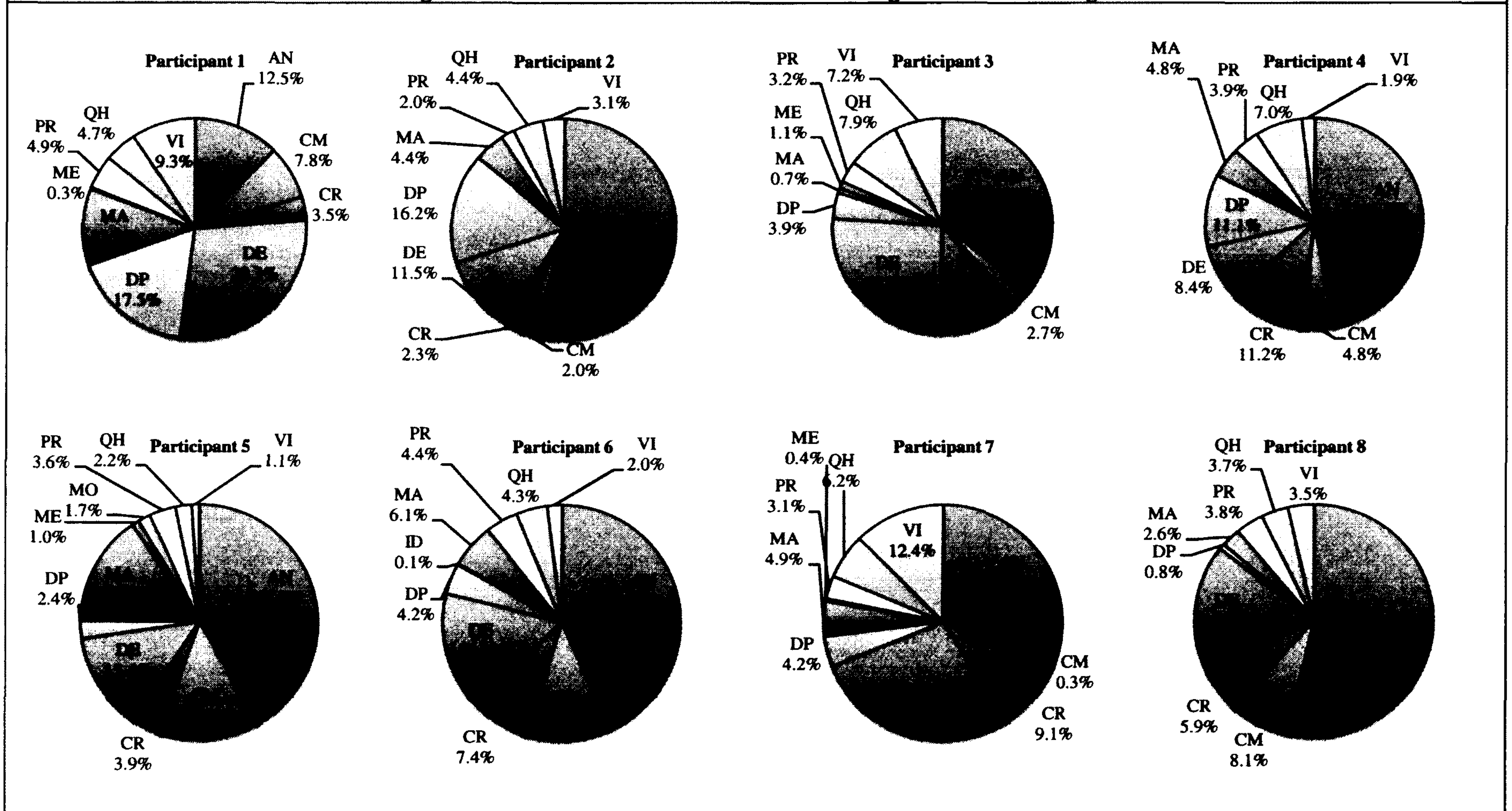
(Adapted from *Project Lead the Way*)

Elements	Weight	5 Points	4 Points	3 Points	2 Points	1-0 Points	Total
Research of Current and Past Solutions		Thoroughly researched and documented existing products and patents.	Many existing products and patents were researched and documented.	A few existing products and patents were researched and documented.	Very little evidence that existing products and patents were researched.	No evidence that existing solutions were researched.	
Multiple Solutions Considered		Considered 5 or more possible solutions.	Considered 4 possible solutions.	Considered 3 possible solutions.	Considered 2 possible solutions.	Did not consider multiple solutions	
Design Justification		Justification for pursuing final design is obvious.	Justification for pursuing final design is evident.	Some justification for pursuing final design is evident.	Very little justification for pursuing final design.	No evidence of justification for pursuing final design.	
Material Selection		All of the materials used were all of quality and enabled the making of a solution that met all of the criteria and constraints.	Most of the materials used were of quality and enabled the making of a solution that met all of the criteria and constraints.	A few of the materials used were of quality and enabled the making of a solution that met all of the criteria and constraints.	Materials used did not aid in the creation of a quality solution.	Materials used did not aid in the creation of a quality solution.	
Performance (filtration)		After filtration, the clarity of the water is less than 5 NTU.	After filtration, the clarity of the water is mostly clear.	After filtration, the clarity of the water is somewhat clear.	After filtration, the clarity of the water has changed very little.	After filtration, the clarity of the water has not changed.	
Performance (time)		The filtration device worked as fast as or faster than other student created filtration devices.	The filtration device took 20% more time than the fastest student created device.	The filtration device took 40% more time than the fastest student created device.	The filtration device took 60% more time than the fastest student created device.	The filtration device took twice as long as or longer than the fastest student created device.	
Product Durability		The final product received no damage or wear and required no adjustments or repairs during testing.	The final product received very little repairable damage or wear during testing and required little adjustment.	The final product received some damage or wear during testing but was easily repaired. Minor adjustments were required.	The final product received some damage or wear during testing that was not easily repaired. Major adjustments were required.	The final product received significant damage or wear during testing that was not easily repaired and interfered with testing.	
Product Ease of Setup		The final product could be easily set up and used with little or no instruction.	The final product could be set up and used with some instruction.	The final product would require careful set up with some instruction.	The final product requires significant set up with detailed instruction.	The final product is very difficult to set up and requires extensive or complicated instructions.	
Engineering		All Best	80% or more of	60% of Best	40% of Best	Less than 40%	

Notebook		Practices for Engineering Notebook are applied (see below). ☐ Quad ruled pages ☐ Bound ☐ Pages numbered, dated, and signed by designer and witness ☐ No blank space ☐ Mistakes crossed through – no erasures ☐ Inserts securely affixed ☐ Sketches labeled and fully annotated ☐ Daily progress entries	Best Practices for Engineering Notebook are applied. The quality of documented information is average.	Practices for Engineering Notebook are applied. The quality of documented information is poor.	Practices for Engineering Notebook are applied. The quality of documented information is poor. Multiple entries are missing.	of Best Practices for Engineering Notebook are applied. Few or no Engineering notebook entries are included.	
Prototype Testing		Test procedures are followed and correct data are collected. The student is knowledgeable regarding the reason for the test, each step in the procedure, and the significance of the data.	Test procedures are followed and correct data are collected. Tests are stopped if unsafe conditions occur.	Minor deviations in test procedures and data collection occur. The student is unfamiliar with the reason for the tests performed.	Test procedures are not followed. Some tests are performed in an unsafe manner. The student did not conduct tests in order to evaluate and improve the prototype.	Little to no evidence exists to indicate that prototype test procedures were conducted.	
Prototype Revision		The test evaluation results in suggestions for improvement. Detailed description of the design modifications that were made based upon the results of prototype testing.	The test evaluation results in suggestions for improvement. Many details of the design modifications that were made based upon the results of prototype testing.	The test evaluation results in suggestions for improvement. Less than adequate description of the design modifications that were made based upon the results of prototype testing.	The test evaluation results in minimal suggestions for improvement. The product includes a less than adequate description of the design modifications that were made based upon the results of prototype testing.	Little to no evidence exists that revisions are considered or made.	
Final Score							

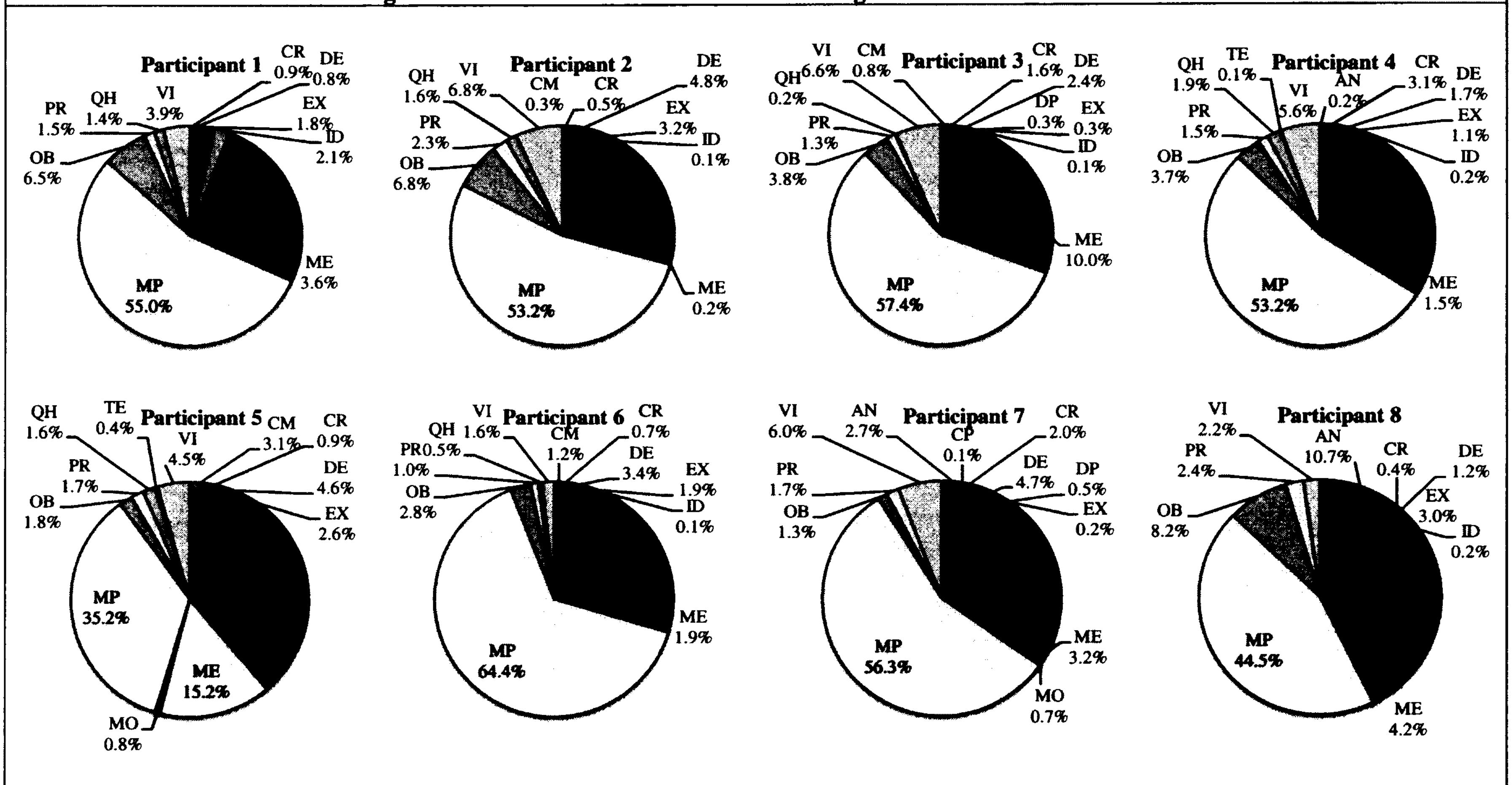
APPENDIX F

Percentage of Time Taken Per Mental Process During the Solution Design Phase



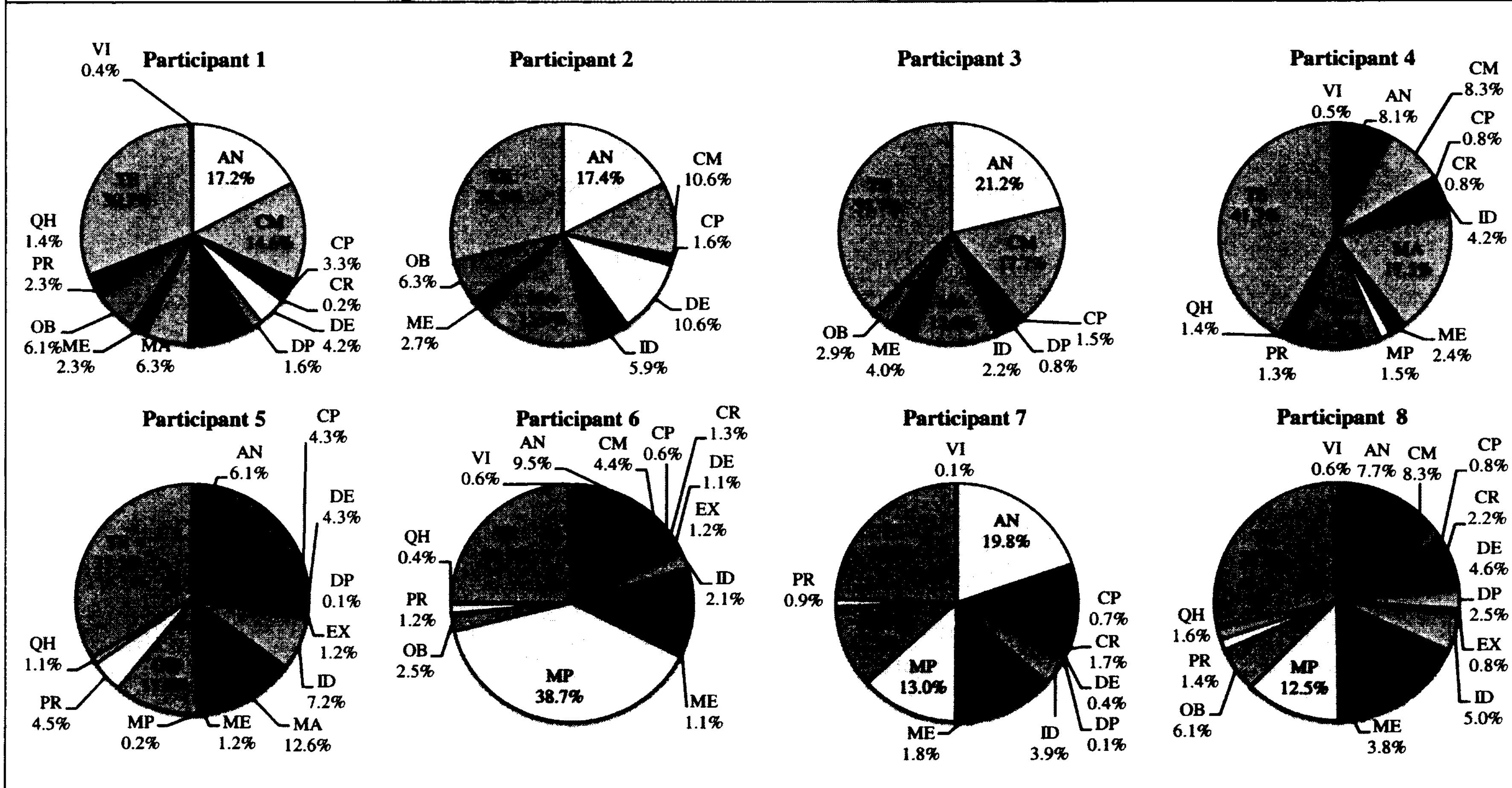
APPENDIX G

Percentage of Time Taken Per Mental Process During the Solution Construction Phase



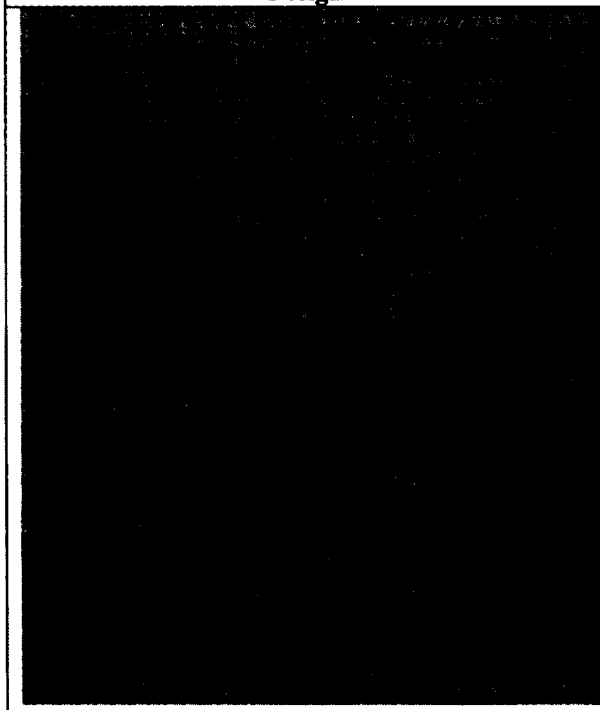
APPENDIX H

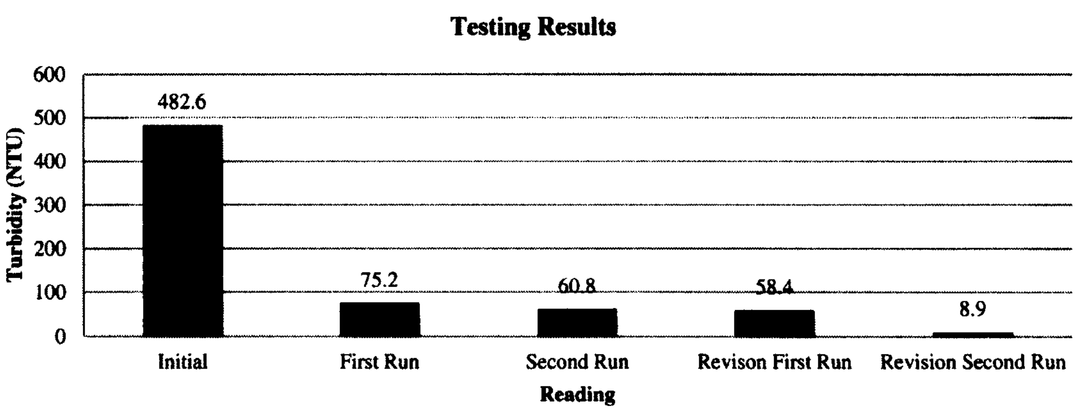
Percentage of Time Taken Per Mental Process During the Solution Evaluation Phase



APPENDIX I

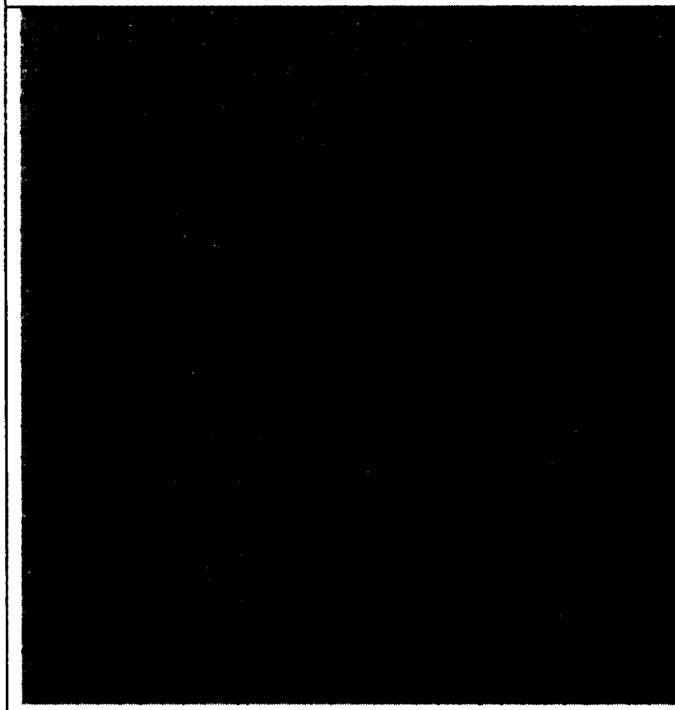
Participant 1 Design Summary

Design	Prototype
	

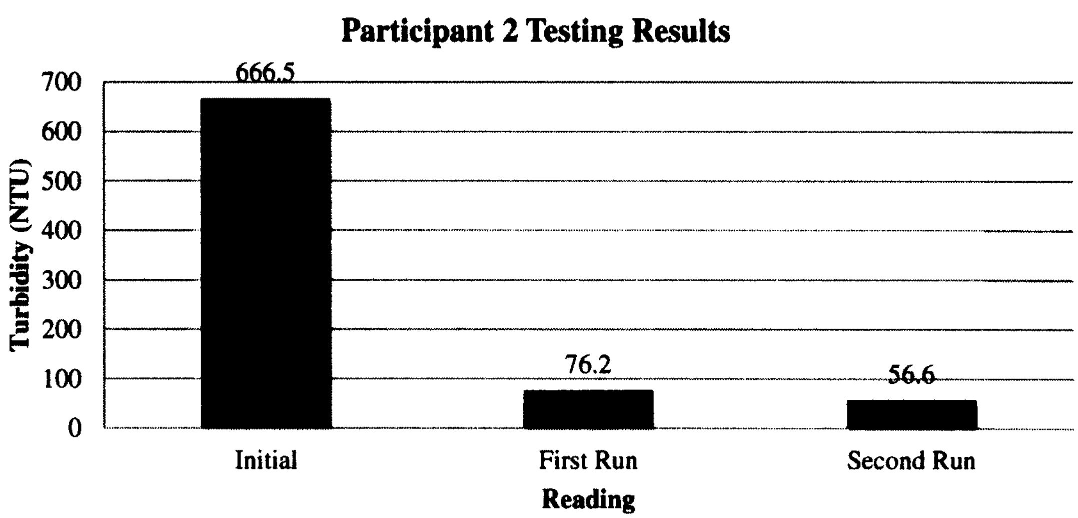


Solution Justification:

I did not get to an NTU level suitable for drinking water, but my system greatly reduced the levels initially and continued afterward in smaller increments. I believe if I were using more water perhaps from a stream or river, it would be easier to differentiate water that I had run through the system multiple times from that which was on its first filtering. I think this kept my result higher for the second and third tests, and although the level still probably wasn't at drinking level, after 5 or 10 repeats, the water NTU would probably be fairly close to drinking level. Water filters through 2 coffee filters activated carbon sand and funnels into the bottom half of the 2-liter soda bottle. Benefits include low cost (under $20), readily available materials, and small amount of assembly and maintenance. It reduces turbid water of 425 NTU.

Participant 2 Design Summary	
Design	**Prototype**
	

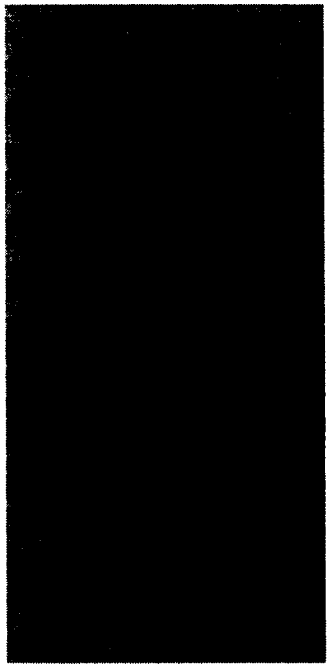
Testing Results:



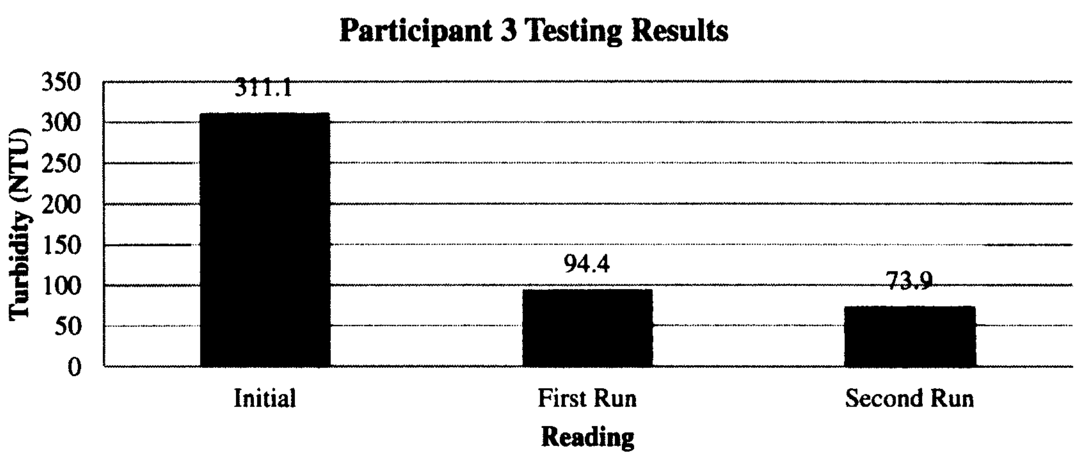
Solution Justification:

The NTU of the contaminated water before being put through my filter was 666.5. After the first run or attempt, the NTU dropped to 76.2. I was fairly pleased with this outcome. Then I put the remaining water from the first run through the filter for a second time, and the results were an NTU of 56.6. So therefore, my filter did reduce the amount of turbidity in the water. I feel that I could have reduced these numbers even more if I had the chance to test the filter more.

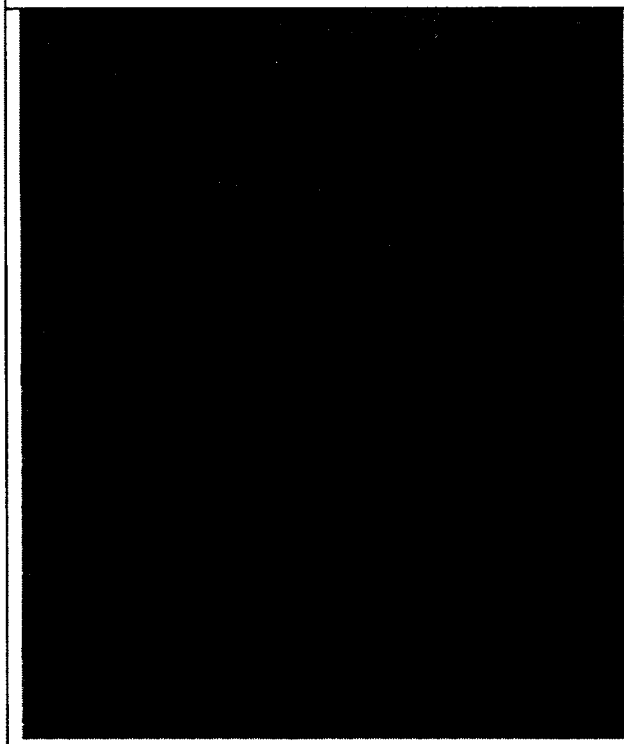
Participant 3 Design Summary

Design	Prototype
	

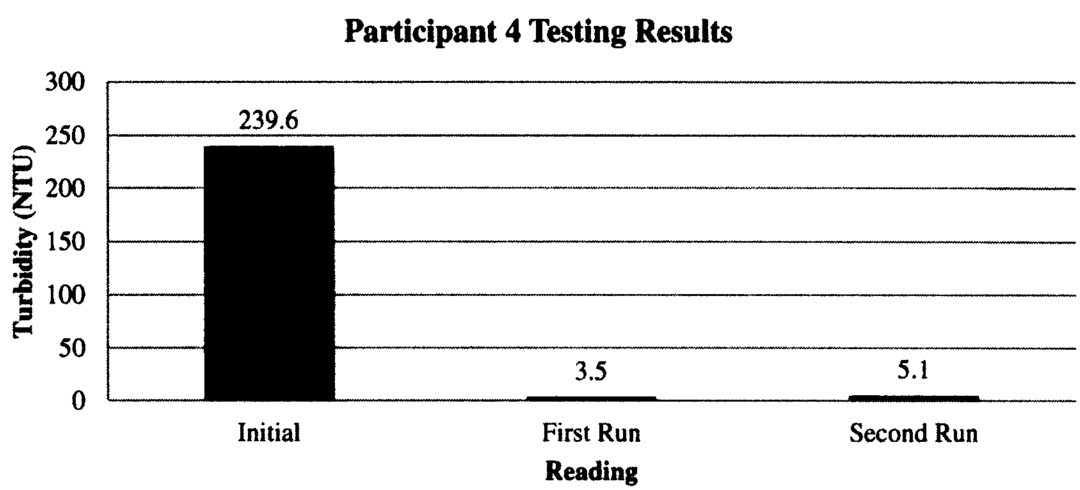
Testing Results:



Solution Justification:
I chose to use this design because you do not need any electricity. Pieces of clothes are easy to buy because everyone wears clothes. Also the materials do not cost a lot of money and the design is not hard to make.

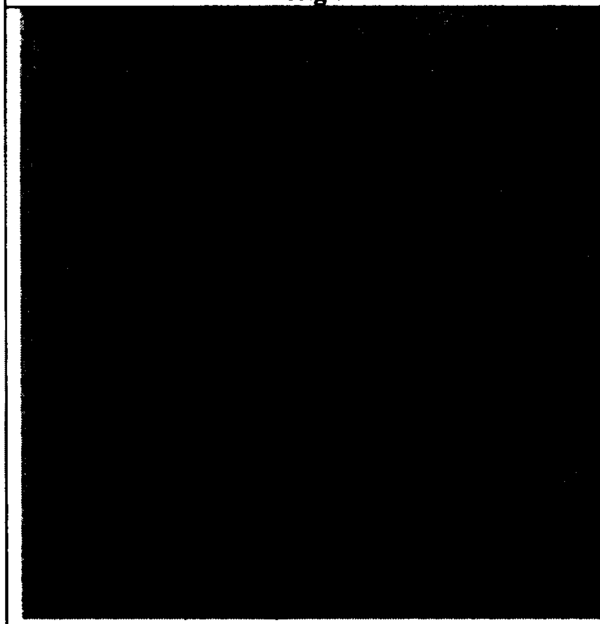
Participant 4 Design Summary	
Design	**Prototype**
	

Testing Results:

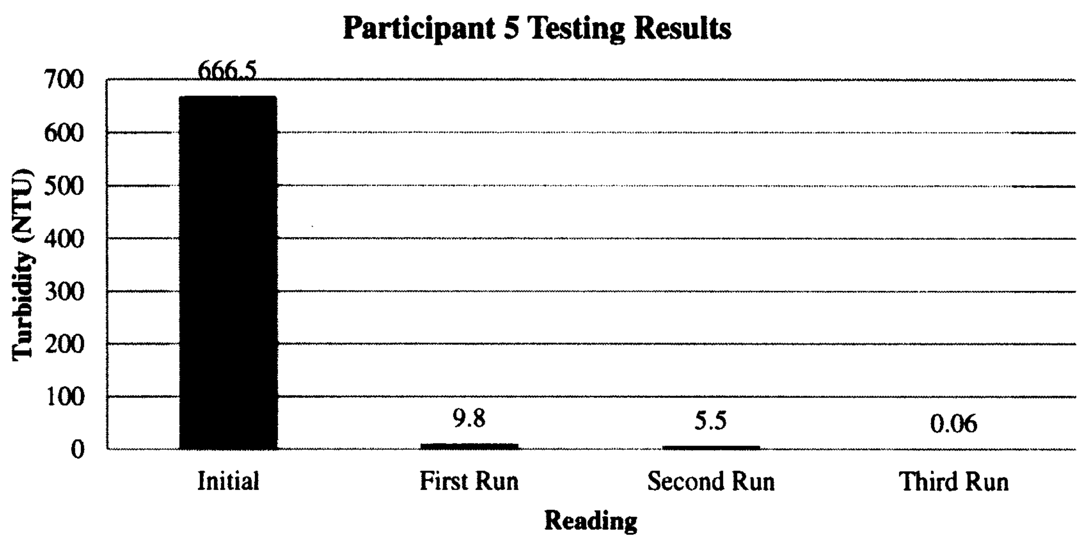


Solution Justification:
The benefit of my filtration system is the ability to get clean water. Testing showed NTU levels below 5, which is the city standard. Due to cost and materials, my device could work in disaster areas or African villages. Water is run through sand and coffee filter, then a coffee filter and gravel, ending with activated carbon and a coffee filter.

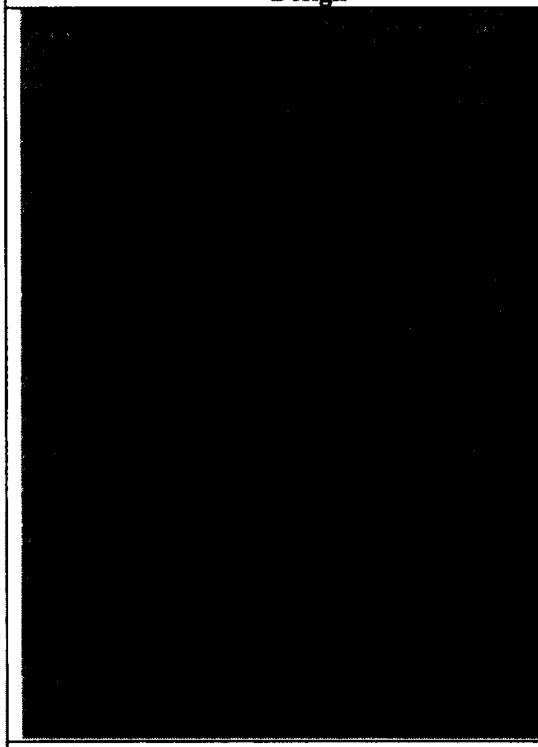
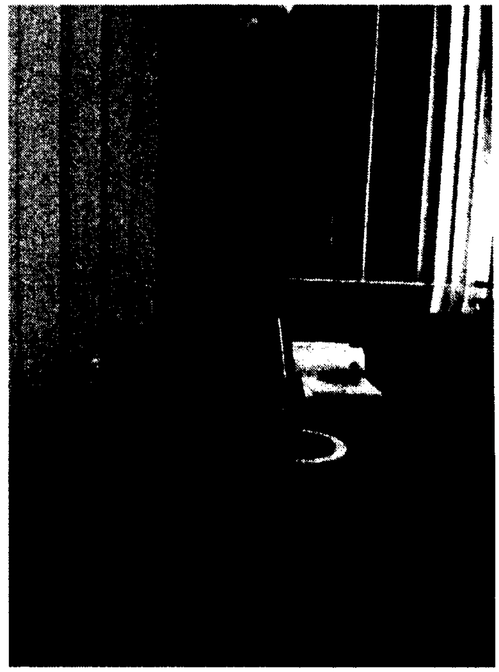
Participant 5 Design Summary

Design	Prototype
	

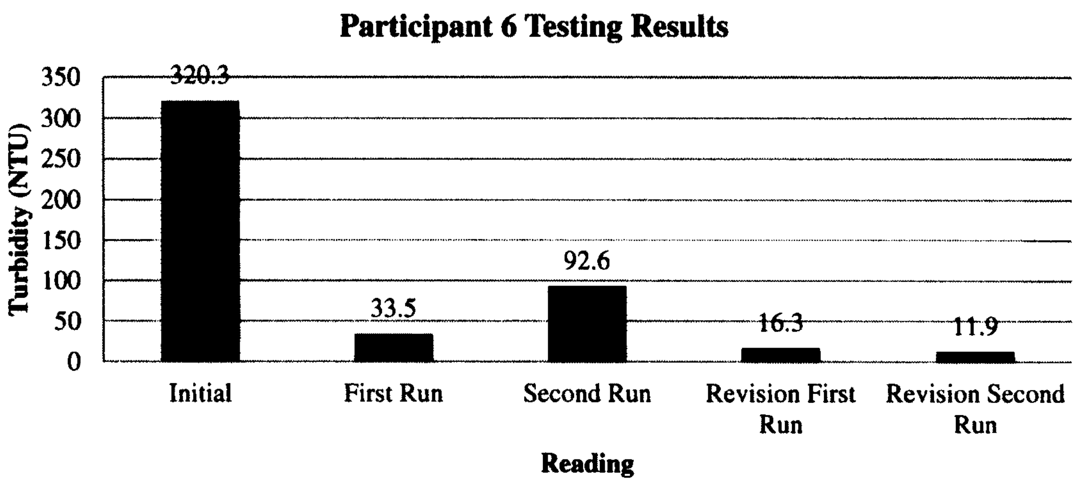
Testing Results:



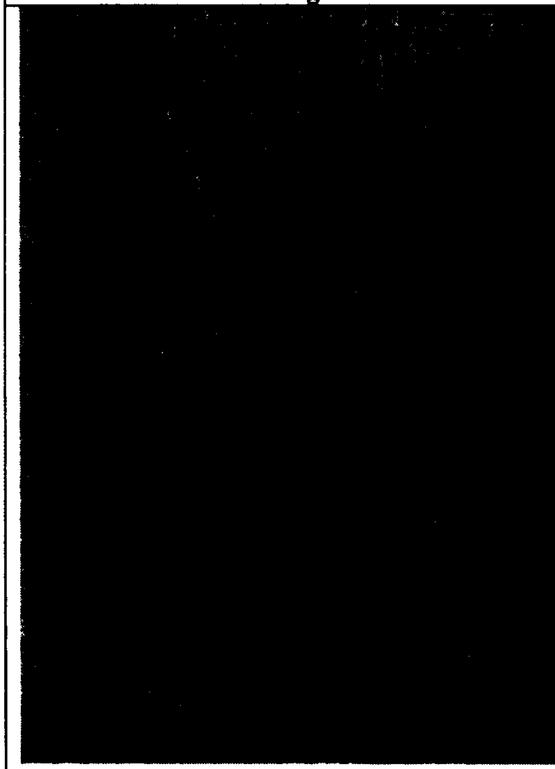
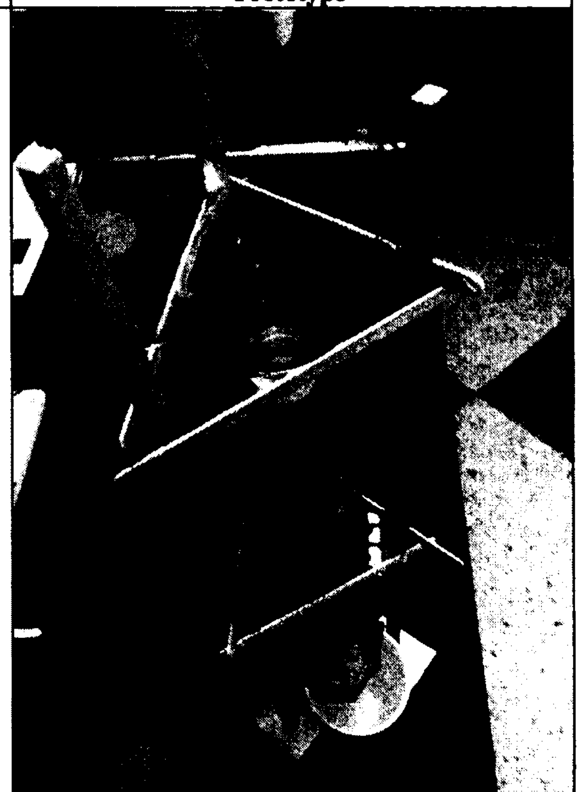
Solution Justification:
I used a 2-liter plastic bottle to hold the contents of my filter. I used a coffee filter to cover the outside of the bottle and a cotton ball to block the hole. I used thin layers of charcoal, 2 different sands, and gravel to fill the bottle. At the top I used a double layer of gravel. I used a plastic cup to catch the draining solution. The charcoal was used to trap the contaminates, and it worked how it was supposed to. My design worked well; after three filters, I had the turbidity down to 0.6 NTU. I would have altered the design if I were doing the project again. I would have used smaller amounts of sand to make the filter work more quickly. I would also use a double layer of gravel in the center as well as the top. Overall it was a good design and a solution to the problem.

Participant 6 Design Summary	
Design	**Prototype**
	

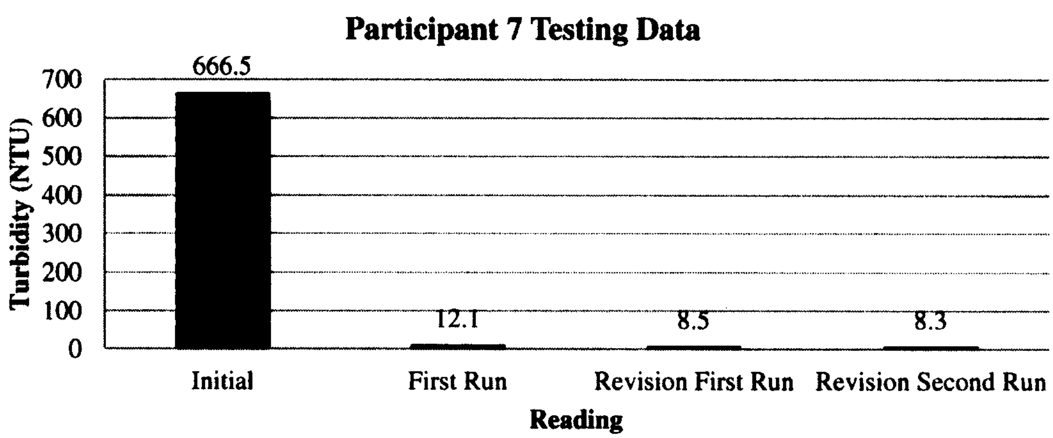
Testing Results:



Solution Justification:
Supposed to filter water to a drinkable state. I have two coffee filters and many netted fibers to filter the turbidity from the water. After the second test the water was still undrinkable but it was much better than the first. Coffee filter benefited. Wouldn't be used for drinking.

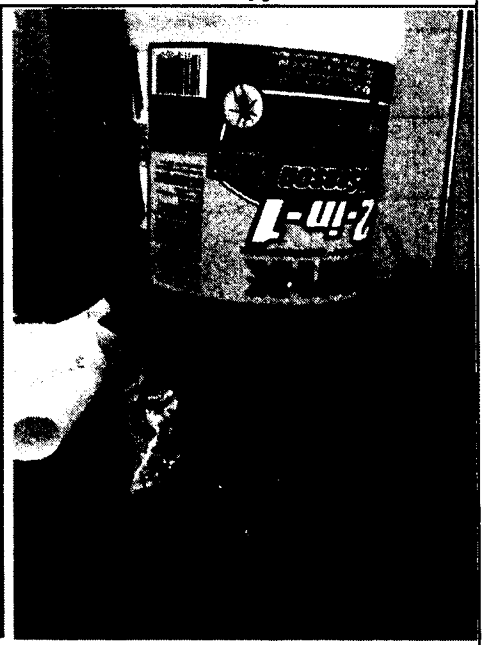
Participant 7 Design Summary	
Design	**Prototype**
	

Testing Results:

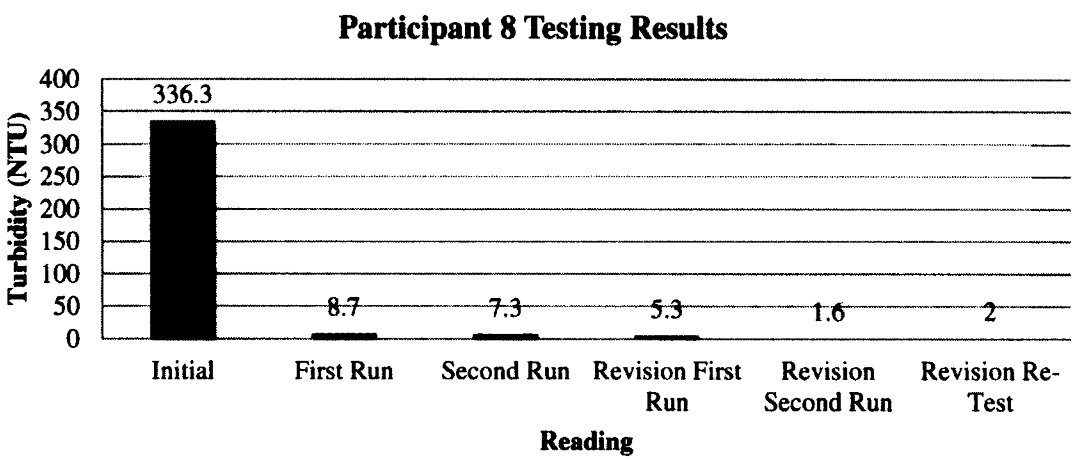


Solution Justification:
The design involved layered filters held together in a tower. First charcoal, then sand, then stuck a cotton ball down in the bottle. Then led to two layers of coffee filters. Advantages: Structurally sound, consists of recycled materials and household items, minimum work, filters several cups of water at a time. Disadvantages: Time consuming (10 minutes to fill), turbidity at 8.5 (3 above visible; 7 above acceptable level for drinking water), nothing in filter acting as a disinfectant; cotton balls, filters, etc. need to be constantly replaced.

Participant 8 Design Summary

Design	Prototype
	

Testing Results:



Solution Justification:
I used a layer of cotton then gravel ten charcoal then sand, a coffee filter, then gravel on top. I could use this design to make safe drinking water from any contaminated source. Any container that can hold your materials in layers and allow water to pass through.

VITA

Greg Joseph Strimel

Education

M.Ed. California University of PA 2010 Technology Education
B.S.Ed. California University of PA 2008 Technology Education

Certifications

Technology Education K-12 Instruction I Certificate (Pennsylvania)
Technology Education 7-12 Standard Professional I Certificate (Maryland)

Professional Experience

2014-Present	West Virginia University, Statler College of Engineering and Mineral Resources, *Adjunct Faculty*
2013-Present	West Virginia University, Academic Innovation, *Director of K-12 Initiatives*
2013-Present	iSTEM~Design Consulting, *Founder & Lead Consultant*
2011-2013	Howard Count Public Schools, *STEM/Career & Technology Education Department Chair*
2011-2013	University of Maryland Eastern Shore, *Adjunct Faculty*
2009-2011	Howard Count Public Schools, *Technology and Engineering Education Teacher*
2002-2008	United States Army, *Infantry*

Service

2011-Present	International Technology & Engineering Educators Association, *Curriculum and Instruction Specialist & National Teacher Effectiveness Coach*
2014	Governor Earl Ray Tomblin's STEM Committee Meeting, *Education Stakeholder*
2014	Nation Academy of Engineering: Guiding Implementation of K-12 Engineering Education, *Steering Committee Member*
2014	Next Generation Science Standards Steering Committee for West Virginia, *High School Member*
2012-2013	Project Lead the Way- *Engineering Design & Development Master Teacher*

Publications

Strimel, G. J. (2014). Authentic education by providing a situation for student selected problem-based learning. *Technology and Engineering Teacher, 73*(7), 8-18.

Strimel, G. J. (2014). Engineering by design high school curriculum. In C. Sneider, (Ed.), *Engineering curriculum: Ready set go*. Thousand Oaks, CA: Corwin Press.

Strimel, G. J., Reed, P., Dooley, G., Bolling, J., Phillips, M., & Cantu, D. V. (2014). Integrating and monitoring informal learning in education and training. *Techniques, 89*(3), 48-55.

Strimel, G. J. (2014). Shale gas extraction: Drilling into current issues and making STEM connections. *Technology and Engineering Teacher, 73*(5), 16-24.

Strimel, G. J. (2013). Engineering by design: Preparing STEM teachers for the 21st century. In J. Williams (Ed.), *Technology education: A play on sustainability* (pp.447-456). New Zealand: Canterbury University.

Huffman, T. & Strimel, G. J. (2013). *Technological design* (3rd ed.). Reston, VA: ITEEA.

Strimel, G. J. (2012). Engineering by design: Preparing students for the 21st century. In T. Ginner, J. Hallström, & M. Hultén (Eds.), *Technology education in the 21st century* (pp. 434-443). Stockholm, Sweden: Linkoping University.

Love, T. & Strimel, G. J. (2012). An elementary approach to teaching wind power. *Technology and Engineering Teacher, 72*(4), 8-14.

Selected Presentations

Strimel, G. J., Cantu, D.V. (2014, March). *I chose an engineering pathway because....* International Technology and Engineering Educators Conference, Orlando, Florida.

Strimel, G. J. (2014, March). *Next generation mathematics for West Virginia schools.* West Virginia Council of Teachers of Mathematics Conference, Stonewall, West Virginia.

Strimel, G. J. (2013, December). *Engineering by design: Preparing STEM teachers for the 21st century.* Paper session presented at the meeting of the Pupils Attitudes Toward Technology Conference, Christchurch, New Zealand.

Strimel, G. J. (2013, July). *K-12 digital transformations to the common core.* West Virginia State Technology Conference, Morgantown, WV.

Strimel, G. J. (2013, March). *Real-world math through digital learning: A WVU initiative.* West Virginia Council of Teachers of Mathematics Annual Conference, Stonewall, WV.

Cantu, D., Roberts, A., & Strimel, G. J. (2013, March). *Addressing common challenges when implementing integrative STEM curriculum.* Paper session presented at the meeting of the International Technology and Engineering Educators Association (1TEEA), Columbus, OH.

Cantu, D., Roberts, A., & Strimel, G. J. (2013, March). *Best practices in integrative STEM.* Paper session presented at the meeting of the International Technology and Engineering Educators Association (1TEEA), Columbus, OH.

Strimel, G. J. (2012, June). *Engineering by design™: Preparing students for the 21st century.* Paper session presented at the meeting of the Pupil's Attitudes Towards Technology international conference, Stockholm, Sweden.

Honors/Awards

ITEEA, CTETE, & FTEE 21st Century Fellow, 2013
Technical Foundation of America International Mentorship Award, 2013
AFCEA STEM Teachers Scholarship, 2013
ITEEA Donald Maley Technology & Engineering Teacher Excellence Scholarship Award, 2012
Technology and Engineering Educators Association of MD New Teacher Excellence Award, 2012
Maryland Governor's Citation for Teaching Excellence, 2012

Grants

WV Department of Education Large Development Grant, 2014
WV Department of Education Small Development Grant, 2013, 2014
AFCEA STEM Education Classroom Grant, 2013
Pitsco/Hearlihy Grant for Excellence in Technology & Engineering Education, 2012