

Model for Developing and Assessing Critical Thinking Skills in an Undergraduate Civil Engineering Program

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Abstract

This paper presents a model for developing and assessing critical thinking in an undergraduate program. The 21st Century Bloom's Taxonomy provides a framework for creating classroom materials that fosters the development and advancement of critical thinking skills. Furthermore, the paper presents an instrument for assessing students' critical thinking progression and development. The proposed strategy is based on a specifically developed process where students are guided to progress from a lower to a higher level of cognitive thinking level during four years of undergraduate study. Placement of course activities in a specially designed sequence, as well as the use of specifically designed critical thinking instructions and assessment process to achieve desired learning outcomes are vital to deliver an effective critical thinking program. The proposed model for advancement and assessment of critical thinking presented in this paper can be used by other programs that plan to implement effective strategy for critical thinking. An example of the Civil Engineering undergraduate program at the United States Coast Guard Academy is presented to illustrate this effective strategy.

Key Words: Critical thinking, development, assessment, engineering, undergraduate education

Introduction

There are many challenges that higher education institutions face today in all academic disciplines and across all levels of education. One of them has been development of critical thinking skills. To meet the needs of a changing and increasingly competitive and challenging world, it is essential that students advance their critical thinking skills to meet the challenges of the 21st century. This paper presents a strategy for developing and assessing critical thinking skills development in an undergraduate program. The framework presented is based on the experience from the civil engineering undergraduate program at the United States Coast Guard Academy (USCGA). The authors support the view that fostering critical thinking skills is one of the primary goals of college education where a variety of pedagogic techniques can be used to advance critical thinking skills. Most STEM programs offer tools for developing critical thinking skills that allow graduates to thrive in modern societies. Rapid scientific and technological progress requires that students develop new skills and abilities to face new situations, analyze them, provide new solutions, and quickly adapt to the changes.

The strategy presented in this paper allows students to advance and master critical thinking skills progressively and sequentially over the four years of an undergraduate education. A sequential process of developing critical thinking skills has been accomplished by a strategy embedded into the civil engineering curriculum at the USCGA. Students' development of critical thinking skills is also progressively assessed to guarantee students' success. An implementation of the

informal course-based assessment process throughout the program delivers an approach that enhances students' mastery of the engineering material as well as critical thinking skills. The Bloom's Taxonomy (Bloom et al., 1956) that was adopted as a foundation in creating classroom materials and exams at the appropriate level of cognitive skill development has worked well to support critical thinking development.

First, the paper introduces effective strategy for critical thinking development that is based on the 21st Model of Bloom's Taxonomy (Anderson et al., 2009). Next, the authors present how Bloom's taxonomy was applied into selected engineering courses where students were able to successfully advance critical thinking skills. This is accomplished by enabling students to answer questions, solve problems, and generate research projects that require development and use of higher-order cognitive skills while applying their engineering skills into engineering applications.

The authors also present that critical thinking outcomes can be assessed through specially designed assignments and with the help of a tailored critical thinking process to the problem-solving methodology. This has been accomplished without adding new courses to the curriculum. Students are introduced to a problem-solving framework in the freshman year that is used as the basis of further instruction in critical thinking in subsequent courses. Several upper-level courses are structured to include project-based learning as well as cooperative learning that promote higher levels of Bloom's Taxonomy skill development in the cognitive domain.

The paper concludes that implementation of critical thinking in a sequential process across several civil

engineering courses throughout four years of an undergraduate curriculum can deliver a solid framework for development and assessment of critical thinking competencies. Assessment data indicate that civil engineering students are making progressive improvement in their critical thinking skills through problem-solving, and therefore, they are better prepared to complete their senior capstone design projects. Students with well-developed critical thinking skills have also shown better preparedness to make the transition to practice engineering in the real world.

Literature Review

The ability to think critically is considered as one of the most critical learning outcomes at any level of education (Arum & Roska, 2011; Murawski, 2014; Al-Kindi & Al-Mekhlafi, 2017). The philosophers, Socrates, Plato, Aristotle, Kant, or Russell were interested in critical thinking, but each of them had a slightly different perspective on the concept. Later, cognitive psychologists began discussing critical thinking and how people think or how they might be able to think under ideal circumstances (Dedovets & Rodionov, 2015; Paul & Elder, 2002). Over the years, educational literature emphasized that students master critical thinking skills and become lifelong critical thinkers when they are exposed to properly designed instruction that fosters critical thinking development and assessment (Ladewig, 2017; Halpern, 2014). Živkovića (2016) argued that critical thinking pedagogy allows students to achieve their full potential for solving problems and finding practical solutions.

Critical thinking development has been embedded into the instruction across academic disciplines (Kelley & Knowles, 2016; Pithers & Soden, 2000). Academic faculty have taken full responsibility for implementing critical thinking techniques into their teaching strategies as they recognize that a simple lecture or memorization do not lead to advancement of the abilities that enables students to apply knowledge to solve problems, create new ideas, and apply them in new situations (Kang & Howren, 2004; Templeaar, 2006).

There are numerous definitions of critical thinking but those that emerging from the philosophical tradition include:

- (1) "the propensity and skill to engage in an activity with reflective skepticism" (McPeck, 1981, p. 8);
- (2) "reflective and reasonable thinking that is focused on deciding what to believe or do" (Ennis, 1985, p.45);
- (3) "skillful, responsible thinking that facilitates good judgment because it 1) relies upon criteria, 2) is self-correcting, and 3) is sensitive to context" (Lipman, 1988, p. 39);
- (4) "purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and

inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or conceptual considerations upon which that judgment is based" (Facione, 1990, p. 3);

- (5) "disciplined, self-directed thinking that exemplifies the perfections of thinking appropriate to a particular mode or domain of thought" (Paul, 1992, p. 9);
- (6) thinking that is goal-directed and purposeful, "thinking aimed at forming a judgment," where the thinking itself meets standards of adequacy and accuracy (Bailin et al., 1999, p. 287); and
- (7) "judging in a reflective way what to do or what to believe" (Facione, 2000, p. 61).

Critical thinking based on the Bloom's taxonomy has been accepted as a standard to measure students' development and progress in the cognitive thinking learning process. Bloom et al., (1956) published, what became the Bloom's Taxonomy-Cognitive domain, where learning has been demonstrated by recalling knowledge, comprehending information, organizing ideas, analyzing and synthesizing data, and applying knowledge, choosing among alternatives in problem solving, and evaluating ideas or actions. Numerous research publications indicate that any learning activity that involves evaluating, analyzing, critiquing information as well as forming a hypothesis, collecting data, analyzing the data and then making conclusions is one of the best techniques for critical thinking development (Ahern et al., 2019; Cotter & Tally, 2009; Fitzgerald, 2000; Elder & Paul, 2010). Instruction that advances critical thinking should be based on questioning techniques where students are able to analyze, synthesize, and evaluate information to solve problems and make decisions instead of repeating and memorizing information that they were expected to master (Johnson et al., 1998).

Research has proven that successful methodologies for developing critical thinking skills include active learning in a group setting where students are accountable for their learning (Al-Qahtani, 2019; Pithers, 2000). Also, students' personal discovery and problem solving especially in group settings allow students to score higher on content-based assessments than students who learn by traditional textbook and lecture methods (Nokes et al., 2007). The use of active and experiential learning techniques to apply and transfer acquired critical thinking skills into new situations and problem solving has been advocated (Kusumoto, 2018). Researchers (Catanach et al., 2000) studied hands-on activities that required students to think critically and apply their knowledge to specific tasks. For example, Ngai (2007) documented that using a project-based team approach and the practical application of learning-by-doing produces strong results. According to Abrami (et al., 2009), the mixed instructional approaches that

combine both content and critical thinking skills had the largest effect.

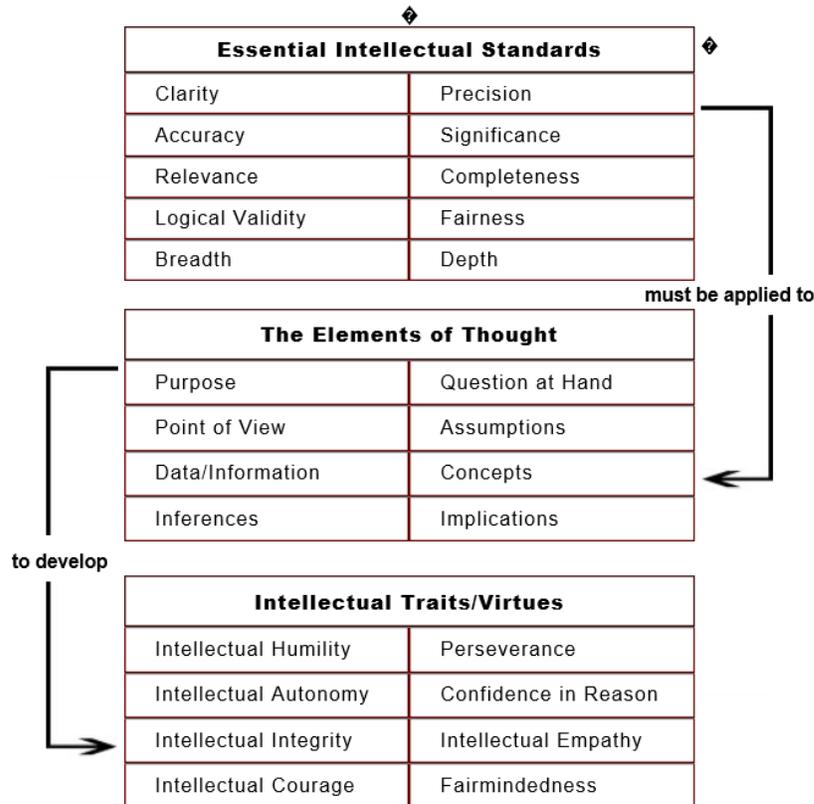
Paul et al. (2013) argue that engineering reasoning is typically considered to be clearer compared to other disciplines because engineers tend to question information, conclusions, and point of views. Their goal is to be logical and objective that results in more accurate, precise, and relevant thought processes. According to the authors, “... engineers concerned with good thinking routinely apply intellectual standards to the elements of thought as they seek to develop the traits of a mature engineering mind...” (Paul et al., 2013 pp. 5.). These intellectual standards include clarity, accuracy, relevance, logic, breadth, precision, significance, completeness, fairness, and depth while the elements consist of purposes, questions, points of view, information, inferences, concepts, implications, and assumptions (Figure 1). The Paul’s critical thinking model was adapted to the challenge of engineering education and published in July 2006 as a guide to *Engineering Reasoning* (Paul et al., 2013). Today, Paul’s model for critical thinking is frequently applied into undergraduate and graduate engineering programs.

Achieving the outcomes presented in Figure 1 requires “the intellectually disciplined process of actively

and skillfully conceptualizing, applying, analyzing, synthesizing, and/or evaluating information gathered from, or generated by, observation, experience, reflection, reasoning, or communication, as a guide to belief or action”, i.e. critical thinking (Scriven and Paul, 1987). These elements can easily be applied to analyzing texts, articles, reports, and entire engineering disciplines.

Many supporters of critical thinking pedagogy disagree on its definition, the method of assessment and the impact of its application in academic, professional, and personal life (Fountzoulas et al., 2019). The United States Engineering Accreditation Board, ABET supports the above statement and requires that graduates from engineering programs demonstrate the following skills (ABET, 2019):

1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.
2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.



Source: <https://www.criticalthinking.org/resources/articles/applying-a-criticalthinking-model-for-engineering-education.shtml>

Figure 1. Critical Thinking Model (Paul et al., 2013)

3. An ability to communicate effectively with a range of audiences.
4. An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.
5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.
6. An ability to develop and conduct appropriate analysis.
7. An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Al-Mahrooqi and Denman (2020), argued that despite the fundamental role that critical thinking plays across all education levels, there are barriers to the development of critical thinking skills. Al Zahrani and Elyas (2017) suggested a long list of barriers to critical thinking, arguing that teaching methods that encourage memorization will limit students' abilities to think critically. The authors also argue that classroom size, as well as social attitudes, poorly developed curriculum, and a lack of instruction in teaching critical thinking are part of the most common barriers. As challenges continue with incorporating critical thinking into engineering curricula and assessing the impact, engineering programs are extensively engaged with interdisciplinary approaches and educational literature to understand critical thinking and to explicitly address them in their curricula (Douglas, 2012). Claris and Riley (2012), as well as Flores et al. (2012) argued that despite these challenges, higher education programs are required to foster critical thinking deliberately and hold it as a core value. An effective way of teaching essentials of intellectual standards can come from a variety of pedagogical techniques. Also, the development of effective critical thinking skills requires extensive deliberate practice and intellectual work (Paul & Elder, 2002). For example, changing from teacher-centered to student-centered approaches enables higher education students to improve their critical thinking skills through problem orientation and experiential learning that develops lifelong learning abilities (Wals & Jickling, 2002; Janssen, et al., 2019). In general, critical thinking teaching strategies should be worked into the specifically designed curriculum. It is also important to monitor and assess the effectiveness of these strategies as well as to provide feedback to the students about their learning progress (Franco et al., 2018). Ahern et al. (2019) argues that designing practical approaches to critical thinking development are best techniques in engineering education. Dominguez (2018a) provides an example of project and focus groups exercises to argue

that they are effective instruction techniques for critical thinking advancement in engineering profession.

Researchers in education have developed some assessment tools in order to cover a broad range of formats, areas of application and scope of constructs to be measured. However, identifying, categorizing, and evaluating students' outcomes in critical thinking still poses challenges. Despite the fact that many assessment tools have been introduced, assessment of critical thinking is a relatively new established field (Fountzoulas et al., 2019). Similarly, Adair and Jaeger (2016) argue that there is little consensus on how to assess students' critical thinking development level. In response to this, Ahern et al (2019) question the effectiveness of teaching strategies used in engineering to promote critical thinking. In their paper, Ahern et al provide suggestions on how to improve the understanding of critical thinking development in engineering education. They also identify best practices for critical thinking advancement and assessment while highlighting the challenges and barriers in the adoption, and implementation of critical thinking educational practices. An assessment method of student critical thinking development as they progress through their undergraduate engineering course has been presented by Adair and Jaeger (2016) where they designed a method to track the development of critical thinking progressively through the undergraduate curriculum. The authors also argue that student feedback is critical as it encourages opportunities for better and more critical thinking assessment and development techniques. There is also need for innovative methods that promote and develop critical thinking skills more systematically and in a continuous way in engineering students (Cruz, Payan-Carreira, and Dominguez 2017; Dominguez 2018a, 2018b).

The goal of this paper is to contribute to the existing literature by providing information that will help engineering instructors acquire practical understanding on how to develop strategies for advancing and assessing critical thinking across an undergraduate engineering education. This paper presents the approach that enables students to acquire critical thinking abilities while working with the engineering concepts and their applications on a specific assignment. The process proposed consists of a series of specific steps in which students are intended to reach the objectives at a specific level of mastery and cognitive thinking. This authors argues that the use of Bloom's Taxonomy can assist engineering educators with structuring their problem-solving problems and projects. This paper outlines the development of educational strategies that progressively advance as well as assess critical thinking progression over four years of undergraduate program. This gradual and continues approach allows students to effectively complete their tasks and appropriately develop their critical thinking skills.

The framework for critical thinking development and assessment presented in this paper is unique as it illustrates how critical thinking can be advanced across an entire engineering program where students are informed about critical thinking strategy. This paper provides a strategy that is flexible as it allows teachers to use their own creativity and innovativeness to effectively advance and implement strategies for advancing and assessing critical thinking skills. This model is successful as it guarantees progressive, continuous, and transparent advancement and assessment of critical thinking skills across the entire curriculum. The paper will help engineering faculty develop program or institutional strategies for the critical thinking advancement.

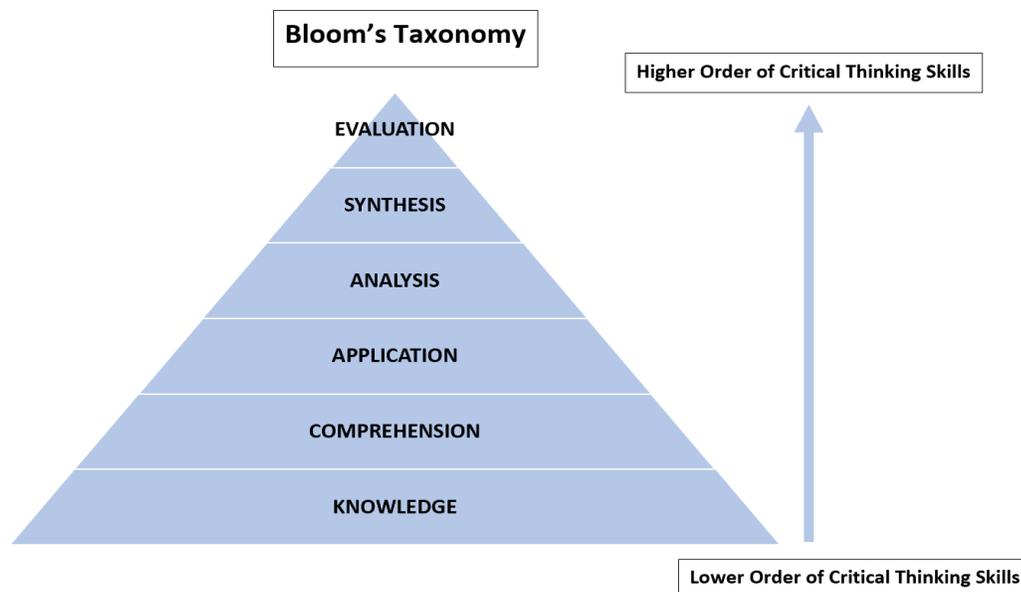
Framework for Developing Critical Thinking Skills

Benjamin Bloom developed taxonomy in which students can develop and master critical thinking skills. The Bloom's *Taxonomy* framework that was originally published in *Taxonomy of Educational Objectives* (1956), proved to be a valued tool. It represents a hierarchical structure consisting of six levels of learning. In this framework, this sequential taxonomy leads to classifications of cognitive learning arranged from lower-order to higher-order level of learning. Bloom's framework includes *knowledge, comprehension, application, analysis, synthesis, and evaluation* levels. This process determines that students must master all steps in the Bloom's recommended order from lower to higher order of critical thinking skills, as presented in Figure 2.

In his model, Bloom et al. (1956) indicated six major levels of cognitive processes, starting from the simplest to the most complex as presented and explained in Table 1.

The 1980s witnessed the beginning of an emphasis on teaching higher levels of thinking, which brought pedagogical research that stressed on the validity of Bloom's Taxonomy and the need to revise the strategies and curricula. As many publications cited evidence of students' inability to answer higher-level questions and apply their knowledge, the Bloom's model was modified into the 21st Century Bloom's Taxonomy framework. As illustrated in Figure 3, in this new framework Anderson and Krathwohl replaced *knowledge, comprehension, application, analysis, and synthesis* with *remembering, understanding, applying, analyzing, evaluating, and creating* (Anderson et al., 2009).

In this revised model, *remembering* involves retrieving relevant knowledge from long-term memory (Anderson et al., 2009, p. 31). *Understanding* can be identified as making meaningful statements or explanations from instructional messages, including oral, written, and graphic communication. *Applying* relates to carrying out or using a task or procedure in a specified situation. *Analyzing* indicates breaking material into vital parts and determining how parts relate to one another and to an overall structure or purpose. *Evaluating* involves making judgments based on criteria and standards. *Creating* involves putting elements together to form a coherent explanation and reorganizing basic elements into a new structure and explanation (Anderson et al., 2009, p. 31).



Source: *Taxonomy of Educational Objectives* Bloom et al. (1956)

Figure 2. The 1956 Bloom's Taxonomy Framework

Table 1. The Original Taxonomy of the Cognitive Process

Cognitive Domain	Description
1. Knowledge	The remembering of previously learned material; this involves the recall of a wide range of material, from facts to complete theories.
2. Comprehension	The ability to grasp the meaning of previously learned material; this may be demonstrated by translating material from one form to another, interpreting material (explaining or summarizing), or by predicting consequences or effects.
3. Application	The ability to use learned material in new and concrete situations; this may include the application of rules, methods, concepts, principles, laws, and theories.
4. Analysis	The ability to break down material into its component parts so that its organizational structure may be understood; this may include the identification of the parts, analysis of the relationships between parts, and recognition of the organizational principles involved.
5. Synthesis	The ability to put parts together to form a new whole; this may involve the production of a unique communication (thesis or speech), a plan of operations (research proposal), or a set of abstract relations (scheme for classifying information).
6. Evaluation	The ability to judge the value of material for a given purpose; The judgments are to be based on definite internal and/or external criteria.

Source: *Taxonomy of Educational Objectives* Bloom et al. (1956)

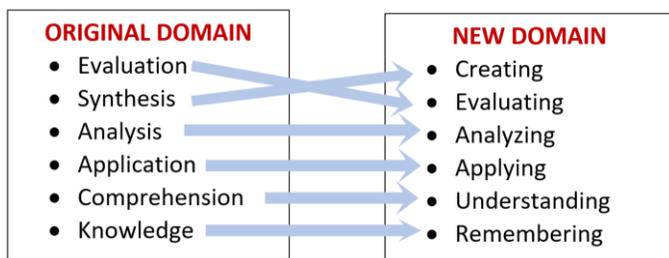


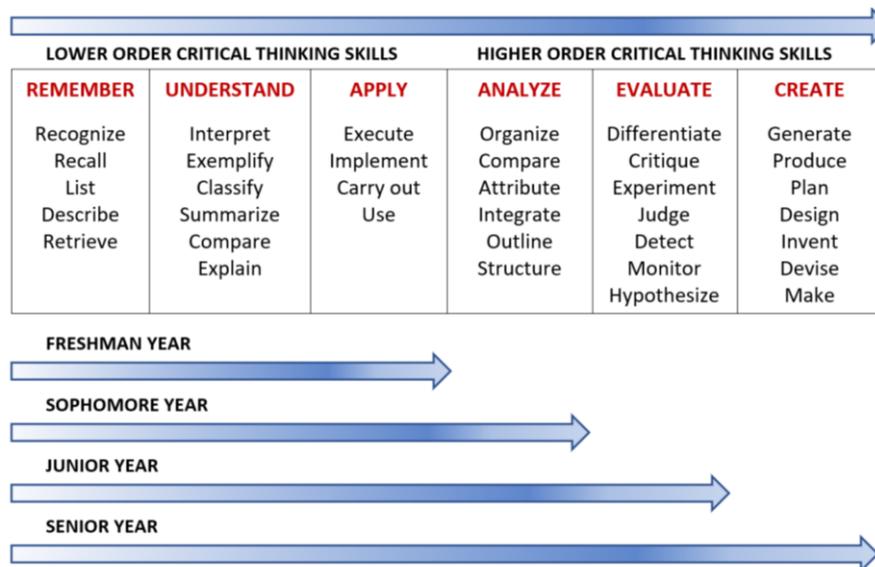
Figure 3. The Bloom’s Taxonomy - Original Domain versus the 21st Century Bloom’s Taxonomy Framework - New Domain.

Model for Developing Critical Thinking Skills in Civil Engineering Program at the USCGA

Since 2005, critical thinking has been accepted as a “shared learning” outcome across all majors at the USCGA. Consequently, teaching and assessment instruments were designed and implemented in the Civil

Engineering Department. Figure 4 illustrates the framework for critical thinking advancement based on the 21st Century Bloom’s Taxonomy model used by the Civil engineering faculty at the USCGA. As can be seen, the lowest level is “Remember,” where students are expected to *recognize, list, describe, identify, retrieve, name, locate, and find* specific concepts that are required to be mastered. The highest level is “Create,” where students are expected to *generate, produce, design, invent, or make* something new based on the concepts learned.

In accordance with Figure 4, the Civil Engineering faculty emphasize the development of critical thinking throughout a specially designed four-year curriculum. They assume that critical thinking skills advancement results in a well-developed ability to identify and understand problems, develop appropriate solutions through a progressive process supervised by faculty and



Source: U.S. Coast Guard Academy.

Figure 4. The Bloom’s Taxonomy - Development by Academic Year

their specially designed exercises and projects. With higher levels of critical thinking, students will significantly improve their ability to analyze complex engineering problems and produce higher quality solutions. Within the civil engineering curriculum, critical thinking skills are developed sequentially and progressively under guidance of each instructor in selected courses in the Civil Engineering Program. This instructor's guidance is required to ensure that each cadet is developing adequate skills that are required in each course.

The USCGA engineering faculty members have been applying *Intellectual Standards* developed by Paul (et al., 2013). The USCGA faculty members believe that to think professionally as an engineer entails having command of these standards. While Paul listed a number of universal standards, the USCGA focuses on some of the most significant that include *clarity, accuracy, precision,*

relevance, depth, breadth, logical validity, and fairness. Those universal intellectual standards must be applied to thinking. These standards are not unique to engineering but are universal to all domains of thinking. Therefore, to think professionally as an engineer involves developing command of these standards.

Civil Engineering is a practical profession that involves the design and construction of numerous forms of infrastructure. As such, critical thinking development within USCGA civil engineering program has been addressed predominately through the problem-solving and design process where *clarity, accuracy, precision, relevance, depth, breadth, logical validity, and fairness* must be present. The design process has been successfully infused in the civil engineering curriculum through progressive and consistent integration of key design principles throughout the four years of education as shown in Table 2.

Table 2. Summary of Design Components that Foster Critical Thing Development by Academic Year within Four-Year Undergraduate Civil Engineering Program

Academic Year	Civil Engineering Course(s)	Design Activity	Design Components Addressed Based on Intellectual Standard (Paul,	Competency Levels based on Bloom's Taxonomy
Freshman	Statics & Engineering Design	Design a truss bridge.	Define problem statement, identify and select appropriate analysis method, perform calculations, verify completeness of solution.	Remember and Understand
Sophomore	Mechanics of Materials	Design and perform an experiment. Compare test results with theory.	Define problem statement, identify and select appropriate analysis method, perform analytical and test calculations, verify completeness of solution.	Remember, Understand and Apply
Junior	Materials for Civil Engineers	Determine Portland cement concrete mix and Asphalt concrete mix ingredients. Pavement thickness design	Define problem statement, research problem, identify and select appropriate analysis/design method(s), investigate alternative solutions, perform design calculations, verify completeness of solution, prepare design documents	Remember, Understand, Apply and Analyze
	Soil Mechanics	Investigate slope stability, complete technical paper	Define problem statement, research problem, Identify and select analysis method, use of software package, evaluation and verification of solution, research technical topic	Remember, Understand, Apply, Analyze, Evaluate and Create
	Steel Design	Design a steel truss railroad bridge		
Senior	Environmental Engineering II	Design sanitary and sewer systems		
	Geotechnical Engineering Design	Design of several geotechnical support structures.	Define problem statement, site visit, research problem, identify and select appropriate analysis/design method(s), investigate alternative solutions, perform design calculations, select best alternative, verify completeness of solution, prepare design documents, assess impact of selected solution	Remember, Understand, Apply, Analyze, Evaluate and Create
	Reinforced Concrete Design	Multi-story building design.		
	Civil Engineering Design	Capstone project-objective dependent on nature of project.		

Source: Civil Engineering Department, U.S. Coast Guard Academy.

Providing exposure to design is one of the requirements civil engineering programs must meet for ABET accreditation. ABET requires that students are “prepared for engineering practice through a curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints” (ABET, 2019). Students are introduced to a problem-solving framework in the freshman year that is used as the basis of further instruction in the design process in subsequent courses. Several upper level courses are structured to include project-enhanced, project-based learning and cooperative learning that promote learning at higher levels of Bloom’s Taxonomy cognitive domain.

Pedagogical Strategies for Developing Critical Thinking Skills

Civil Engineering approach to fostering critical thinking skills includes several pedagogical strategies such as: (1) use of a general problem-solving framework that is progressively infused throughout curriculum; (2) development of professional skills; (3) integration of project-based and active learning; (4) emphasis on student-focus teaching that takes into account the various learning styles; (5) promotion of field trips and exposure to professional practice; and (6) creation of opportunities where students interact with professional engineers.

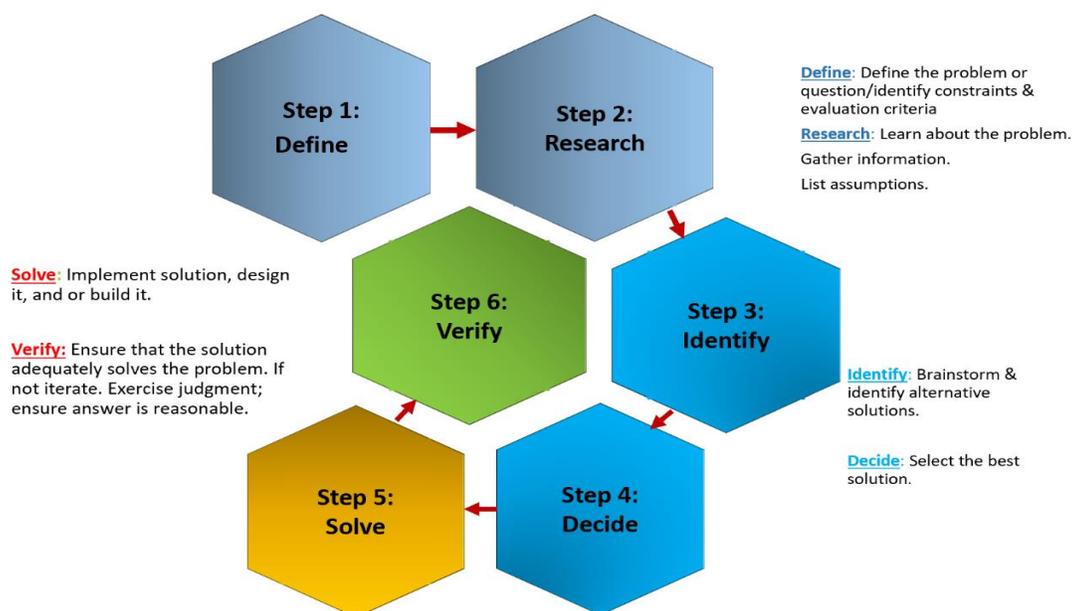
All those approaches are designed so that civil engineering majors will be able to raise the right

questions, focus on the real problem or decision to be taken; gather and assesses relevant information, develop well-reasoned conclusions and solutions, test them against relevant criteria and standards, rely on recognizing and assessing assumptions, implications, and consequences, and communicate effectively with others in finding solutions to complex problems.

As already mentioned, one of the strategies for critical thinking development in civil engineering major is a focus on developing problem-solving skills. Figure 5 illustrates the framework for the problem-solving process that has been developed and successfully implemented within the civil engineering courses.

The process for problem-solving process begins with defining the problem, stating a research question, identifying solutions and answers, selecting the best answer, providing a final solution and verifying the final solution and answer. Most of the engineering assignments and problem-solving assignments are designed to guide students through those six steps. All assignments must be wisely crafted to ensure that each step is carefully practiced and accomplished. Both faculty and students benefit from introducing the critical thinking development through the design process in the freshman year and reinforcing it throughout the four years of undergraduate engineering education. The more frequently students are exposed to and given opportunities to apply the various components of the design process, the better prepared they will be when they graduate.

The US CGA Civil Engineering Problem-solving Framework



Source: USCGA Civil Engineering Department, 2019.

Figure 5. The USCGA Civil Engineering Problem-Solving Framework

This progressive and faculty guided approach enables students to become skillful problem-solving experts. This approach is applied across all courses that were presented in Table 2. A more advanced problem-solving framework that is used in the upper-level coursework is presented in Figure 6. This expanded or advanced framework involves having students investigate alternative solutions, address several design constraints, and prepare design documents.

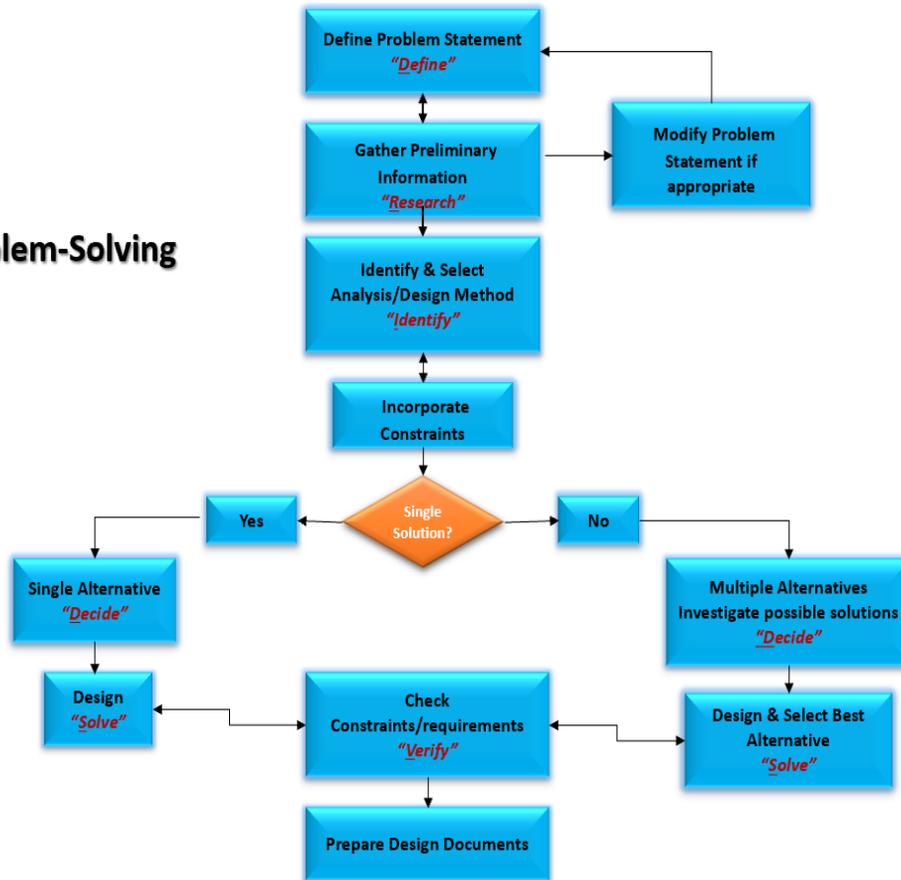
Examples of advanced problem-solving activities during senior year are illustrated in Table 3. In the *Geotechnical Engineering Design* course, students are required to complete a series of open-ended design projects that are structured to balance the need for fundamental engineering instruction with an infusion of skills required for engineering practice. The courses incorporate project-based learnings with open-ended projects that require students to make decisions and develop alternative solutions. The projects are designed to progressively lead students through several levels of Bloom’s Taxonomy cognitive domain. In the *Reinforced Concrete Design* course, teams of 3-4 students are assigned to design a multistory building. This project is also integrated in two other courses (*Geotechnical Engineering Design* and *Construction Project*

Management) to further foster progressive critical thinking development. Specially designed collaborative efforts were made within these courses to enhance the activities and guide students through the critical thinking and design processes.

Table 3. Advanced Problem-Solving Activities in Selected Senior-level Courses

Academic Year	Civil Engineering Courses	Problem-Solving Activity Problem Statement
Senior	Geotechnical Engineering Design	Design several geotechnical support structures including retaining wall and foundation system to a multi-story building used in Reinforced Concrete Design.
	Reinforced Concrete Design	Analysis and design of a Multi-story building. Design, build, and test a full-scale beam to investigate various concrete failure modes.
	Civil Engineering Design - Capstone	Complete a comprehensive civil engineering project to meet clients’ needs. Capstone project-objective dependent on the nature of project.

Advanced Problem-Solving Framework



Source: USCGA Civil Engineering Department, 2019.

Figure 6. The USCGA Civil Engineering Advanced Problem-Solving Frameworks

As indicated in Table 3, the culminating design experience in the Civil Engineering curriculum occurs during the last semester of senior year in the capstone design course, *Civil Engineering Design*. The deliverables vary in complexity, but they all provide students with real exposure to the design, planning, and management of actual civil engineering projects through which further critical thinking development occurs. All the senior-level courses listed in Table 3 involve the completion of one or multiple projects that fosters the application of the essential intellectual standards shown in Figure 1 to develop some of the intellectual traits identified by Paul, et al. (2016). The experiential and hands-on approaches used in these senior courses facilitate learning at all six levels of Bloom's Taxonomy.

Assessment of Critical Thinking Development

Assessment is the process of evaluating evidence of student learning with respect to specific learning goals. Developing strong and effective assessment methods is a challenging task. Alignment of course activities with learning outcomes is critical to obtain an effective strategy. The Civil engineering program at the USCGA has implemented assessment mechanism for critical thinking advancement in order to recognize shortcomings and to propose changes to accurately and reliably improve its critical thinking development strategy. The assessment is based on the design process that addresses critical thinking competencies at the various levels of cognitive learning as indicated in Table 1.

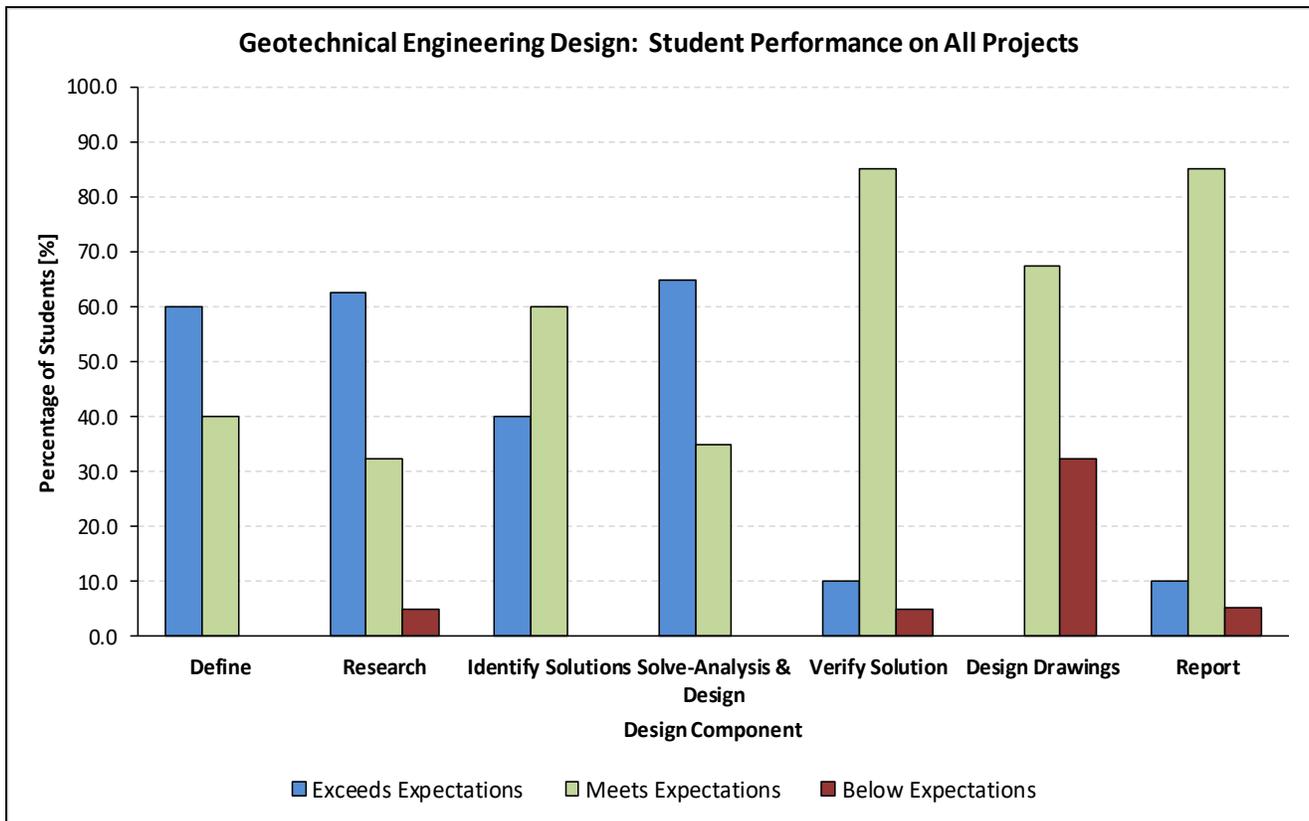
This process has been accomplished in each designated course throughout all four years of the undergraduate civil engineering program. In each course that develops critical thinking, faculty members are responsible for analyzing and evaluating the assessment results to determine the extent to which students are achieving the desired goals and outcomes of critical thinking at their level of development. Once, changes and improvements in a course are done, faculty members share their discoveries to further assess their courses and available resources to identify strategies and processes to execute action plans that will identify new and required changes and improvements. A final stage of the process is to evaluate the results of executed strategies and action plans to determine the extent to which they resulted in the desired outcomes, i.e., repeat the assessment process and determine realized outcomes. This process of closing the loop begins at the End-of-Semester Course Review that is conducted each semester. The loop is closed when proposed changes are made before the courses are offered again.

An example of assessment in the first two upper-level courses shown in Table 3 is presented here due to space limitation. In both courses, *Geotechnical Engineering Design* and *Reinforced Concrete Design*, a

common grading rubric was developed, tested, and used concurrently to assess students' critical thinking and design competencies as well as communication skills. Students were provided a copy of the rubric on the first day of class and were encouraged to consult it when completing each phase of the projects in both courses. As previously mentioned, the projects in these courses were designed to lead students through several levels of Bloom's Taxonomy within the cognitive domain.

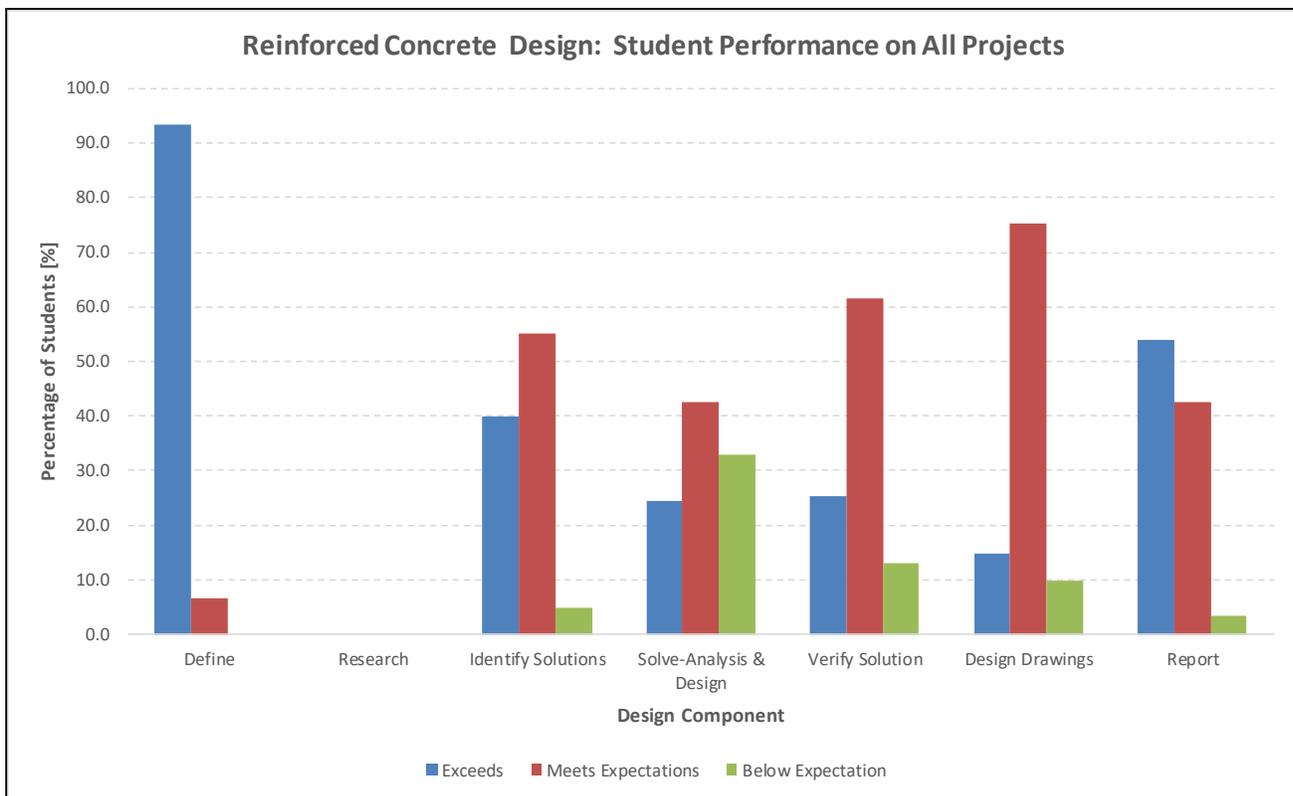
Based on the common assessment rubric, the average performance of students for the graduating class of 2019 are shown in Figures 7 and 8 for the Geotechnical Engineering Design and Reinforced Concrete Design course, respectively. These figures show the average performance on all the projects at by the end of the semester. The various components of the rubric include critical thinking aspects that are based on the Bloom's levels. By capturing student performance on these components, their critical thinking development and design skills can be progressively tracked as they complete the assignments.

This assessment method places students into one of three categories (exceed, meets, or below expectation) that corresponds to each stage of critical thinking progression (exemplary, competent, and developing). In both courses, a number of students underperformed in the "drawing documentation" criterion and this was identified as an area for improvement in future course offering. Part of the reason why student underperformed in is area is due to the fact that there is no drafting or engineering drawing requirement in the curriculum. Therefore, some students struggle to visually represent details of their project calculations and solutions. About 33% of students performed "below expectation," in both courses in the "solve-analysis & design" criteria because of the open-endedness of the project assignments. This corresponds to "developing" category within the critical thinking assessment strategy. The open-ended structure of assignments challenged students to think more deeply about the solutions and cognitive process engaged students at high levels within Bloom's taxonomy. Furthermore, an additional critical thinking self-assessment survey was administered at the end of the semester in the Geotechnical Engineering course. The survey required students to indicate their level of cognitive competency achieved in the course. The results are summarized in Table 4, indicate that about 80% or more of the students indicated competency in levels 1 to 5 of Bloom's Taxonomy, and 65% indicated competency at the highest level (6) of Bloom's Taxonomy. Overall, the overall assessment data indicate that students are making progressive improvement in their problem-solving abilities, performing better on their senior capstone design projects, and showing better preparedness to make the transition to practice engineering after graduation.



Source: U.S. Coast Guard Academy Civil Engineering Course.

Figure 7. Assessment of Student Performance in 2019 Geotechnical Engineering Coursework



Source: U.S. Coast Guard Academy Civil Engineering Course.

Figure 8. Assessment of Student Performance in 2019 Reinforced Concrete Design Coursework

Table 4. Critical Thinking Competency Survey Results for Geotechnical Engineering Course

Critical thinking level (based on 2001 Bloom's taxonomy)	Description (action verbs)	% of Students indicating competency
Remember/Knowledge	I can recall facts and basic concepts (define, duplicate, memorize)	87%
Understand/Comprehension	I can explain ideas and concepts (classify, describe, identify, discuss)	78%
Apply/Application	I can use information in new situations (implement, execute, solve, sketch)	78%
Analyze/Analysis	I can draw connections among ideas (differentiate, organize, compare, examine)	83%
Evaluate/Evaluation	I can justify a stand or decision (defend, appraise, select, support)	83%
Create/Synthesis	I can produce new or original work (design, assemble, construct, develop, investigate)	65%

CONCLUSIONS

An approach to critical thinking instruction that is appropriate for undergraduate students can be based on the conceptualization of critical thinking that incorporates the 21 Century Bloom's Taxonomy framework. Six formal stages of critical thinking and reasoning must be sequentially used to foster independent and critical thought. Teaching students to think critically requires more than simply providing them with facts, theories, and techniques. Creating frameworks or perspectives for critical thinking takes time, patience, and the intentional design of classroom exercises and assignments that guide students to practice critical thinking sequentially throughout the specifically designed six stages of the 21 Century Bloom's taxonomy.

Teaching and learning critical thinking take time, and it must be a continuing process. As development of critical thinkers who are competent in making effective decisions is crucial, instructors must develop specially designed assignments or projects that gradually, over four years, promote advancement of cognitive thinking. The authors strongly believe that there is need for more research in an area of critical thinking development and especially in assessment of students' progression in critical thinking advancement within Bloom's Taxonomy.

Critical thinking is as a proficiency outcome across the civil engineering curriculum at the USCGA. The 21st Century Bloom's Taxonomy model has been adopted to provide a foundation in developing classroom materials and assessment instrument at the appropriate level of Bloom's Taxonomy. Civil Engineering students take several design courses during the senior year that provide extensive opportunities to gain design experience by performing analysis and design of various components in well-coordinated comprehensive projects between three civil engineering courses. Furthermore, courses in the sophomore and junior years

are structured to include project enhanced, project-based learning.

These progressive design experiences have helped students perform at higher levels of cognitive learning. With higher levels of critical thinking, students significantly improve their ability to analyze complex engineering problems and produce higher quality solutions. The use of case studies and real-life situations appears to be also effective in engineering as a means of encouraging students to develop critical thinking skills. This paper confirms the argument developed by Dominguez (2018b), Ennis (2016), and Adair and Jaeger (2016) that to develop effective critical thinking pedagogical tools, the faculty must include approaches of solving real problems of the workplace and allow students to experience the stages of project management. This paper also contributes to work by Adair and Jaeger (2016), by providing a simple assessment instrument that allows evaluation of critical thinking across variety of teaching techniques as well as over time.

As identifying effective techniques in engineering education is unique, this paper contributes to the literature by illustrating an assessment of various critical thinking teaching techniques and showing their effectiveness in engineering education. The results presented in this paper, illustrate how to obtain an improvement in teaching effectiveness when including the critical thinking learning stages and assessment procedures. This paper contributes to the literature on critical thinking in engineering education as it highlights the challenges and barriers in the adoption and implementation of critical thinking educational practices, presents the effective teaching strategies in engineering to promote critical thinking, identifies best practice for critical thinking teaching and evaluation, and presents how to addressing knowledge gaps in engineering education discussed in the current literature.

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