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Evaluation of a High School Engineering Short Course Integrating the Engineering Design Process, Creativity, and Innovation (Evaluation)

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ABSTRACT

Tomorrow's engineers need to be innovative problem solvers able to approach multidisciplinary engineering challenges creatively yet methodically. Across the United States and the world, stakeholders, including NAE, NSPE, and ASEE, increasingly acknowledge the importance of creativity in engineering design. High school curricula are starting to introduce engineering concepts, including robotics, 3D printing, and the engineering design process. Traditionally, these technical concepts have been separated from opportunities to practice creativity and innovation. In this setting, students are led to think that creativity and innovation are not compatible with engineering design.

The following paper evaluates the effectiveness of strategies geared toward encouraging creativity and innovation in conjunction with the engineering design process to foster new, unique, or atypical approaches to engineering problems. In a one-week civil engineering summer course, high school students were challenged to approach engineering problems with this integrated mindset. The authors introduced the students to an eight-phase engineering design process on the first day of class. This framework was developed in [1] based on realistic scenarios used in engineering and was proven effective in the literature for novice audiences in engineering. In class, students interacted with real-world problems and brainstormed creative and innovative solutions each day, either working toward the final project or with in-class activities. Using this framework, students were encouraged to identify and/or create new, unique, or atypical solutions while accommodating real-life constraints such as budget, location, and affected communities. Throughout the week, students were given various opportunities to practice brainstorming creative solutions in the context of the engineering design process from the point of view of different engineering disciplines.

The effectiveness of the curriculum and the teaching approach is evaluated based on student evaluations, pre- and post-class surveys, student artifacts throughout the week, and a final multidisciplinary poster presentation. As part of this evaluation, a rubric based on the work by [2] was adapted to assess creativity and application of the engineering design phases in the final project. In general, students showed increased knowledge and application of the engineering design process over the course. This assessment suggests that creativity can be fostered through well-designed course materials. From the authors' perspective, the developed curriculum was effective since it included diverse course activities championed in the literature, including problem-based learning, interaction with physical models, multidisciplinary case studies, site visits, new and modern technology, and a real-world, problem-based, summative assessment. Furthermore, the solutions presented in the poster show the use of problem-solving skills and the integration of multiple engineering disciplines. Finally, the paper shares detailed techniques and curricula that can be implemented in engineering courses to foster creativity and innovation while developing a better understanding of the engineering design process.

Tags: pre-college, engineering, engineering design process, innovation, creativity, high school

INTRODUCTION

For decades, the US has identified a shortage of engineering professionals. The national discussion on the shortage of engineers in the market started as early as 1959, with empirical evidence of the need for more engineers and scientists to meet the demands of the growing country [3]. The conversation initially focused on increasing the workforce to compete with other countries [4]. Recently, the conversation shifted toward the need for skilled engineers who bring new ideas and perspectives to the profession. Reflecting this trend, stakeholders, including NAE [5], NSPE [6], and ASEE [7], are increasingly acknowledging the importance of creativity in engineering design. All recognize that the shifting world presents challenges that require innovation, and as such, engineering education should concentrate on training engineers with the capacity to innovate.

The National Academy of Engineering (NAE) and the National Research Council (NRC) Center for Education established principles in 2006 to guide pre-college engineering education, including emphasizing engineering design and promoting an engineering mindset that encourages creativity [8]. However, integrating engineering concepts into pre-college curricula remains difficult, particularly in STEM classrooms. Despite engineering occupying a significant place in STEM, it is often seen as separate from other subjects, including the arts. As demonstrated in [8], STEM concepts naturally relate to each other, with scientific investigation guiding engineering design decisions. While engineering alone is valuable, it becomes a powerful tool when combined with science, mathematics, and technology [9]. Along with creativity and innovation, engineering can lead to new solutions, adaptations, discoveries, and improved quality of life.

Creativity and innovation are fundamental components of engineering. The ability to generate new ideas and think outside the box is crucial for brainstorming solutions to multifaceted problems and developing new technologies. Creativity powers significant steps toward better approaches to old problems but must be fostered alongside traditional STEM curricula. The separation between STEM and creativity has drawbacks for both parties. For example, STEM professionals have missed opportunities of participating in design-thinking careers, and art professionals have missed the technical knowledge to provide innovative solutions [10]. In addition, STEM faculty and practitioners have suffered a disconnection from creativity and abstract thinking, while artistic community members have struggled to keep pace with the quickly advancing technological society [11].

In the classroom, educators should encourage the early development of new ideas to foster creativity and innovation with engineering design. Learning from industry partners' success stories can provide insights into practical approaches, such as teamwork assignments, hands-on activities, and formative feedback. However, instructors should exercise caution when implementing pedagogical methods. For example, structured and forced stimulation can benefit creative processes, while negative stimuli, such as off-topic conversations, can have a negative impact, as shown in [12]. Successful integration involves having practical tools available to assess the content provided and analyze the effect of the pedagogy on student learning. Unfortunately, limited literature is available on these topics, and further research is necessary to identify and develop suitable tools for effectively evaluating pedagogical practices focused on creativity and the engineering design process.

The following paper evaluates the effectiveness of strategies geared toward encouraging creativity and innovation in conjunction with the engineering design process during a one-week civil engineering summer course. The evaluation methodology used three assessment tools to evaluate creativity and innovation: class surveys, student artifacts, and instructor feedback. First, pre-and post-course surveys were administered to measure the effectiveness of the pedagogy on students' understanding of creativity and innovation in relation to engineering design. Additionally, an analytic scoring rubric was used to assess creativity, innovation, and engineering design process application in student artifacts. Instructor feedback was also analyzed to illustrate the student's experience during the course week and to highlight instances where students effectively engaged with the pedagogy prepared for the course. Finally, this paper shares program elements developed to teach the engineering design process and promote creativity and innovative solutions. The techniques and curricula presented in this study can be implemented in other engineering courses and pre-college classrooms to similarly foster creativity and innovation.

BACKGROUND

The Engineering Design Process

The engineering design process is a multistep model representing a problem-solving scheme in the engineering field. Multiple models [13]–[22] have been provided in the literature to capture the process engineers follow to arrive at a solution. The model referenced in this study was proposed by the Massachusetts Department of Education (DoE) [13]. The Massachusetts DoE developed this model with substantial input from several groups focused on education, faculty, practitioners, and professional engineers. Although no engineering education-wide consensus exists on the definition or steps in the engineering design process, the concepts in the Massachusetts DoE model align with other models in the literature [1], [23].

The model includes eight steps in the engineering design process: (1) identify a design need, (2) research a design need, (3) develop design solutions, (4) select the best possible design, (5) construct a prototype, (6) test and evaluate a design, (7) communicate a design, and (8) redesign. The research team of the present study selected the DoE model for various reasons. First, it holistically encompasses all the researchers' activities when approaching engineering problems. Second, the model targets higher levels of Bloom's [24], [25], and Webb's [26] taxonomy. Third, the model is easy to interpret and uses familiar words to describe its cycle. Figure 1 shows a visual representation of the model.

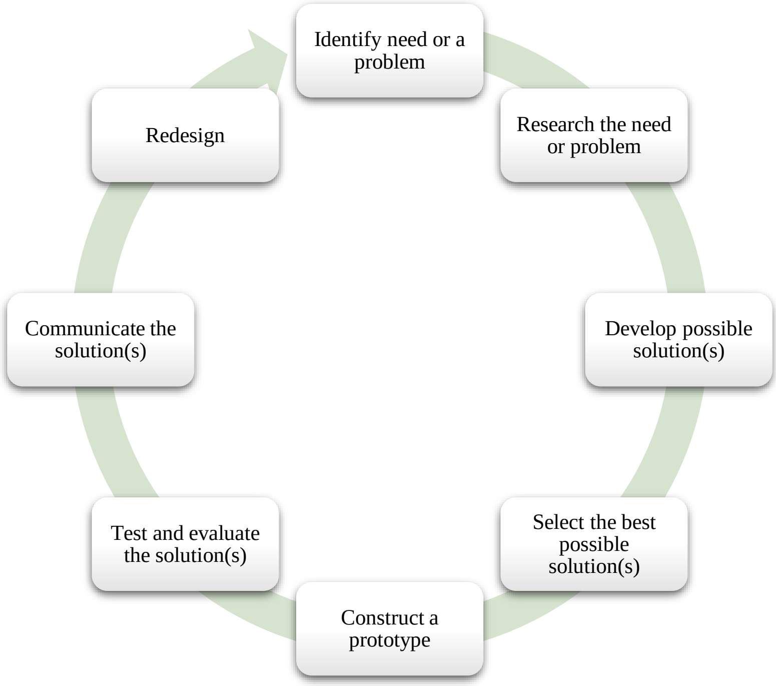

Figure 1. Illustration of the engineering design process model adapted from the Massachusetts DoE [13]

Teaching and learning with the engineering design process

Identifying a design process model to use is merely the first step. Students must be exposed to this process and learn to apply it. In the course, instructors used techniques including regular practice, the introduction of real-world applications, exposure to junior versions of the problem, and independent student brainstorming to help students remember the process and practice applications. Furthermore, students were required to engage in iterative design cycles, where they refined course project designs based on feedback.

Creativity and Innovation in Engineering

In recent literature, the notion that only a single form of creativity exists within the field of education has been dispelled. This common misconception has been challenged by several studies, indicating the existence of multiple forms of creativity, each with its unique characteristics. For example, music improvisation has been proven unrelated to general creativity [27], and creative engineering design differs from general creativity [28].

Literature in [29] also talks about the differences in creativity based on two areas of thinking: divergent thinking and convergent thinking. Divergent thinking is a form of thinking that involves exploring different directions and considering various aspects to generate innovative ideas and solutions [29]. Convergent thinking, on the other hand, consists in gathering and analyzing information to arrive at a single solution to a problem [29]. Usually, convergent thinking is defined as a thinking process that focuses on solving problems with only one correct answer. Nevertheless, they are both associated with creativity in engineering.

Assessment of Creativity and Innovation in Engineering

Creativity and Innovativeness Assessment Methods have been developed by multiple authors [30]–[33], [28], [34]–[37]. The authors of this study grouped these methods into the following categories:

- Self-reported creativity assessment methods: CPS (creative personality scale) [32], CREAX [33], CRT (cognitive risk tolerance) [28].
- Third-party evaluation: CEDA (creative engineering design assessment) [34], CT (creative temperament) [34], Owens Creativity Test [35], Purdue Creativity Test, TTCT (Torrance Test of Creative Thinking) [36], RAT (Remote Associates Test) [37].

Similar studies to the ones presented above have found that the creativity assessment methods presented above focus on either one component of creativity: divergent thinking (Purdue Creativity Test, Owens Creativity Test, Torrance Test for Creative Thinking, and the Structure of Intellect Model) or convergent thinking (Remote Associates Test). However, engineering creativity requires both convergent and divergent thinking.

Charyton et al. [34] proposed the Creative Engineering Design Assessment (CEDA) to measure convergent and divergent thinking. This assessment has been found in the literature to be effective at measuring engineering creativity [28]. Moreover, CEDA has been proven to have statistically significant consistency when applied and later reapplied to the same population [34].

CEDA measures creativity in three aspects:

- Fluency: number of responses
- Flexibility: number of response categories defined as a variety of responses or number of category types
- Originality: uniqueness of the solution

Shah et al. [38] recommend that the assessment of the creative engineering design not only relies on novelty but also satisfies the intended function. Accordingly, Shah et al. proposed four separate effectiveness measures:

- Novelty: how unusual or unexpected an idea is compared to others.
- Variety: measure the explored solution space during the idea generation process.
- Technical Feasibility: feasibility of an idea and how close it meets the design specifications.
- Quantity: total number of ideas generated.

Further studies have tried to consolidate the metrics presented before in [38] and [34] and with the analysis of [39] into MPCA (Multi-Point Creativity Assessment) and CCA (Comparative Creativity Assessment) scores [30]. However, the authors in [30] found a limited statistical correlation between the judges' and CCA scores. Therefore, another assessment approach is needed to measure creativity and innovation in student artifacts. Furthermore, the limited statistical correlation between the presented scores indicates that the existing models may not be sufficient. As such, the CEDA framework will be used to evaluate creativity in this context.

STUDY POPULATION AND EFFECTIVE STRATEGIES TO ENCOURAGE CREATIVITY AND INNOVATION IN THE ENGINEERING DESIGN PROCESS

Study population

The study was performed in a one-week, one-credit course introduction to civil engineering under Purdue University's For-Credit Fun-Sized Courses for high school students. The course aims to provide students with a multidisciplinary understanding of civil engineering, foster interest in engineering, and increase creativity and innovation through hands-on projects. The course was open to rising high school juniors and seniors. Course enrollment was 28 students: 21 male and 7 female; these students were from 11 states. Students received approximately six hours per day of face-to-face instructor time during the five days of class. In addition, the instruction time included field trips, active learning activities, field data collection, inversion with new technologies, and discussion on relevant current events.

The course covered specific topics of hydrology, geomatics, surveying, structures, and transportation. Students had multiple opportunities during the week to practice the concepts learned in class, ask questions to the instructor during office hours, and interact with their classmates outside class time. In addition, homework was assigned every day covering topics reviewed in the class sessions and due before the next day's class.

Effective strategies to encourage creativity and innovation in the engineering design process

The instructors designed the summer course to follow the engineering design process, foster creativity and innovation, and achieve various levels of Bloom's and Webb's taxonomy. The effective approaches are detailed in the following sections.

<u>*Brainstorming – Draw the Engineering Design Process*</u>

The students' first approach to the engineering design process was a classroom activity in which the students were asked to draw a flowchart a professional would follow during the engineering design process. Next, the students were encouraged to work in teams and use a whiteboard to visually represent their ideas for the process's beginning, middle, and end stages.

The students shared their initial ideas on the engineering design process and learned new insights from their team members. All student submissions included at least three steps in the process and demonstrated the ability to develop solutions. However, the step of evaluating the solution and making necessary changes was missing in all of them. Overall, this activity proved to be an effective tool for linking their prior knowledge to upcoming activities.

<u>*Engineering Design Process through an example*</u>

The students were introduced to the engineering design process through a real-life example of a well-known disaster in the U.S. Students were asked to research solutions developed during the aftermath of the disaster. This activity included instructor-led knowledge and incorporated suggestions from the student's prior knowledge. By the end of the activity, the students could accurately identify the application of each step in the engineering design process.

Case Studies – Engineering Design Process

The students were divided into teams and given an engineering problem to solve by applying the engineering design process steps. For example: low water levels in Lake Mead, the Fukushima nuclear disaster, Flint Michigan lead in water, and Evergreen ship running aground. The problem was presented through abbreviated news articles that provided contextual information, and the students were given a worksheet to follow the process steps. The activity encouraged the students to utilize their existing knowledge and engineering judgment to develop new solutions and consider the ones provided in the article. Overall, the students successfully identified instances of the process and were able to come up with alternative solutions beyond those presented in the article.

Daily homework and its connection to the final project

Homework served as an opportunity for students to practice what they had learned in class. In addition, instructors included questions about the final project deliverable to enhance their understanding. These questions were graded on completion and provided formative feedback throughout the week-long course. The questions were designed to ensure that students were progressing toward the final deliverable, meeting daily milestones, exploring creative solutions, and utilizing the resources provided in class.

The instructors found that homework questions were an essential tool for ensuring the success of the final project, as they allowed even quieter students to receive feedback and gauge their progress toward achieving course goals. Instructors were available for additional support during office hours and team project time, but homework assignments provided students with independent practice and feedback.

Field visits

The instructors organized field visits in the afternoon of the first day of classes for the students to connect with the final project, ask questions, brainstorm solutions, and better understand the problem they were tasked to solve. The visits were conducted in smaller groups to ensure that students could interact with their teammates, ask questions, and be inspired by the facilities they visited. Instructors observed that student interest in the project increased after the visits, as evidenced by informal conversations, students taking pictures of the area, and some students beginning to draft ideas immediately after the tours ended.

Hands-on activities

Throughout the week, instructors provided carefully designed hands-on activities to align with the learning objectives and course goals. These activities allowed students to become more engaged with the course material, apply the concepts to their final project, and foster creativity and innovation within the guidelines. The hands-on activities included:

- Tension and compression member analysis using a bridge engineering kit
- Traffic counting within the final project area
- Surveying and mapping using manual equipment and drones

- Treasure-hunt style activities in the classroom building to find ADA accommodations or lack thereof.

Feedback and evaluation surveys indicated a high level of acceptance and encouragement to include more activities in the future. In addition, the instructor graded the student artifacts produced from these activities, which indicated an extremely high completion rate.

Final project deliverable – Academic Poster

The summer course required students to work in teams and prepare an academic poster presentation on a local mobility issue. In addition, the course focused on providing valuable learning opportunities for the final project. Throughout the week, the instructors offered multiple opportunities for students to practice the engineering design process and refine their solution thinking process. The daily homework included specific activities to reveal the students' progress on the poster, and the instructors provided formative feedback on these assignments.

The poster activity measured the students' direct application of the engineering design process during the week-long course. The posters showed how the students incorporated the feedback into their final deliverable and encouraged creativity throughout the teamwork. In addition, dedicated project time was provided to the students during the last part of each day during the week-long course. Finally, instructors could answer questions and provide guidance when teams needed it.

ASSESSMENT METHODS FOR EVALUATION OF CREATIVITY, INNOVATION, AND THE ENGINEERING DESIGN PROCESS

Pre- and post-course surveys

The surveys were designed to allow students to self-assess changes based on their perspectives over the course. At the same time, instructors used them to observe students' growth in creativity, innovation, and engineering design process application over the week-long course. Developing a survey that effectively measures abstract constructs like creativity is difficult. As such, the surveys do not capture evidence of growth alone and instead are used to complement the information obtained in the artifacts mentioned in the following section. The survey questions are provided in the appendix of this study.

The authors used the same survey questions at the start and finish of the course to assess student progress. In addition, the authors compared the pre- and post-course surveys and looked for evidence of change over the course duration.

Evaluation survey

The evaluation survey was designed to collect feedback regarding the content of the summer course and the teaching techniques used by the instructors. The survey included Likert-scale questions to rate agreement with feedback statements and open-ended questions to collect information on successes and points of improvement of the implemented curricula. In addition, the anonymous survey responses were analyzed to determine evidence of technical knowledge gained in various areas taught by the instructors. The evaluation survey is included in the appendix of this document.

Final project deliverable: academic poster

The final course deliverable was a group project poster and presentation. The prompt was a real-world campus design challenge that was purposely broad enough to cover all civil engineering disciplines and has a wide variety of reasonable solutions. In addition, students were asked to address the challenges associated with traffic from large events on campus, like sporting events or concerts.

Apparatus

The tool used to illustrate the engineering design process to students was an adaptation of the Massachusetts DoE model [13], encompassing the eight steps in the engineering design process. The instructors provided the students with multiple formative assessments to help students practice the process. The topics addressed design needs from all five civil engineering concentrations presented in the summer course, and active learning activities enhanced their learning experience in the classroom.

Assessment framework

Bailey and Szabo [2] argue that assessing students' learning of the engineering design process is difficult. In their study, they provide a summary of all possible assessment options with the advantages and disadvantages of each of them. For example, while some options have the advantage of being less time-consuming, they tend to target lower levels of Bloom's and Webb's taxonomies. On the other hand, other assessment options can target higher levels of Bloom's and Webb's taxonomies. Still, they do not apply to artifacts focused on design skills, such as surveys with open-ended questions.

In this study, the authors propose a multi-part assessment framework using recommended techniques from the literature.

First, this study considers Bailey and Szabo's recommendation [2] of assessing the final project deliverable due to its efficiency and relevance to engineering settings, where the customer is most interested in the final result. Second, the framework incorporates survey responses at the individual level, covering additional levels of Bloom's and Webb's taxonomy and able to capture changes in student knowledge before and after the summer course [40]. They are included in the framework as they complement the final project deliverable assessment [2]. Finally, instructor feedback is included in the framework to provide information on knowledge and interest growth during the week-long course that the surveys or student artifacts may not have captured.

In summary, the framework includes the following:

- Assessment of the final project deliverable: academic poster
- Assessment of responses from surveys with close-ended and open-ended questions
- Instructor feedback.

Assessment of the Engineering Design Process

The final design project deliverable consisted of an academic poster. A rubric was developed to evaluate the final design project since rubrics have been proven to reduce variation between graders, normalize differences in approaches, and reduce variability in the sample [41]. An analytic scoring rubric is selected to score the student posters to measure students' knowledge covering different parts of the engineering design process. A rubric with multiple levels was created to evaluate student work. The rubric has been divided into eight items corresponding to the eight steps of the engineering design process used in this study. Even though the final score is an addition to all the levels, more meaningful information is provided by each level illustrating which level the student knows more about by the highest number of points.

Assessment of Creativity and Innovation

The same analysis measured creativity and innovation by adding items to the rubric developed to assess the engineering design process. The other criteria were selected from the tools provided in the literature that were proven effective in measuring creativity and innovation in student artifacts. Below are the selection criteria to determine what to include in the rubric.

Fluency and Flexibility metrics from the CEDA tool proposed by Charyton et al. [28] did not apply to the final design project since only one solution was requested and was omitted from the assessment framework. On the other hand, *Originality* from CEDA applies to the design project and consequently adds to the rubric.

Variety and Quantity metrics from Shah et al. [38] similarly do not apply to the final design project since only one final solution was requested. The metrics rely on assessing multiple solutions from the same team. However, *Novelty* and *Technical Feasibility* apply to the final design project, therefore, were included in the rubric.

The three selected metrics—*Novelty, Originality, and Technical Feasibility* — have been explored in [42] and rely on formulas—presented in the reference—to arrive at a creativity score. However, expressions like this can be convoluted and increase the uncertainty and inconsistency of the method. In addition, several repeatability studies conducted in the literature [42] have demonstrated that utilizing scales with fewer intervals improves the results' repeatability. Therefore, this study used an abbreviated version of each metric, and the authors adapted them for an analytical rubric with fewer scales.

In this study, the authors used a consolidated approach applying the work of Shah et al. [38] and Charyton et al. [28] and by selecting the metrics detailed above as presented in [42] and summarized here:

- Novelty metric: as introduced by Shah et al. [38]
- Originality metric: as introduced by Charyton et al. [28]
- Technical feasibility metric: as introduced by Shah et al. [38]

The Originality metric and Novelty metric are similar in that they both measure the uniqueness of an idea in comparison to others. However, there are some subtle differences between the two.

Novelty metric

The novelty metric is defined in [38] as a measure of how unusual or unexpected an idea is compared to other ideas, *regardless of the market*. Not all new ideas are novel, as they are to some extent considered common or expected, which is known only after the idea has been acquired and analyzed. The same study recognizes that the novelty metric is subjective to the number of similar ideas produced in a given market.

Originality metric

The Originality metric is introduced in [34] and defined in [42] as a further step from novelty—the metric measures how unusual or unexpected an idea is compared to other ideas *in the market*. The evaluator considers the innovation of the design based on their understanding of the existing market competition.

The Originality metric is evaluated in the original study on an eleven-point scale. A study in [42] modified the originality metric into a four-point and three-point scale, proving that the reduced version was more repeatable than its larger version. In addition, an adaptation in [43] modified the metric description for a more intuitive scale. This scale is adapted by the authors and introduced in the rubric.

Difference between Novelty and Originality metrics

The authors recognize that the words novelty and originality are often used interchangeably. For this study, an example can better establish the difference between the two metrics. The reader can imagine a student project requires the students to develop a new design for a smartphone. Applying the different metrics:

- The evaluator will use the Novelty metric to compare the smartphone design with other designs the evaluator has seen or to other designs for similar products, such as tablets or laptops. Based on the comparison, the design might be highly novel if it is unlike anything the evaluator has seen before and uses completely new and unexpected approaches.
- The evaluator will use the Originality metric to compare the design to the latest brand of smartphones only. Based on the comparison, the design might be highly original if it offers new and innovative ideas on the smartphone and is significantly different from any smartphone currently available.

Technical Feasibility metric

The Technical Feasibility metric is defined in [38] as the measure of the feasibility of an idea and how close it meets the design specifications. The metric evaluates the design idea and does not test the prototype built from that idea. As such, the metric can be a powerful tool to determine which ideas should be considered for further improvement and posterior construction of prototypes.

The three modified metrics have been introduced in the final rubric presented in Table 1.

Assessment of the final design project deliverable

Table 1 presents an analytical rubric built considering the eight steps in the engineering design process and the metrics to measure creativity and innovation. The researcher will use this rubric to grade the de-identified student artifact (poster).

Table 1 Rubric to evaluate the Engineering Design Process and the incorporation of Creativity and Innovation in student artifacts

Criteria	**2 points**	**1 point**	**0 points**
Engineering Design Process			
Identify a design need	The student identifies a specific design need and defines it clearly and concisely.	The student identifies a design need, but it is not clearly defined.	The student does not identify a specific design need.
Research a design need	The student demonstrates thorough research and analysis of the design need, including a clear understanding of the problem and potential solutions.	The student partially demonstrates research and analysis of the design need, indicating some understanding of the problem and potential solutions.	The student does not effectively demonstrate research and analysis of the design need, lacking a clear understanding of the problem or potential solutions.
Develop design solutions	The student develops two or more design solutions before comparing them to the criteria, each well-thought-out and feasible based on the described context.	The student develops less than two designs or proposes solutions that are not well-thought-out or feasible based on the described context.	The student does not develop any design solutions.
Select the best possible design (based on criteria)	The student evaluates the design solutions against criteria and selects the best one based on specific criteria.	The student chooses a design solution but does not evaluate it based on specific criteria or evaluates designs without choosing the best one.	The student does not select a specific design solution nor evaluate any against criteria.
Construct a prototype	The student proposes a prototype that is easily identifiable and addresses design needs.	The student creates an identifiable prototype.	The student does not create a prototype.
Test and evaluate a design	The student evaluates the proposed design and identifies two or more strengths of the design using visual information.	The student evaluates the proposed design and identifies one strength of the design using visual information.	The student evaluates the proposed design and identifies no strengths of the design using visual information.
Communicate a design	The student communicates the design need, solution, process, and results using clear and concise text and useful images.	The student communicates the design through the poster using *either* clear and concise text *or* useful images.	The student does not effectively communicate the design through the poster (neither clear text nor useful images.)
Redesign	Summative assessment cannot capture Redesign and is not included in the rubric.		

Criteria	2 points	1 point	0 points
Creativity and Innovation			
Novelty metric	The solution is highly novel and unexpected compared to other ideas, regardless of the market.	The solution is somewhat novel and considered unusual compared to other ideas, but not wholly unexpected.	The solution is not novel and considered common or expected compared to other ideas.
Originality metric	The solution is highly original and innovative compared to existing solutions in the market.	The solution is somewhat original and adds value to existing solutions in the market.	The solution is not original and does not offer a new or unique perspective compared to existing solutions in the market.
Technical feasibility metric	The solution is technically feasible and closely meets the design specifications.	The solution is partially technically feasible and meets some, but not all, design specifications.	The solution is not technically feasible and does not meet the design specifications.

On Redesign

Redesign, the last step in the engineering design process, could not be captured using the proposed rubric in this study. Evaluating the redesign step based only on one summative assessment is not possible since the core of the redesign step entails addressing feedback provided and measuring the artifact's improvement. In addition, redesign intends to capture the student iteration when working on the project, and change cannot be measured at only one point. As such, this item was omitted from the evaluation.

Application of the rubric to the student artifacts

The rubric was used to assess the academic posters, the final deliverable for the week-long course. The student artifacts were deidentified by the instructors and provided to an independent researcher with no involvement in the course development, instruction, or grading. The researcher applied the rubric to the posters and analyzed the results looking for patterns between each category in the rubric, trends in high grades for category among the groups, and relating the engineering design process evidence with creativity and innovation. This analysis is presented in the following section.

PROGRAM EVALUATION

Results from the framework to assess engineering design process with creativity and innovation

The framework developed in this paper included the application and analysis of three areas: assessment of the final project deliverable: academic poster, assessment of responses from surveys with close-ended and open-ended questions, and instructor feedback. The data was collected during the week-long course either at the start (pre-course surveys) or at the end (academic poster, post-course survey, and instructor feedback). An illustration of the framework proposed in this study is presented in Figure 2.

Figure 2. A proposed framework to assess creativity and innovation in the engineering design process

The data source was analyzed by the researchers looking for evidence of growth in knowledge of the engineering design process and how their deliverables include creative and innovative ideas. The analysis presented before used quantitative data obtained by grading the academic posters using the rubric developed for the study. The grades provided a clear picture of the knowledge acquired during the week-long course and how the posters showed creative concepts and innovative ideas uncommon for the type of problem presented to solve. In addition, the pre-course surveys provided an idea of the prior knowledge the students had regarding the engineering design process and gave a comparison point for the study to identify if the week-long course contributed to their learning of the process.

In addition, the post-course survey and the instructor feedback provided another point to identify evidence of the student's understanding of the engineering design process. The rubric data provided a quantitative indicator of innovative and creative solutions, and the post-course survey demonstrated how students shifted their thinking from identifying creativity in traditional places (art class, music) to an engineering setting (buildings, bridges). The quantitative and qualitative analysis results confirm that the engineering design process can be taught in a classroom using active learning, and the solutions are not only feasible but also creative and innovative.

Assessment of responses from pre- and post-course surveys

Students completed three surveys presented in the appendix, including a course evaluation, at the end of the summer course. The surveys had questions about engineering, creativity, and innovation, including agreement-based and open-ended questions. The surveys were analyzed for common themes and trends, and connections were evaluated between categories to understand growth in confidence or understanding of the engineering design process, creativity, and innovation. The results complemented the graded posters.

The students' surveys showed that their confidence in naming design process phases and relating engineering to real-life challenges improved the most. However, despite many students reporting an increase in their ability to name design process phases, their self-reported problem-solving ability showed limited change. Furthermore, there appears to be no influence between increased confidence in engineering problem-solving and knowing the design process phases, suggesting that students may not be connecting the design process as an engineering problem-solving tool.

The surveys also revealed that some students entered the course with an understanding of the design process (“agree” or “strongly agree” self-reported responses). In addition, some of these students gained confidence in their ability to think through an engineering problem, while others did not. This suggests that repeated exposure to the design process may enable students to utilize it as a problem-solving method, but other factors are also involved.

In the pre- and post-course surveys, students were asked to self-report their understanding of the engineering design process. For example, in response to the question: "I can think through an engineering problem and propose solutions,” students self-reported to agree and strongly agree more in the post-course survey than in the pre-course survey. This result suggests that the course and project helped students develop their problem-solving skills and confidence in proposing solutions to engineering problems. Similarly, in response to the question: "I can name at least 3 stages of the engineering design process", students self-reported higher agreement in the post-course survey than in the pre-course survey. This result indicates that students gained a better understanding of the engineering design process due to the course content.

Figure 3 suggests that students' initial or developed interest in civil engineering as a creative field may be related to their ability to perceive it as such. Specifically, students who initially rated themselves as creative in art and photography were more likely to view problem-solving as a creative outlet by the end of the course. The frequency of responses related to problem-solving increased from the pre-course surveys to the post-course surveys. Conversely, the frequency of responses related to engineering/construction, education/learning, everyday life, entertainment/leisure, and home showed little to no change. However, responses related to artistic pursuits showed a slight decrease, potentially due to the influence of engineering concepts on the students' perception of creativity, shifting from artistic expressions to problem-solving.

Moreover, students who changed their answers to include particular branches and challenges beyond building bridges and safety tended to increase their agreement with “[understanding] the relevance of civil engineering in real-life problems.” The changes observed imply that students may possess vague ideas about engineering before beginning the course. However, without purposeful exposure to these concepts, they may encounter difficulties establishing connections between them, their interests, and significant global issues.

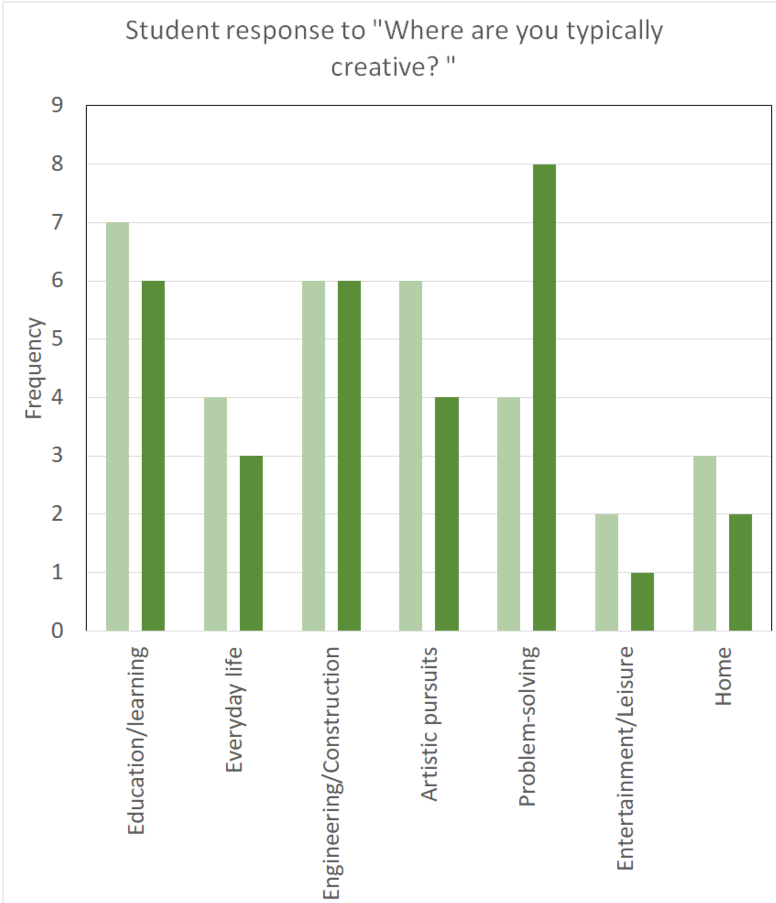

Figure 3. Student response to the question, "Where are you typically creative?". Light green indicates the frequency of the response in the pre-course survey. Dark green indicates the frequency of the response in post-course surveys.

Assessment of academic posters

Based on the rubric developed in Table 1 to evaluate the academic poster, the best performance was observed in "constructing a prototype" and "identifying a design need." These categories may have been the most straightforward for students to comprehend and implement in their designs. On the other hand, the lowest ranking was observed in the "select the best possible design" category, which suggests that students found it more challenging to choose the optimal design solution for a given problem. However, since all the others showed good and excellent performance, the results in this category may be an outlier. Figure 5 presents the results of the poster grading.

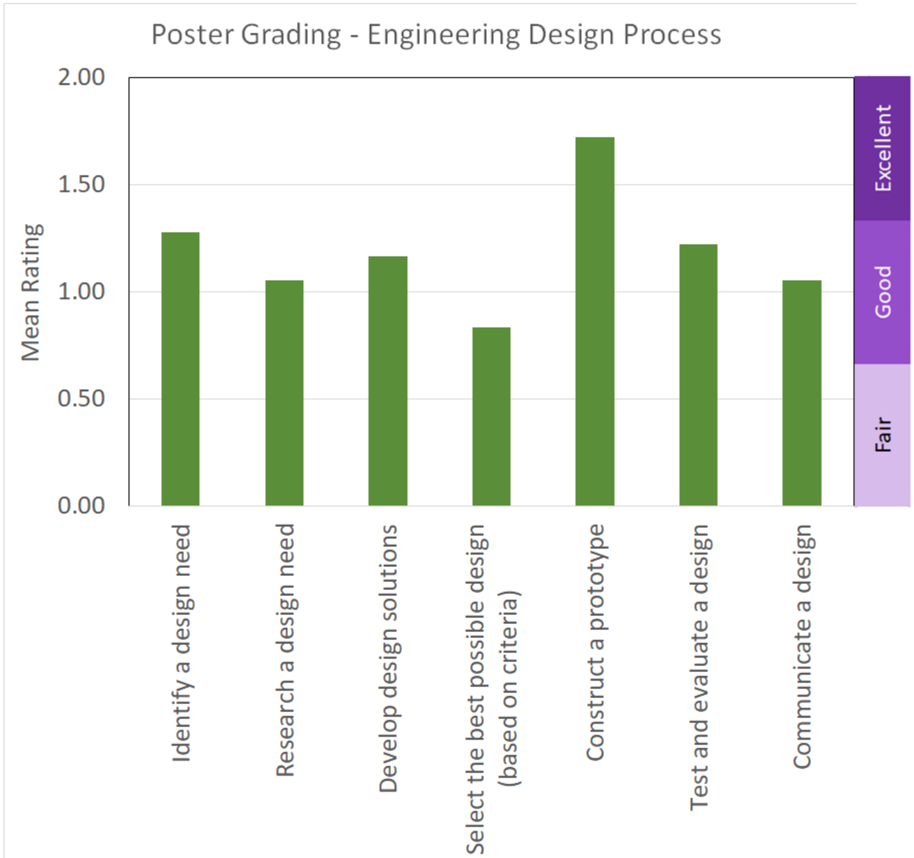

Figure 4. Poster grading on the Engineering Design Process

The rubric developed to evaluate the academic posters also included three categories to measure creativity and innovation: Novelty, Originality, and Technical feasibility. The results, presented in Figure 5, indicate that the students performed excellently in the technical feasibility category, suggesting that they were able to create designs that were feasible to construct and implement. Additionally, students performed well in the originality category, indicating that they were able to generate novel ideas for the design process. However, the results suggest that students performed only fairly in the Novelty category. This category indicates the level of innovation in the design process, regardless of the market, and the lower ranking suggests that students were less successful in generating out-of-the-box ideas. It is possible that students struggled with developing highly innovative ideas due to the nature of the problem or the limited time available during the week-long course.

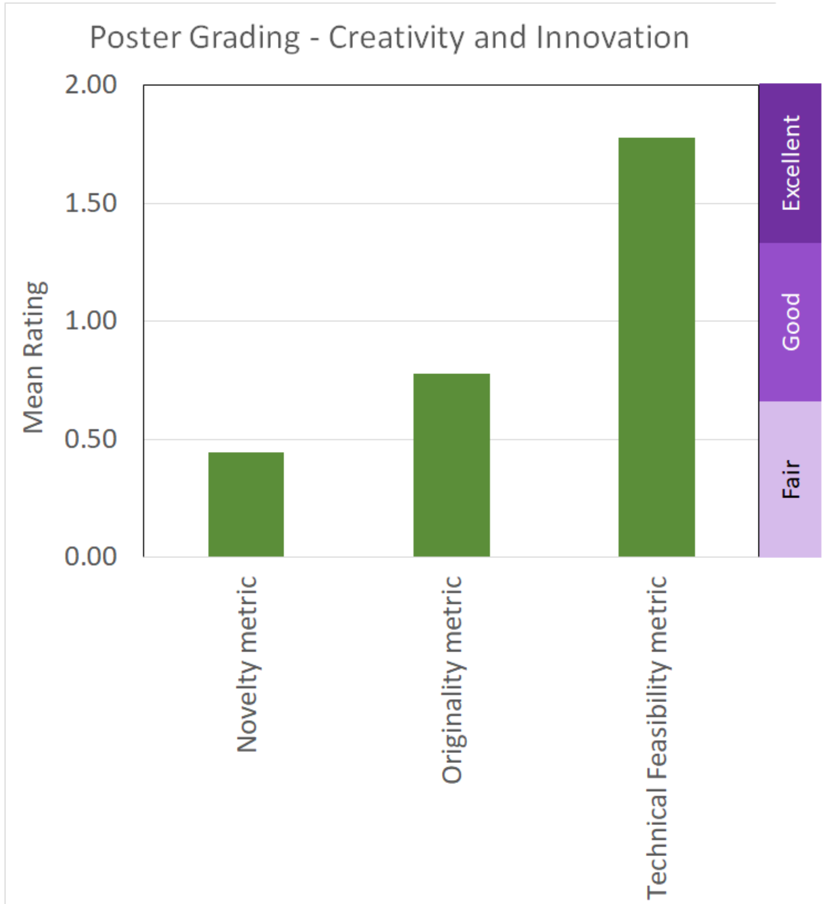

Figure 5. Poster grading on Creativity and Innovation

Assessment of responses from evaluation surveys

Upon looking at students' ratings of course activities and content delivery methods, there are several trends in their qualitative responses when noting their connections with activity engagement and specific takeaways. For example, in several instances, when students described their favorite activities using favorable terms such as "fun," "interesting," and "game," they also described specific technical takeaways from those lessons tied to our engineering design process framework, such as "solving," "factors," "knowledge to the real world," and "trial and error." Select quotes to demonstrate such outcomes are presented below:

- "It was really interesting to see how the behavior of fluid changes based on certain types of obstructions."
- "I also enjoyed calculating the capacity of cars that the roads can handle. It was [an] interesting topic and I [liked] solving it."
- "I found it very interesting how various factors can affect traffic."
- "Land surveying was memorable because it was the first time we applied our knowledge to the real world. It was exciting to learn through trial and error and see my progress right in front of me."

These outcomes indicate that the instructors effectively engaged students during lessons with real-world examples and in conveying and reinforcing complex STEM concepts, such as understanding relationships between variables. It is worth noting that students provided positive feedback about the instructors, describing them as “informative, knowledgeable, kind, patient, and passionate.” Some students suggested improvements, such as reducing morning lectures and increasing instructor interaction time.

CONCLUSIONS

This paper highlights the importance of creativity and innovation in engineering design and the need to integrate these concepts into pre-college curricula. The study evaluates the effectiveness of strategies geared toward encouraging creativity and innovation in conjunction with the engineering design process during a one-week civil engineering summer course using three assessment tools: class surveys, student artifacts, and instructor feedback. The assessment of the engineering design process and creativity and innovation was conducted using an analytic scoring rubric based on tools provided in the literature.

The surveys revealed that students' confidence in naming design process phases and relating engineering to real-life challenges improved the most. However, the students did not self-identify a significantly greater ability to solve engineering problems, indicating that students may not be connecting the design process as an engineering problem-solving tool. Based on the final project and pre-post course surveys, the students demonstrated an enhanced comprehension of the design process and an increased ability to use creativity in design.

Moreover, all students expressed confidence in linking engineering to real-world issues, as demonstrated by their ability to suggest technically feasible design solutions. Although the final project problem statements may have limited the student’s ability to apply concepts from every branch of the course, their evaluations revealed specific technical knowledge gained in various areas, indicating a solid understanding of the relevant topics covered in the course.

The posters showed that most students proposed feasible solutions, but some focused on incorporating creativity and prioritizing new topics such as innovation, the environment, and ADA accessibility. Students who initially rated themselves as creative based on art and photography were more likely to add problem-solving as a creative outlet at the end of the course. The evaluation surveys indicated that students enjoyed and learned from real-world examples and complex STEM concepts, and they provided positive feedback about the instructors. Overall, the summer course improved students' understanding of the engineering design process, creativity, and innovation.

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APPENDIX A – COURSE SURVEYS

Pre-Course and Post-Course Survey

Likert Questions

1. I can think through an engineering problem and propose solutions
2. I can name at least 3 real-life engineering challenges
3. I can name at least 3 stages of the engineering design process
4. I understand the relevance of civil engineering in real life problems
5. I am interested in studying civil engineering in college

Open Ended Questions

6. How would you define civil engineering?
7. What do civil engineers do?
8. What should engineers think about when designing tomorrow's infrastructure?
9. In your opinion, are civil engineers creative? Why or why not?
10. Where are you typically creative?

Evaluation Survey

Course Materials Questions (Likert)

1. The instructional materials (i.e., slides, readings, handouts, etc.) increased my knowledge and skills in the subject matter.
2. The course was organized in a manner that helped me understand underlying concepts.
3. The lectures, readings, and assignments complemented each other.
4. Assignments were reflective of the course content.

Course Structure Questions (Likert)

1. I understand the relevance of the material to real world challenges.
2. I believe what I learned in this course is important.
3. Expectations for learning were clearly defined.
4. Student learning was fairly assessed (e.g., through quizzes, homework, projects, and other graded work).

Course Learning Questions (Likert)

1. This course helped me develop professional skills (e.g., written or oral communication, reading computer literacy, teamwork, etc.).
2. This course broadened my knowledge of the study and practice of civil engineering.
3. This course helped me understand the engineering design process.
4. This course encouraged creative thinking.
5. This course encouraged me to consider a career in civil engineering.

Open Ended Questions

1. What were one or two of your favorite course activities? Why were these memorable?

2. What do you think could be improved in this course?
3. Would you recommend this course to a friend? Why or why not?
4. Anything else you would like us to know?