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# Immersive Learning Based Introduction to Engineering Design

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## ABSTRACT

Automation is changing the definition and allocation of jobs in most engineering fields including civil engineering. This digital disruption of civil and environmental engineering (CEE) could potentially result in the extinction of the traditional role of structural engineers. In response, educators must strive to provide students with an evolving skill set, nurturing their creativity and engineering judgment. Students will have to design resilient and sustainable solutions for the built environment in a dynamic, virtually connected setting where clients, architects, and contractors are stakeholders with shrinking budgets but public safety remains paramount. This requires a paradigm shift, not only in the methods of teaching or the equipment used, but actually, in the way the students interact and employ such tools and how they swiftly adapt with a dynamically changing set of objectives. The paper is presenting a case study aiming to improve the civil engineering design process through running a mock classroom experience. This class is mimicking the introduction to engineering design (IED) course, offered at Rensselaer Polytechnic Institute's School of Engineering (SOE), taught to undergraduate students mentored by senior undergraduate teaching assistants, and supervised by civil engineering professors. The educational module experimented through the mock class proved to revolutionize the way CEE students are introduced to the design process, by radically changing the design methodology and the classroom technology, with respect to the general SoE IED. The new CEE IED offered students the opportunity to brainstorm their designs through cloud-based modeling software, hold client-contractor interactive meetings through a flipped classroom setting, hold prototype analysis and shape optimization meetings through both cloud-based meetings and classroom team discussions, 3D print prototypes, and mechanically test these prototypes. Direct feedback and exit surveys showed that the participating students were able to put in practice what they have learned in their introduction to civil and environmental engineering courses. The current version of the course will help future CEE students to apply the skills that they have learned from CEE introductory courses taught in the semesters prior into IED class.

## INTRODUCTION

The development of engineering design education is a consistently developing subject in educational research. The reason is that the engineering profession is very dynamic and constantly developing, with new needs and tools evolving with time. (Dixon 1991) defined engineering design as cognitive activity based on knowledge, which could be described as: a) expanding engineers' scope from technical design to engineering design, b) it is not limited to the four years time-frame to teach engineering students everything needed about engineering design, c) engineering design educators should focus on cognitive fundamentals of design, to improve future engineering design practice, and d) improving engineering design by relating the current practice to scientific foundations. The interest in the development of engineering design was motivated during the late 1980's by ABET (Dym 1999), which focused on preparing graduating engineers for industrial requirements, and the negative effects of neglecting engineering design education (Dixon and Duffey 1990). Since then, researchers studied several aspects affecting student's success in engineering education.

Earlier research for engineering education focused on basic teaching strategies. For example, (Cynthia and Bursic 1996) studied the effect of using textbooks compared to only verbal protocols, (Atman et al. 1999) compared the performance of freshmen and seniors and found that performing iterative design assists the improvement of performance for both groups, (Mills and Treagust 2003) compared the process if being problem based or project based.

(Atman et al. 2007) compared the design behavior of students and expert engineers, where nineteen experts from a variety of engineering disciplines and industries each designed a playground in a lab setting, and gave verbal reports of their thoughts during the design task. It was shown that information gathering are major differences between advanced engineers and students, and experts spent significantly more time solving the problem than the students did, especially in the problem scoping stage.

From Pedagogical point of view, engineering design courses could be divided in four Pedagogical quadrants: Individual-content centric, Team-content centric, Individual-process centric, and Team-process centric (Sheppard et al. 1997). Within those quadrants, there are different styles of engineering education. It could be project based, problem based, or a mixed mode (Mills and Treagust 2003). It is also important to define evaluation and reward system, in order to help faculty and students involved to improve their performance (Todd and Spencer 2004, Carberry et. al 2010), which could be either quantitative and/or qualitative measures (Leydens et al. 2004, Lewis 2005). Some researchers studied the effect of game-based learning (Mavromihales et al. 2019), competition on learning outcomes (Gadola and Chindamo 2019), education background (Silva et al. 2019), and instructor's approach to the presented problem (Tekmen-Araci and Mann 2019) on the Pedagogical process.

In this paper, the authors are motivated by the proposed research questions in (Dym et al. 2005), which are intended to improve design education: What is Design Thinking? How Can PBL (Project Based Learning) Be Made Better? An Experiment in Globally Distributed PBL, and How Can Students Learn Design Thinking More Effectively?. Inspired by (Ringwood et al. 2005) in the use of Lego Mindstorms in engineering design classes, 3D Printing was used to execute proposed ideas. CAD tools were utilized to facilitate virtual design, as suggested by (Robertson et al. 2007, Yang et al. 2018, and by Shivakumar et al. 2017). Finally, heavy emphasis was put on laboratory testing, as it is important to improve students' design skills (Feisel and Albert, 2005), focusing on critical thinking and reflection about the iterative process and the use of analysis and optimization in engineering design (Asunda and Hill 2007) through iterative optimization, as suggested by (Carstensen and Bernhard 2019). Similar research approach could be found in (Spearrin and Bendana 2019), yet it does not address design optimization.

## METHODOLOGY

To enable a strong and immersive experience for the engineering students as they are being introduced to the engineering design process, the following goals were set:

**Speeding up production:** Typical tools given to students include workshop space with machining tools and raw materials like wood, metal and plastics. Additional materials or devices are bought by the students. Since these activities are time consuming and physical resources are limited, students do not have enough exposure to the brainstorming part of the design process. In fact, within each group, the preliminary idea is defined and outlined by one to two students only. Some times, those are the ones with better manual or computerized drawing skills. In addition, once a preliminary design is proposed, teams indulge in mainly machining activities. It is not until close to the presentation deadline do the students assemble their system and fully test it. Therefore, our goal here is to use advanced tools that are already the language of the future to help students contribute individually and collaboratively to all steps. This is done by using: 1) Fusion 360 which is a 3D CAD prototyping and analysis software, 2) Medium scale plastic 3D printing using a gallery of printers with print volumes up to 16”x16”x20”, 3) Interactive and collaborative media using smart boards through the Rensselaer Beta Classroom which enables students to work collaboratively on a common large HD LCD screen, 4) Enabling virtual evaluation through the built-in analysis tools in Fusion 360 which allow students to eliminate infeasible solutions before wasting their time in building them and without the need to have strong analytical and design background that they don’t have in their early years.

**Standardized testing:** In many cases, students are only testing their scaled projects using custom loading (sand bags, steel blocks). This limits them from drawing quantitative conclusions about their project and components behavior. Therefore, our goal here is to give students access to the mechanical testing labs available at the department and allow them to quantitatively compare the predicted capacities from Fusion 360 analysis with the accurate experimental results. Equipment used includes universal tension/compression machines (50 kips capacity) along with displacement sensors data acquisition.

**Understanding the difference and tradeoffs between modeling and reality:** A major drawback of limited exposure to testing, especially in civil engineering, is that students do not correlate well between simplified model assumptions and actual behavior. This is because testing full scale structures is beyond feasibility. Thus, as the students learn about design they are hardly exposed to material scale testing (if any). This limits their appreciation of abstractions made during the modeling process. For example, the difference between the truss hinged connections in the model and the real partial fixation in reality. Therefore, our goal here is to provide such appreciation through scaled projects testing. This can help students understand real constraints in the physical environment on construction, materials, element sizes, connections, and more. In fact, by introducing this element early on in the engineering education, students will be able to understand better code limitations and assumptions as they are introduced to it in their design classes (Steel, concrete and Timber design classes for example). In addition, they will be able to better imagine and consider such constraints in their Capstone projects. This goal is basically enabled through the integration between high production speed, virtual testing through analysis, and standardized testing. Students reporting on their findings of how experiments differ from model results are an invaluable knowledge that they acquire from this step.

**Enabling iterative design and optimization:** Again, due to time and space constraints, students hardly put down one plan, execute it and maybe tweak partial parts of it (sub-systems), yet, the chances to try/perform largely different iterations to reach an optimal solution (that could be simply accounting for difference between model and reality), is nearly impossible. Our goal here is to enable iterations throughout the overall design process. With virtual testing, we enable preliminary design iterations. Additionally, due to increased production speed through CAD and 3D printing, more time is available for iterating between alternative designs, and finally, with the ability to quantitatively test the produced elements as well as the ease of redesigning, iteration over the whole design cycle is enabled too.

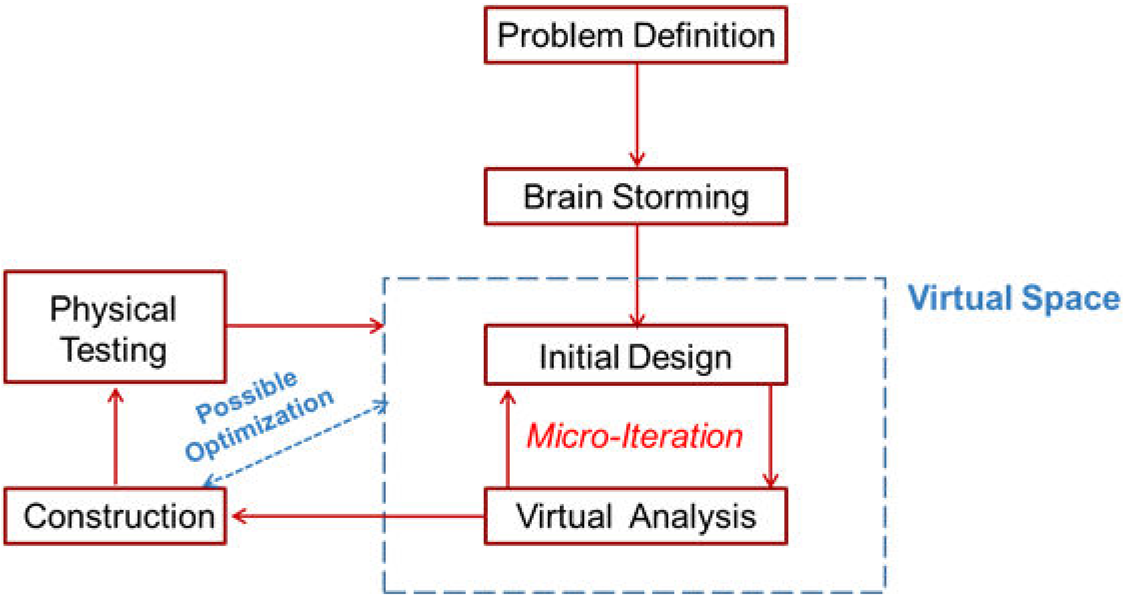


**Figure 1. New CEE-IED design flow**

## COURSE SETUP AND INNOVATIVE CHANGES

The Introduction to Engineering Design (IED) course offered at RPI's School of Engineering (SOE) is mainly taught at the sophomore or junior year to students from various engineering disciplines, the learning outcomes of the course are listed in Table 1. The course focuses on developing the engineering design process and enhancing the creative thinking for the students, these objectives are done through breaking the course into two parts. First, the mini-project part where students are paired to work on a small and simple project with predefined rules which includes limitations and guidelines for specifications, the learning outcome of this phase is to train the students to work with a partner on the same project and work the inverse problem of estimating the customers and their needs which dictated the given rules. The mini project is designed, built and tested in a four week span. Then comes the main part of the course the team project, the students are divided in teams (5-7 students each) where students propose a problem and work on a project solving that problem. The teams are formed of students with diverse majors, interests and skill set in order to insure a wide range of ideas for the problem under investigation. The project time is about twelve weeks with several milestones to ensure that the quality and complexity of the project is up to the standard of the course. The students start by proposing the problem, suggested solution and the project subsystems. After the instructor approves the idea the students design the subsystems and integrate them into a functional prototype, which is demoed in front of the instructors and the rest of the class. Finally, students present and submit a design memo for the whole process of the team project.

**Table 1. IED course learning outcomes**

| # | Outcome Description |
|---|---|
| 1 | Students will have the capacity to identify, formulate and solve complex engineering problems by applying principles of engineering, science and mathematics. |
| 2 | Students will know how to apply the engineering design process to produce solutions that meet specified needs with consideration for public health and safety, and global, cultural, social, environmental, economic factors. |
| 3 | Students will exercise and improve important design skills of visualization, calculation, experimentation, and modeling. |
| 4 | Students will have skills in organizing people and ideas for successful design. Skills include teamwork, project management, verbal and written communication, and documentation. |
| 5 | Students will be able to function on a team whose members together provide leadership, create a collaborative environment, establish goals, plan tasks, and meet objectives. |
| 6 | Students will develop the ability to communicate effectively with a range of audiences. |
| 7 | Students will develop their ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments. |
| 8 | Students will have the ability to acquire and apply new knowledge as needed, using appropriate learning strategies. |

The new CEE IED follows the main learning objectives of the general IED, however there are some essential differences between the two versions. The main difference being the use of provided technologies to save time and enable iterations both at a micro-scale (only during the design stage) and at a macro-scale (after building and testing). So, during the “Mini-project” part, a defined problem is to be given to the two student teams with a detailed outline of the problem and the requested system to design, however, the students are asked to brainstorm not only on paper but actually using the Fusion 360. The students are asked to hold virtual meetings in the Beta classroom and to discuss the alternatives they created. Then, using the software, they are required to analyze the proposed system and predict its capacity. Next, they are asked to iterate to optimize a single parameter, which is the weight to load carrying capacity ratio. Once virtual optimization is done (micro-iteration), the teams build their models using 3D printing and then test them mechanically. Teams are required to report on the results and discuss why the results matched or did not match the modeling. Next, in the “Main-project” part, the two teams are challenged by a general problem that is civil engineering related problem. Here, the problem is not precisely defined and is given in a way similar to a general customer. The students are asked to go through the whole engineering design process from the beginning including retrieval of customer needs and preparing specifications up to the final testing using scaled 3D printed models. The main differences in this stage compared to the original IED are in enabling iterations (similar to the mini-project stage) and in introducing the students to the concept of change orders. This later one was very important and cannot be introduced without the flexibility enabled by the virtual design stage. For this part, the instructors play the role of the customer and/or the contractor. In either cases, during the design stage or construction stage, change orders are very common in civil engineering projects. For example, changes in allocated budget could force the customer to ask for a change of the proposed bride design (reducing the number of lanes for example). Also, contractors may find different soil conditions at the site when they start excavating that were not encountered during initial contracting stage. While these are very advanced concepts for the students, being able to iterate and redesign virtually, enables the introduction of such concepts. Thus, the instructor's role is to hold a meeting with the student teams and change one of the specifications that were given to them after they have produced a virtually optimized project. The students document the change order and produce a modified design which is later approved by the instructor. Finally, the students finish the project, 3D print it, and then test it. All of these steps are documented in the student's final report and the report has to reflect on the challenges and methodologies that were used to overcome these challenges.

## CASE STUDIES EVALUATED DURING COURSE TIME

The authors ran a mock-up CEE-IED course following closely the outlined details in the previous section. In the course, two student teams were formed and for each team, an undergraduate TA was assigned. The course followed the general two-stage IED system where the students were first given a mini-project then they were given a main project. But before this part started, the authors (which were the course instructors), wanted to evaluate the time and effort needed for general CEE students to learn the basics of the software by themselves with very limited TA guidance. So, the actual mock-up course included a pre-course evaluation step. The details of the steps are discussed here.

**Pre-course Fusion 360 learning stage:** Before student teams were hired for the mock-up course project, the two TAs were hired. They were asked to learn the software and use the available online tools for it (forums and examples). In one day, TAs were able to build models with imbedded components. In the next day, they were able to analyze these models and display deformations and Von-Mises stresses identifying critical locations in the models. These were very simple beam models with simple supports and loading at the mid-span. Yet, this initial trial proved that students could easily learn how to use the software even without instructions from the instructors. Yet, to better guarantee uniform and smooth building of these skills, the two student teams were hired and were asked to learn the software by themselves first, then, the TAs presented the beam example to the students as a one session tutorial. This session was video-recorded and screen-captured, to be used as an additional resource for the fully implemented CEE-IED course. After performing this preliminary study, it was decided that the tutorial becomes the first lab session in the student's future schedule.

**Mini-Project stage:** Here, students are assumed to be familiar with the software. In the mini-project, the students were required to design a CEE educational toy that consists of a 10 bay Warren truss bridge. The bridge should be simply supported over a 1m span and is made from members connected through real jointing only at the members intersections (no member joints are allowed). The truss overall dimensions were fixed to mimic constructability and clear height constraints. Interesting enough, even with all these limitations given to the students, the two teams came up with two different designs based on how they designed the joints. As can be seen from Figures 2 and 3, both teams had multiple iterations to optimize the member ends along with their connection design.

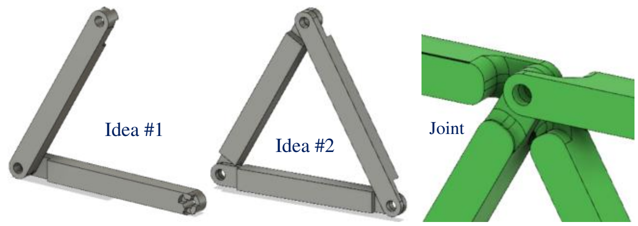


**Figure 2. First team truss design**


**Figure 3. Second team truss design**

In Figure 2, the first team chose to link the members with only one pin, they went from a complex interlocking joint design to a simple flat end that varies depending on the member location (idea 1 to idea 2). The second team (see Figure 3), considered concentric loading of the member but they iterated with the way they will make the joint around the member ends. Both teams had multiple virtual iterations through the analysis (see team 1 truss analysis in Figure 4). Next, the teams printed the truss members and assembled them. Finally, the two trusses were tested in the structural engineering testing lab as shown in Figure 5.

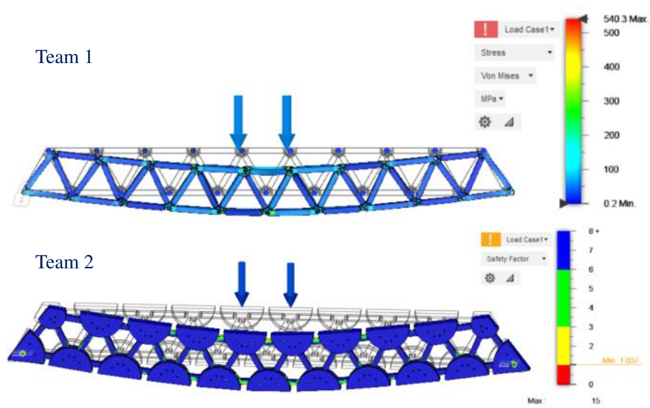


**Figure 4. Teams trusses analysis**

One of the most important outcomes of this last step is the experience that the students gained from real testing. In the models analysis (see figure 4), the truss is loaded in its plan and the analysis was linear static, thus, buckling out of plan was not captured by the analysis. When tested in the lab, both trusses buckled way before their predicted failure loads. Team 1 truss buckled earlier than team 2. In their reports, the students reported this mismatch in failure and understood the limitations of the model and how reality can be different. They also reported on the fact that truss 2 buckled after truss 1. They quickly realized that having joint plates (truss 2) versus single pinned connections introduced out of plane stability to the truss. In fact, the students had so much to learn only from this mini-project experience.

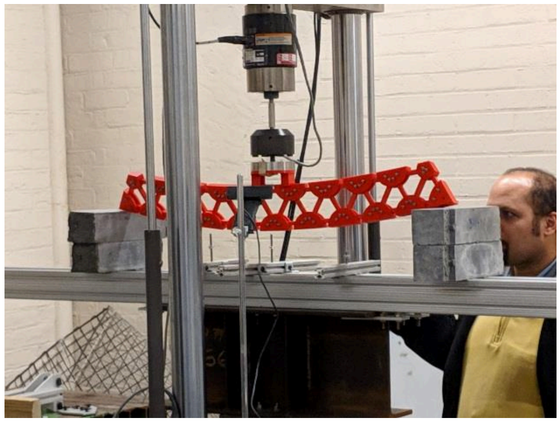

**Figure 5. Second team truss testing**

**Main project:** After finishing the mini-projects tests, each team was given a different challenge as their main project task. One team was given a structural engineering challenge and the other was given a geotechnical engineering challenge. Here we will focus only on one of the projects to demonstrate the process. The structural engineering team was asked to develop an exclusive track for pedestrians and cyclists that spans across the Hudson River from Albany to Troy New York. A map of the location was given to the students (see Figure 6).

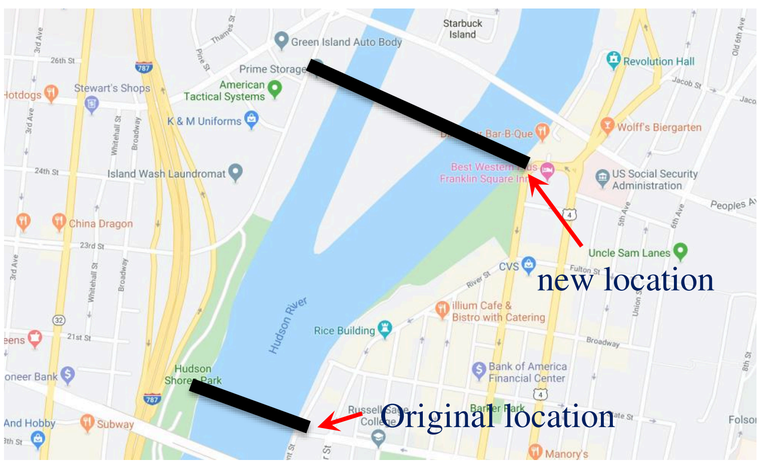


**Figure 6. Project location map (Courtesy of maps.google.com)**

With this open statement, the students started to solicit detailed customer needs that they converted into specifications. They introduced the idea of making it enclosed instead of being open so that it can be operational even during snowstorms during the long upstate New York winter season. They also proposed the use of openings so that the bridge still provides a pleasant view for the users to the Hudson River. Following specifications stage, they started to evolve their ideas by looking at different geometric forms as shown in Figure 7. The original design was supposed to cross the River at a small span away from the island (see Figure 6), then after proposing their initial design, the instructors asked for a change order by moving the bridge location more to the north over and have it pass by the island so that is serves better the people living in downtown Troy. This has significantly changed the bridge spans but the students were able to quickly edit their design and check the new one using the software. Important to mention here is that during the whole project, the students were always modeling and designing a scaled version of the real bridge so that they can 3D print it. The final design is shown in Figure 8. The bridge was 3D printed in parts and was loaded at the center. Again, students realized the difference between modeling and reality because, when they printed the bridge, they had to make it from multiple parts and glue them. In the test, the glue failed but in the model, the structural members did. But, overall, multiple virtual iterations were enabled and the authors were very confident that in the real application of the course, the students will be actually able to reiterate also during the full testing stage (macro-iteration) because the whole mock-up class was performed in less than a full semester.

*The Lucky knot bridge in China (Courtesy of inhabitat.com)*

*The Helix Bridge in Singapore (Courtesy of commons.wikimedia.org)*

**Figure 7. Examples of bridges that inspired the students' geometric design**

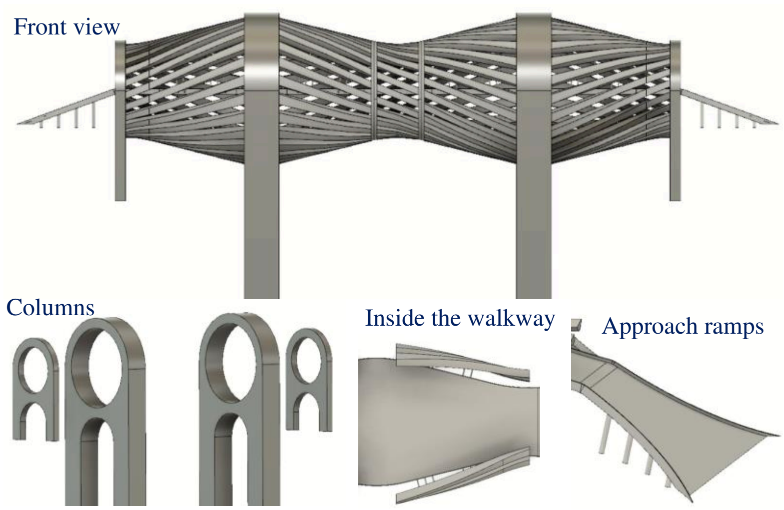


**Figure 8. Final proposed bridge design**

## ASSESSMENT OF THE PROPOSED METHODOLOGY

At this point, only the mock-up class was executed. It is expected that the full class will be implemented in the CEE curriculum in the coming year. Therefore, quantitative assessment of the change by comparing student's performance in the original versus new IED classes is not possible at this time. Yet, the authors used the feedback from students as well as the clear observed increase in number of iterations as clear indicators of the success of the proposed methodology. For example, the students say in their final poster "The mock class allowed for students to put in practice what they have learned in their Introduction to Civil and Environmental Engineering courses". This statement is contradictory in many times with the