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# Designing Project-Based Learning (PBL) Units Using Culturally Relevant Pedagogy to Develop Engineering Learners' Critical Consciousness in a Statics and Dynamics Class

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## ABSTRACT

Engineering learners must develop skills to design holistic solutions that take competing and complex economic, environmental, and social factors into account. Yet, these skills are not simply cognitive in nature. To develop holistic solutions, engineering learners must develop their affective attitudes so that they can gain an awareness of inequities and injustices in the world so they can then envision themselves as future agents of change with the capability to upend those injustices through their engineering efforts. Put simply, they must develop their critical consciousness to prevent becoming future engineers who inadvertently worsen existing systemic inequities. This paper summarizes the instructional design strategy, assessment, and overall effectiveness of two project-based learning (PBL) units used in a 16-week-long, introductory engineering mechanics class – statics and dynamics. The successive PBL units were designed using principles in backwards-centered design and culturally relevant pedagogy such that small teams of engineering learners could share, negotiate, and critically evaluate their engineering problem solving efforts in response to real-world, ill-structured scenarios. Learner's reflective writings were thematically analyzed at two points in time to assess in qualitative form the development of their critical consciousness in relation to an a priori 4-level scale for critical consciousness. The results indicate that the instructional design promoted approximately a third of the class to express higher forms of critical consciousness. Notably, the second PBL unit was described by the learners as being more conducive to their critical consciousness development because the scenario was viewed to be more "wicked" than the first PBL unit. The findings in this paper are valuable for engineering educators seeking to advance curricular interventions that positively shape learners' affective attitudes and have the potential to be adapted and explored in many other engineering mechanics classrooms and institutional contexts.

**Key words:** Critical consciousness, instructional design, project-based learning

## INTRODUCTION

Engineers in the 21st Century need a broad range of skills to solve complex, technical problems; including broadened perspectives to design solutions that take various economic, environmental, and social factors into account in their engineering problem solving efforts. Without these broadened perspectives, engineers can inadvertently worsen socioeconomic conditions and equitable access to resources, particularly for marginalized communities who are often overlooked in typical engineering design processes (Easterly, 2006). The development of infrastructure over the decades, for example, has upended vibrant communities of color (Kahler & Harrison, 2020; Avila, 2014) or worsened the quality of local environments leading to poorer health outcomes (Johnston & Cushing, 2020). In other examples, emergent technologies have mischaracterized vulnerable persons in autonomous vehicle collision avoidance scenarios (Deb *et al*., 2020; Colley *et al*., 2019) or misconstrued a diverse range of human inputs because training algorithms were biased toward dominant populations (Schwartz *et al*., 2022; Benjamin, R., 2019; Calders & Žliobaitė, 2013). Worse yet, engineers without broadened perspectives can come to view engineering as a purely technical endeavor devoid of any responsibility toward the human condition (Bielefeldt, 2018; Lachney & Banks, 2017; Cech, 2014), which can reinforce asocial, apolitical, and apathetic attitudes in the engineering profession (Cech, 2013; Rugarcia *et al*., 2000) and in engineering practice (Karwat *et al*., 2015). In short, engineers without broadened – and critical – perspectives can come to unknowingly compound or exacerbate injustices through their engineering efforts.

In response to this problem, an increasing number of engineering education scholars have called for the creation and deployment of new curricular interventions that equip the next generation of engineers with the skills necessary to design holistic solutions that meet the needs of our increasingly diverse nation and globalized economy (Leydens & Lucena, 2017; Riley, 2008; NAE, 2005). A vast number of engineering educators have responded to that call by exploring interventions that develop engineering learners' sense of social responsibility – or their set of beliefs on how they come to understand themselves and their obligations to the world (Lathem *et al*., 2011; Vanasupa *et al*., 2006). Many engineering educators have shared the effectiveness of high-impact learning experiences (e.g., service learning, community-based learning, etc.) that positively shape engineering learners' attitudes about the human element in engineering design (Cabedo *et al*., 2018; Rulifson *et al*., 2018; Bielefeldt & Canney, 2014; Zoltowski *et al*., 2010). Others have explored how immersive experiences (e.g., humanitarian engineering, international field work, study abroad, etc.) also positively shape engineering learners' attitudes toward social responsibility (Berka *et al*., 2021; Ngo & Chase, 2021; Smith *et al*., 2020; Amidei & Sandekian, 2010; Passino, 2009). Though impactful, these interventions can be resource intensive for an individual instructor (e.g., monies, time, energy, etc.), require careful nurturing of relationships with community partners, and demand meticulous monitoring of student learning to ensure that learners do not take away the wrong lessons (e.g., promoting neo-colonialism (Birzer & Hamilton, 2019) or problematic superiority complexes (Bauschpies *et al*., 2018; Lambrinidou & Canney, 2017)).

As such, a large number of engineering educators have alternatively explored and shared the value of developing engineering learners' perspectives and attitudes within classroom-specific contexts. For example, in contrast to well-defined problems often featured in engineering science textbooks, an instructor's use of ill-structured (Akinci-Ceylan *et al*., 2021; Strobel & Pan, 2011; Jonassen *et al*., 2006) and "wicked" problems (Lönngren & Van Poeck, 2021; Schuelke-Leech, 2020) that juxtapose technical problem solving within ethically ambiguous scenarios can challenge individual learners to inspect the social consequences and impact of any technical solution they may consider. Arranging learners into small, cooperative groups like think-pair-share exercises (Asok *et al*., 2016) can additionally prompt learners to share, debate, negotiate, and compromise on their technical solution spaces as constrained by every individual's own intrinsic value system and moral beliefs. Temporally brief exercises such as problem-based learning (Hoffmann & Borenstein, 2014) can offer targeted instances in developing learners' attitudes while temporally extended activities such as project-based learning (Castaneda *et al*., 2022) can afford instructors more opportunities for formative feedback as learners develop, refine, and optimize a team-negotiated solution over a period of time.

Those scholars who have explored these types of classroom-specific, team-based, and project-based learning activities find that it promotes engineering learners' approach to holistic problem-solving (Miner-Romanoff, 2019), self-regulation (English & Kitsantas, 2013; Stefanou *et al*., 2013), and teamwork (Xia *et al*., 2020; Alford *et al*., 2014). Additionally, many engineering educators have noted the strengths of ill-structured, team-based, project-based learning activities as mirroring the real-world scenarios that engineering learners will face in future engineering practice (Boss & Krauss, 2022; Regev *et al*., 2009). Yet very few studies have explored how these types of classroom-specific learning activities contribute toward an engineering learners' attitudes on how their technical problem-solving efforts might improve or worsen economic, environmental, and social conditions. Moreover, there are very few disseminated innovations that describe how such classroom-specific learning activities might manifest in an engineering mechanics context where instructors cover a wide-range of canonical technical topics often leaving very little room for non-canonical elements to be included (e.g., engineering ethics or social responsibility).

Culturally relevant pedagogy is a means of approaching instructional design in order to develop learners' attitudes toward economic, environmental, and societal considerations by addressing three skillsets: (1) academic mastery, (2) multicultural competency, and (3) critical consciousness (Ladson-Billings, 2014; Ladson-Billings, 1995). Critical consciousness can be defined as an individual's awareness of injustices in the world around them while enacting ways to take action to upend those injustices. Critical consciousness was posited as a construct by Paulo Freire in 1970 (Freire, 2000), and it has been extended and used in a wide range of studies seeking to explore how individuals become aware of injustices and act to eliminate those injustices (Diemer *et al*., 2021; Watts *et al*., 2011). Culturally relevant pedagogy is increasingly manifesting throughout engineering education via revised syllabi (Nelson *et al*., 2020; Savaria & Monteiro, 2017; Larke, 2013), alternative textbook adoptions (Morrison *et al*., 2008), the incorporation of sociocultural contexts in engineering problem solving efforts (Jordan *et al*., 2019; Pitsoe & Letseka, 2015), the use of ill-structured problems (Castaneda *et al*., 2022; Castaneda, 2019), and the uncovering of hidden curriculum in engineering (Villanueva & Sunny, 2022).

This paper presents the instructional design strategy, assessment, and overall effectiveness of two successive project-based learning (PBL) units intended to promote the development of engineering learner's critical consciousness in the classroom-specific context of a 16-week, sophomore-level offering of an introductory level engineering mechanics – statics and dynamics – course. The instruction was conducted at a public regional university in the Mid-Atlantic region of the US, which is designated as both a primarily undergraduate institution (PUI) and a predominantly White institution (PWI). Specifically, the PBL units were designed to develop individual learner's critical consciousness in response to ill-structured scenarios situated in real-world engineering contexts familiar to them.

## INSTRUCTIONAL DESIGN STRATEGY

The lead author, as both the instructor of the course and a researcher of the instructional intervention, worked with the co-authors to establish guiding principles for the instructional design strategy in order to achieve the instructional goal. The overarching goal of the intervention was for engineering learners to develop their critical consciousness and come to view community stakeholders as partners rather than constraints in engineering problem solving, particularly in the context of a 16-week-long engineering mechanics course – statics and dynamics. To achieve this instructional goal, the team adapted principles in backwards-centered design (Wiggins & McTighe, 2005) and culturally relevant pedagogy to design two successive, team-based project-based learning (PBL) units. The first PBL unit centered on engineering statics topics whereby students designed a truss bridge for a nearby community, using *human-centered design* (HCD) and *design thinking* (DT) (Fila *et al*., 2018; Zoltowski *et al*., 2021; Dym *et al*., 2005; Simon, 1969). The second PBL unit centered on engineering dynamics topics whereby students designed an amusement park attraction for a land developer, using the *engineering for social justice* (ESJ) approach (Leydens & Lucena, 2017; Leydens *et al*., 2014). Both PBL units shared mirroring elements, and both PBL units featured characteristics of ill-structured problems.

Table 1 summarizes the key elements for the two PBL units. Our use of backwards-centered design led to splitting the 16-week-long course into two eight-week-long learning experiences: the first half

***Table 1. The four deliverables in each of the two project-based learning (PBL) units used in a 16-week-long engineering mechanics class – statics and dynamics. The 16-week-long class was evenly divided between an eight-week-long Statics PBL unit (Weeks 1 through 8) and a subsequent eight-week-long Dynamics PBL unit (Weeks 9 through 16).***

| | |
|---|---|
| **Written Reports Focused on:** | |
| **Deliverable 1 –** Assigned in Week 1 (or 9) and due in Week 2 (or 10) | 1) Gathering background information on disparate candidate sites based on engineering research;<br>2) Empathizing with disparate stakeholders;<br>3) Creating stakeholder personas based on interviews; and<br>4) Reflecting on how gathering information on the candidate sites and stakeholders informed learners' thinking about the engineering design process. |
| **Deliverable 2 –** Assigned in Week 3 (or 11) and due in Week 4 (or 12) | 1) Summarizing a specific engineering design framework;<br>2) Creating 'problem or need' statements based on background information and a specific engineering design process;<br>3) Creating value propositions that respond to the 'problem or need' of each group of stakeholders; and<br>4) Reflecting on how creating 'problem or needs' statements informed learners' thinking about the engineering design process. |
| **Deliverable 3 –** Assigned in Week 5 (or 13) and due in Week 6 (or 14) | 1) Creating analytical and/or physical prototypes that optimize technical and non-technical dimensions in the context of a specific engineering design framework;<br>2) Validating the analytical and/or physical prototype based on the personas; and<br>3) Reflecting on how creating prototypes informed learners' thinking about the engineering design process. |
| **Oral Presentation Focused on:** | |
| **Deliverable 4 –** Assigned in Week 7 (or 15) and due in Week 8 (or 16) | 1) Justifying how the team's proposed solution responds to the 'problem or need' for a group of stakeholders;<br>2) Justifying how the team's proposed solution creates non-technical value for the group of stakeholders; and<br>3) Reflecting how the use of a specific engineering design framework informed learner's thinking about the engineering design process. |

in engineering statics and the second half in engineering dynamics. Each PBL unit was divided into four deliverables, and each deliverable was designed to contain learning activities that a team of four to six students could accomplish within a seven-day, outside-of-class period. As team-based PBL units, each deliverable was designed to ensure that individual learners engaged in the typical characteristics of PBL units (Merritt *et al*., 2017; Palmer & Hall, 2011; Prince & Felder, 2006; Dym *et al*., 2005) and ill-structured problems (Hoffmann & Borenstein, 2014), including having learners (1) gather information to inform their problem-solving efforts; (2) reconcile competing tradeoffs; (3) evaluate open-ended solutions situated in a real-world setting; (4) deliberate and negotiate with their teammates to reach well-informed compromises; and (5) justify a final solution that is substantiated with an abundance of evidence and engineering analysis.

In addition to the team-based PBL units, culturally relevant pedagogy informed our development of instructional activities that supported individual learner's academic understanding of the course content, multicultural competencies, and development of their critical consciousness. Thirty-two 50-minute lecture periods were used by the instructor to support learners' academic success by overviewing engineering mechanics topics in:

- *Engineering Statics:* inspecting forces and moments as vectors; establishing force systems and drawing free-body-diagrams; calculating centroids of distributed loads; and applying equilibrium to static force systems (e.g., beams, trusses, frames, and machines) to solve for external reactions and internal forces.
- *Engineering Dynamics:* applying equilibrium to dynamic force systems; solving for (angular) position, (angular) velocity, and (angular) acceleration as time-dependent functions in straight-line, erratic, and circular motion; leveraging conservation of work and energy principles in solving problems; and determining the mass moment of inertia in rotational systems.

Six 50-minute lecture periods were used by the instructor to engage in case-based learning discussions in order to promote learners' multicultural competencies while focusing on critical consciousness. Lastly, learners were assigned individual, weekly homework assignments that included typical textbook problems and the creation of 'sketchnotes' – or concept maps – that summarized technical and design concepts in visual illustrations (Ferreira & Hernández-Ramírez, 2023; Paepcke-Hjeltness & Mina, 2021). The learning objectives for the two PBL units are summarized in Figures 1 and 2. Our use of backwards-centered design led learners to achieve high levels of learning (i.e., "evaluate" and "create") by the end of each PBL unit. It is important to note that the PBL units were designed such that the learning activities for each were highly mirrored to one another across the two halves of the course, and their principal differences were the engineering mechanics topic and the engineering design framework.

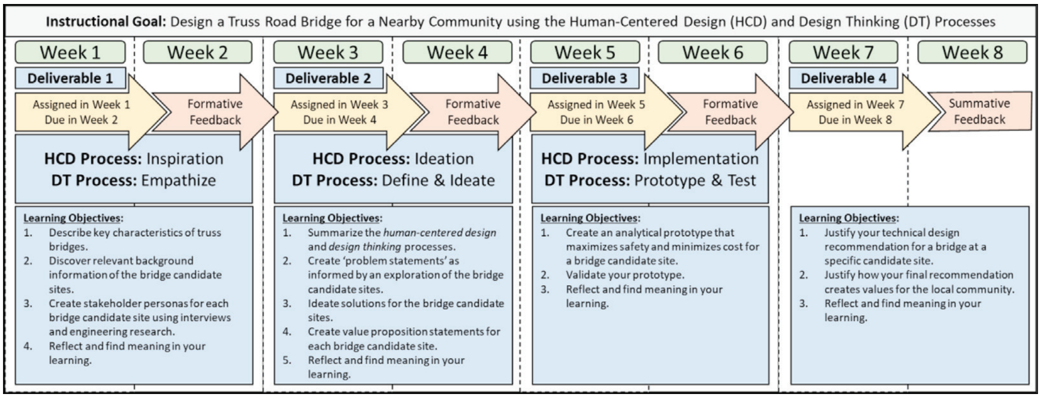


***Figure 1. The first PBL unit trifurcated the five steps of design thinking (DT) and three steps in human-centered design (HCD) into three distinct deliverables, which tasked students to learn about key characteristics of truss structures, empathize with stakeholders at a nearby community, draft problem statements, ideate and prototype multiple solutions, and justify their overall recommendation in a final technical presentation.***

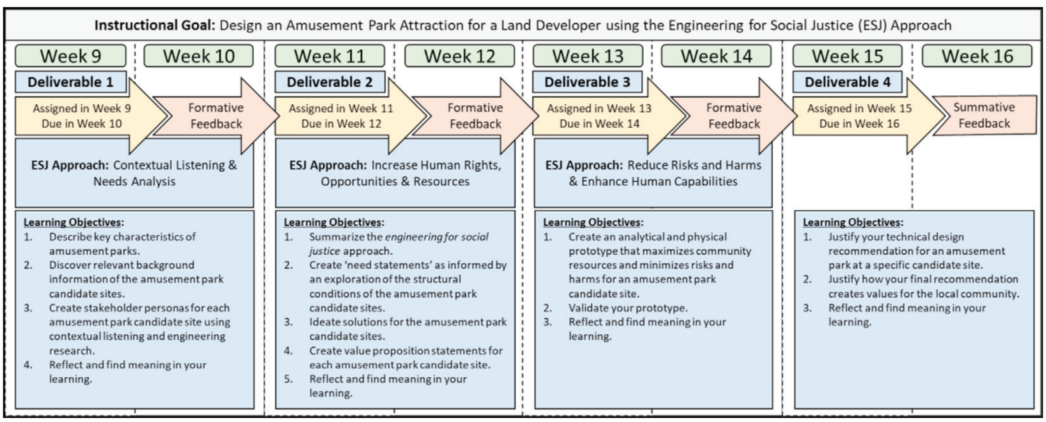


***Figure 2. The second PBL unit trifurcated the seven steps of the engineering for social justice (ESJ) approach into three distinct deliverables, which tasked students to learn about key characteristics of moving attractions, empathize with stakeholders at a nearby community, draft need statements, ideate and prototype multiple solutions, and justify their overall recommendation in a final technical presentation.***

### Adjustments to the Course as a Result of Adding the PBL Units and Case Study Discussions

The addition of the PBL units and case-based learning discussions necessitated adjustments to the form of the course as it was previously taught. First, the course schedule was adjusted to allow for six 50-minute lecture periods to be used for case-based learning discussions. The course had previously made use of four total 50-minute-long high-stakes exams divided evenly between engineering statics and engineering dynamics topics, as well as a high-stakes, cumulative final exam. The replacement of these high-stakes exams with open-ended, project-based learning was merited since the instructional design sought to achieve certain types of learning outcomes (Goorts, 2020; Knight, 2002) that seek to prepare students with the skills and mindset needed to be successful in their future careers (Daniels *et al*., 2002). Secondly, the course includes a laboratory component that is used to provide reinforcement of the course material through experiments. In its previous form, ten technical laboratories were conducted in the course. Five laboratories in statics had students manipulate load cells in a number of different configurations to conceptually explore uniaxial force, systems of forces, moment and moment arms, and force equilibrium. Five additional laboratories in dynamics had students use various sensors to measure displacements, velocity, and acceleration of objects subjected to straight-line motion and circular motion. These ten laboratories were redesigned to be accomplishable within six laboratories, divided evenly between statics and dynamics topics. The elimination of the four high-stakes exams and the reduction of the laboratory exercises from ten to six allowed for the insertion of six case-based learning discussions and eight team-based project deliverables.

The redesign of the course also required the redistribution of how instructional activities contributed toward the final grade, specifically in relation to the effort exerted by students and student teams to meet the course learning outcomes. Prior to the redesign, the high-stakes exams were weighted 50% toward the final grade (see Table 2). After the redesign, the PBL units – comprised of six total technical reports and two total presentations – were weighted 50% toward the final grade (see Table 3). The course learning outcomes were adjusted so that the new design-based elements of the PBL units as well as the reflective practices could be integrated across many instructional activities. The redistribution of the grade weights not only enhanced the emphasis on the PBL units but also ensured that student effort and collaboration were more accurately reflected in their final grades.

### Design of the First PBL Unit using Human-Centered Design (HCD) and Design Thinking (DT)

The first PBL unit (see Figure 1) was designed to support the learning of truss structure analysis and design in the context of an eight-week-long suite of learning activities of engineering statics topics. A real-world setting was identified at a rural, low-density community approximately 15 miles away from the university campus where localized traffic congestion at a highway interchange had

***Table 2. Tabular presentation of instructional activities weighed toward the final grade, prior to the redesign of the course.***

| | Major course components: | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Rationale for weighting of major components on final course grade** | **In-Class Activities, Participation, and Quizzes** | **Homework (x15)** | **Lab Reports (x10)** | **Exam #1** | **Exam #2** | **Exam #3** | **Exam #4** | **Final Exam** |
| **Upon completion of this course, students should be able to:** | | | | | | | | |
| Analyze forces in real-world applications by constructing free-body diagrams and applying corresponding equilibrium equations. | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ |
| Analyze particles, systems of particles, and rigid bodies by applying kinematics, energy, and momentum methods. | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ |
| Describe, analyze, and interpret experimental data and articulate key findings. | | | ✓ | | | | | |
| Solve statics and dynamics problems using hand-calculated and computational methods. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Communicate lab results in oral presentations and technical memos. | | | ✓ | | | | | |
| **Weight on final course grade:** | 10% | 15% | 25% | 10% | 10% | 10% | 10% | 10% |

been highlighted by the state department of transportation for its high number of traffic collisions. This setting was selected for the first PBL unit context because the area was familiar to the students and readily accessible for further exploration, thus highlighting the potential for relevancy for the students. Three potential bridge candidate sites at this nearby community were listed for the student teams to consider in order to divert local traffic away from the interchange, requiring a tradeoff analysis to (1) an industrial area, (2) an agricultural area, and (3) a residential area. These three candidate sites were selected to prompt learner exploration of economic, environmental, and social factors in engineering problem solving efforts. The PBL unit included four key deliverables (see Table 1) and was structured using the *human-centered design* (HCD) and *design thinking* (DT) processes as it was a familiar engineering design framework for the learners used in a prerequisite,

***Table 3. Tabular presentation of instructional activities weighted toward the final grade, after the redesign of the course.***

| | **Rationale for weighting of major components on final course grade** | **Major course components:** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **In-Class Activities, Participation, and Case Studies** | **Homework (x15)** | **Projects – Statics (x3)** | **Labs – Statics (x3)** | **Presentation – Statics (x1)** | **Projects – Dynamics (x3)** | **Labs – Dynamics (x3)** | **Presentations – Dynamics (x1)** |
| Upon completion of this course, students should be able to: | Analyze systems of forces by constructing free-body diagrams and applying corresponding equilibrium equations. | ✓ | ✓ | ✓ | ✓ | | | | |
| | Analyze particles, systems of particles, and rigid bodies by applying kinematics, energy, and momentum methods. | ✓ | ✓ | | | | ✓ | ✓ | |
| | Conduct experiments and analyze generated data to determine key findings. | | | | ✓ | | | ✓ | |
| | Justify engineering recommendations using engineering principles and methodologies. | | | ✓ | | ✓ | ✓ | | ✓ |
| | Communicate engineering results via technical writing and oral presentations. | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Adopt a consistent practice of reflection and sense-making for developing professional skills in the context of engineering design. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Weight on final course grade: | 5% | 15% | 15% | 15% | 10% | 15% | 15% | 10% |

sophomore-year engineering design course. The HCD process entails three phases (*inspiration*, *ideation*, and *implementation*), and the DT process entails five phases (*empathize*, *define*, *ideate*, *prototype*, and *test*) and is often overlayed with the HCD process. As such, the student teams summarized the HCD and DT approach and framed 'problem statements' for each candidate site in Deliverable 2, and created analytical prototypes that maximized safety and minimized costs for each candidate site in Deliverable 3. Then, student teams justified a final recommendation in a technical presentation as Deliverable 4. Other key steps within the PBL unit tasked students to describe key characteristics of truss structures, discover relevant background information of each community site, and create 'value proposition statements' that connected each candidate site to a possible solution. Figure 1 summarizes the instructional goal, scaffolded learning activities, and learning objectives for the first PBL unit.

To support learning, the student teams were provided guidance from their instructor to learn about the HCD and DT processes as a five-part engineering design framework that involves (1) empathizing with stakeholders, (2) defining the problem statement, (3) ideating divergent solution possibilities, (4) prototyping convergent solution possibilities, and (5) testing final solutions with user feedback. As part of the instructional design, the five-part design framework was trifurcated into three distinct deliverables (see Figure 1). Student teams were tasked to empathize with stakeholders by identifying stakeholders at disparate candidate sites, conducting interviews with stakeholders, gathering background information on stakeholders' "pains" (due to existing problems) and "gains" (from a proposed solution), and developing personas for representative stakeholders. The exploration of stakeholders at each candidate site was included in the project prompts specifically to develop students' critical consciousness.

**Design of the Second PBL Unit using Engineering for Social Justice (ESJ)**

The second PBL unit (see Figure 2) was designed to support the learning of engineering dynamics topics (i.e., straight-line motion, circular motion, and work-energy principles) over eight weeks by designing a moving attraction typical in an amusement park. A fictitious scenario was developed by the instructor whereby a land developer proposed to raze one of three suburban, moderate-density neighborhoods within the university city limits to develop a new amusement park. Similar to the first PBL unit, this setting was selected for the second PBL unit because the area was familiar to the students and readily accessible for further exploration, again highlighting the potential for relevancy for the students. The three candidate sites were site-bounded to require students to engage in an analysis of the wants and needs of (1) a low-income, predominantly Hispanic community adjacent to an economically vibrant shopping mall and various commercial businesses; (2) a medium-income, predominantly White community adjacent to a university-managed arboretum with environmental conservation goals; and (3) a low-income, predominantly African-American community with historically-rooted sociocultural preservation goals. Similar to the first PBL unit, these three candidate sites were selected to prompt learner exploration of economic, environmental, and social factors in engineering problem solving efforts. Moreover, these three candidate sites are imbued with real-world implications of redlining practices, segregation, gentrification, and pollution disparities increasingly observed by practicing engineers (Estien *et al*., 2024; Lane *et al*., 2022). The second PBL unit included four key deliverables (see Table 1) and was structured using the *engineering for social* *justice* (ESJ) approach, which was an entirely new design framework for the learners to consider in their engineering problem solving efforts. The student teams summarized the ESJ approach and created 'needs statements' for each candidate site in Deliverable 2, and developed analytical and physical prototypes that maximized community resources and minimized risks and harms for each candidate site in Deliverable 3. The student teams justified a final recommendation in a technical presentation as Deliverable 4. Other key steps within the second PBL unit tasked students to describe key characteristics of moving attractions, discover relevant background information of each community site, and create 'value proposition statements' that connected each candidate site to a possible solution. Figure 2 summarizes the instructional goal, scaffolded learning activities, and learning objectives of the second PBL unit.

The use of the ESJ approach was an entirely unfamiliar design framework to the learners, so the instructor provided instructional guidance by categorizing the seven-parts of the ESJ approach into three categories to make it comparable to the HCD and DT processes (see Figure 3). The first category was entitled *Empathizing and Understanding*, where the instructor highlighted the effort

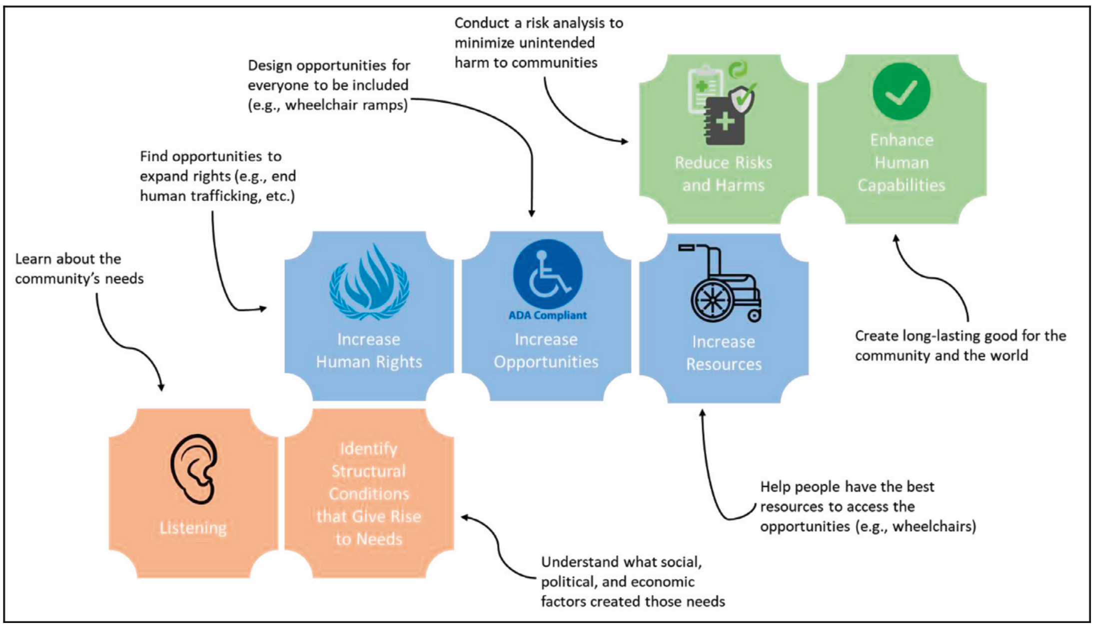


***Figure 3.** A graphic generated by the instructor and shared with the learners in the project prompt. The seven-parts of the ESJ approach was trifurcated into three distinct steps as part of the instructional guidance shared with learners to use the design framework in their engineering problem solving efforts in the second PBL unit.*

as being comparable to the Empathize step in the DT process. This first category contained the first two steps of the ESJ approach, where engineers are tasked to engage in (1) *contextual listening* to discover the community's needs in its broadest sense, which includes learning about a community's present-day political, economic, and social needs. Discovering these community needs allows engineers to conduct a (2) *needs analysis*, which tasks engineers to understand the historical context of a community that has resulted in the present-day needs.

The second category was entitled *Ideating Broader Solutions* and contained the next three steps of the ESJ approach; and the instructor highlighted its comparability to the Problem and Ideate steps in the DT process. Student teams were tasked to write 'needs statements' that sought to (3) *increase human rights*, (4) *increase opportunities*, and (5) *increase resources*. To support learning of these topics, the instructor provided instructional examples of how the United Nations' Universal Declaration of Human Rights (UN, 1949) and the Americans with Disabilities Act (Mayerson, 1992) has shaped engineering problem solving efforts in positive ways (e.g., development of wheelchairs) while underlying socioeconomic conditions can hinder the adoption of such engineering solutions (i.e., wheelchair affordability). As such, the second category of the ESJ approach was described by the instructor as requiring divergent solutions to not only address a technical problem (i.e., an ideated solution to resolve a stated problem) but to consider underlying social, economic, and environmental conditions in the development of those divergent solutions (i.e., to ideate broader solutions that resolve technical problems in community-specific contexts).

The third category was entitled *Implementing Long-Lasting Solutions* and contained the final two steps of the ESJ approach: (6) *reduce risks and harms* and (7) *enhance human capabilities*. The instructor highlighted similarities to the Prototype and Test phase of the DT process, whereby engineers must explore the feasibility of their convergent solutions through testable prototypes and seek out end-user (or community) feedback on those solutions, lest an engineering solution compound or worsen existing conditions. The instructor provided instructional examples of engineering solutions that overlooked community needs (e.g., the Texas Petroleum Chemical plant explosion at Port Neches, Texas, in 2019, and the Union Carbide India Limited pesticide plant explosion in Bhopal, India, in 1984), encouraging students to seize the opportunity to create extraordinary value for the community by imagining how their engineering solution could resolve the engineering problem at-hand *and* enhance human capabilities. The ten types of human capabilities by philosopher Nussbaum (2007) were listed in the project prompt.

To minimize the risk of learners overwhelming community organizations and community individuals with a high volume of interview requests, the instructor pointed the student teams to discover information about the three candidate sites from public postings and websites maintained by civic agencies, community organizations, and the Justice Map maintained by the Energy Justice Network

(2023). Student teams developed their stakeholder personas using this publicly discoverable information, optional interviews as initiated by the students themselves with community members, and gathering background information for each candidate site. The development of personas based on the exploration of community wants and needs was included in the instructional design specifically to develop students' critical consciousness.

### Role of Case-based Learning

Additionally, six in-class case-based learning discussions were facilitated by the instructor to prompt learners to discuss key sociotechnical tradeoffs in engineering statics and engineering dynamics contexts. The learning objectives for the six case study discussions are summarized in Figures 4 and 5.

In the first half of the course, three case studies prompted the discussion of different bridge types and their best contextual uses, how non-technical features in bridges are influenced by architectural and sociocultural factors, and the role that bridge engineers have to play in human safety and well-being (see Figure 4). The statics-based case studies focused on US-centric (e.g., replacement of the Los Angeles 6$^{th}$ Street Bridge in 2022, collapse of the I-35W Bridge in Minneapolis, Minnesota, in 2007, etc.) and non-US-centric (e.g., Falkirk Wheel in Scotland, United Kingdom, Dragon Bridge in Vietnam, Henderson Waves Bridge in Singapore, etc.) examples. In the second half of the course,

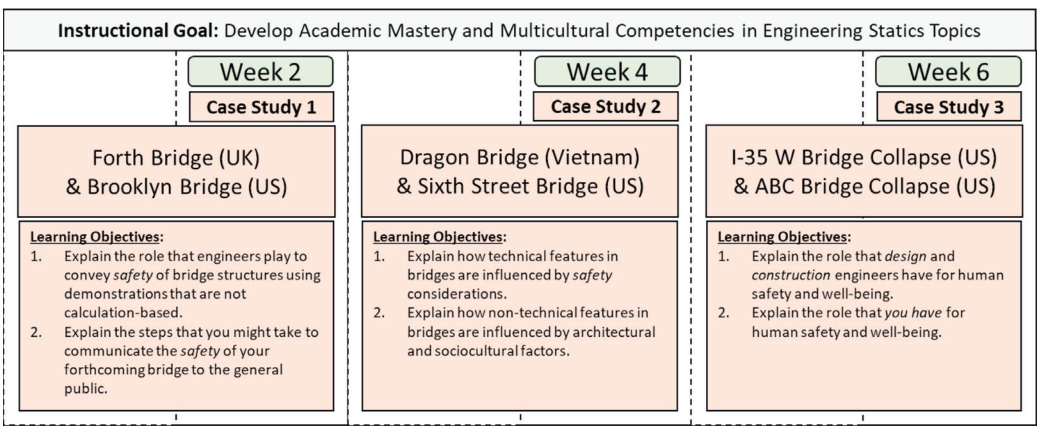


***Figure 4. Three case study discussions were facilitated by the instructor in Weeks 2, 4, and 6 of the first-half of the semester. The selected video clips and readings prompted discussion on how engineering solutions involving statics incorporated matters of human safety and well-being, sociocultural considerations of engineering design, and intrinsic responsibilities that engineers maintain for the public good.***

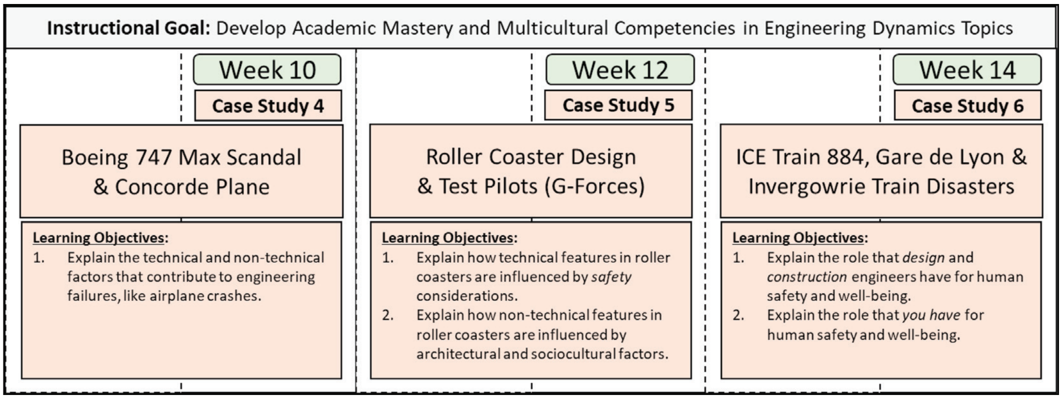


***Figure 5. Three case study discussions were facilitated by the instructor in Weeks 10, 12, and 14 of the second-half of the semester. The selected video clips and readings prompted discussion on how engineering solutions involving dynamics incorporated matters of human safety and well-being, sociocultural considerations of engineering design, and intrinsic responsibilities that engineers maintain for the public good.***

three additional case studies prompted the discussion of sociotechnical tradeoffs engineers make when design developing new aeronautical innovations, how non-technical features in roller coasters are influenced by architectural and sociocultural factors, and the role that high-speed train engineers have to play in human safety and well-being (see Figure 5). The dynamics-based case studies focused on US-centric (e.g., Stratolaunch systems) and non-US-centric (e.g., the Ethiopian Airlines Flight 302 plane crash in 2019, the Gare de Lyon rail accident in France in 1988, etc.) examples. These case study discussions were included in the instructional design in order for students to share with each other their reactions to how engineering artifacts manifest in other parts of the world that are unfamiliar to them, thus developing their multicultural competencies. Moreover, students who related the sociocultural connections of these case study discussions to their ongoing PBL unit efforts contributed to the development of their critical consciousness.

### Formative Feedback Provided by the Instructional Team

Students submitted their work as PDFs to the course learning management system (LMS) as either (1) individual homework assignments and case study submissions or (2) as team-based project report submissions. A combination of assessment rubrics and formative assessment was used by the instructor and undergraduate teaching assistants. Weekly homework assignments, which included well-defined problems (i.e., textbook problems) and the creation of 'sketchnotes' – or concept maps – were assessed by undergraduate teaching assistants using instructor-developed rubrics. The rubric standard for assessing the textbook problems was for students to provide sufficient explanation of their work in reaching the final numerical answer. The standard for assessing the 'sketchnotes' included two dimensions: (1) the appropriate use of visual, graphical illustrations to convey relationships between ideas and concepts and (2) the appropriate use of text to explain the illustrations and relationships.

The six case study submissions and eight team-based project report submissions were graded by the instructor alone. The rubric standard for assessing the case study submission was for students to explain in approximately 100 to 250 words their understanding of the case study at hand in response to specific prompts (see Figures 4 and 5). It was necessary for students to submit their case study assignment in advance of the discussion facilitated during class time. The rubric standard for assessing the team-based project report submissions was for the students to organize their efforts in textual narrative and graphical illustration in response to specific prompts (see Figures 1 and 2). Additionally, the rubric standard for assessing the reflective writings was for students to respond to the listed prompt in approximately 100 to 250 words. Irrespective of the assignment type, the instructor and undergraduate teaching assistants shared formative feedback using built-in 'comment' feature of the LMS. Specifically, the instructor provided wide-ranging formative feedback to students' case study submissions and project report submissions that recurringly took on the form encouraging remarks and the use of Socratic questioning to guide students to delve more deeply into topics in future submissions for a more holistic understanding of the engineering problem (i.e., ill-structured, real-world scenario) at hand. Formative feedback for the team-based project report submissions was shared within seven days so that the student teams could incorporate the instructor feedback for their subsequent project deliverable.

## ASSESSMENT OF STUDENT LEARNING

Each learner's development of critical consciousness was assessed by thematically analyzing prompted, written reflections due in the second deliverable of each PBL unit. It is important to note that critical consciousness exists on a spectrum, and not all students come to the classroom with the same level of critical awareness. Therefore, it was important to assess the development of critical consciousness in qualitative form. For this study, the research team decided that student reflections from Deliverable 2 of the first PBL unit would serve as the proxy baseline dataset because the students would have engaged with a limited amount of class instruction at this point (two weeks), limited to information gathering of truss structures and the candidate sites. Moreover, the students additionally completed a prerequisite, sophomore-year engineering design class emphasizing the HCD and DT processes, meaning these were familiar engineering design frameworks for the learners to apply within the engineering statics context. The reflections from Deliverable 2 of the second PBL unit would serve to provide insights on how critical consciousness developed over the course of the intervention. At this point, students would have engaged with an extended amount of class instruction (ten weeks), having received recurring feedback from the instructor over the first PBL unit. Additionally, students would have been introduced to the ESJ approach, which was a new and unfamiliar engineering design framework for the learners to applying within the engineering dynamics context.

The students' reflections were initially open-coded and subsequently axially categorized (Saldaña, 2013) to a pre-established critical consciousness scale. That assessment allowed for a quantification of critical consciousness at two discrete instances during the class and allowed for a comparative analysis on how the students' critical consciousness compared between the successive PBL units. Learners were tasked to respond individually to the following question in Deliverable 2 of each PBL unit:

- *Prompt in Statics PBL Unit*: How was your understanding of the stakeholders' needs better understood as a result of your efforts using the human-centered design (HCD) and design-thinking (DT) processes?
- *Prompt in Dynamics PBL Unit*: How was your understanding of the stakeholders' needs better understood as a result of using the engineering for social justice (ESJ) approach?

The authors have described their overall qualitative analysis methodology in greater detail elsewhere (Castaneda *et al*., 2022). The selected scale to axially categorize the inductively generated codes was Carlson *et al*.'s (2006) four-stage understanding of critical consciousness, and it was selected because the definitions for its four dimensions most closely resonated with the generated data. The four dimensions in this scale are *passive adaptation*, *emotional engagement*, *cognitive awakening*, and *intention to act*; and these four dimensions were adapted for this study as:

- **Passive Adaptation** – Lacking awareness (or any desire to gain awareness) of any combination of economic, environmental, and/or social (i.e., societal) injustices. Exudes a *Not my problem* attitude toward societal injustices. No evidence of critical consciousness.
- **Emotional Engagement** – A superficial realization that societal injustices exist, with a slight propensity to act and upended those societal injustices by asking *Who is responsible?* Rooted mostly in sympathetic emotions for others. Low form of critical consciousness.
- **Cognitive Awakening** – A realization that typical engineering problem solving efforts (e.g., Given: Find) are partly responsible for contributing to societal injustices, which prompts an

awakening that engineers *Are part of the problem*. There is not necessarily a propensity to act, but an urge to act may be evident. Moderate form of critical consciousness.

- **Intentions to Act** – A realization that typical engineering problem solving efforts can be upended or challenged (i.e., propensity to act) to alleviate societal injustices. A realization that engineers *Are part of the solution*. High propensity to act or propose action to upend a societal injustice in a specific context. High form of critical consciousness.

The data analyzed in this study was generated in the Spring 2021 academic semester in a 16-week, sophomore-level offering of an introductory engineering mechanics class – statics and dynamics. The class modality was hybrid, due to the persisting COVID-19 pandemic. The class included asynchronous pre-recorded video lectures of statics and dynamics course content, synchronous case study discussions over Zoom, synchronous in-person laboratory activities, and synchronous hybrid activities for both PBL units. Thirty-six students were enrolled in the class, which took place at a primarily undergraduate institution (PUI) and predominantly White institution (PWI) in the Mid-Atlantic region of the US.

## RESULTS AND DISCUSSION

Thirty-six students submitted written reflections, and three students were removed from the analysis. Two students were removed for not responding to both prompts in the first and second PBL units and a third student was removed because their responses deviated significantly from the prompted question. This resulted in thirty-three students' writings being analyzed in this study. Approximately 75% of the students self-reported as male and 25% of the students self-reported as female ($n_{male}$ = 25, $n_{female}$ = 8), and the vast majority of the students could be classified as traditional students (i.e., enrolled in college right after high school, aged 19 to 21, single without children, living on campus, etc.).

The initial inductive coding of the generated data resulted in 43 open codes in the first PBL unit and 54 open codes in the second PBL unit. These 54 total open codes were axially categorized using Carlson *et al.*'s (2006) critical consciousness scale. This categorization resulted in 24 codes being matched to the 4-hieararchal categories in the critical consciousness scale and the remaining 30 codes being set aside from this analysis. Table 4 summarizes the number of students and percent of students who manifested at each hierarchal category across the two successive PBL units. All 33 students manifested at some stage of the critical consciousness scale for both PBL units, and some students' reflective writings manifested across multiple stages of the critical consciousness scale which led to summary counts larger than 33 in Table 4.

***Table 4. Number (n = 33) and percentage (%) of learners whose reflective writings were organized within the four-stage understanding of critical consciousness across the two mirrored PBL units.***

| Critical Consciousness (CC) | PBL Unit 1 | PBL Unit 2 |
|---|---|---|
| **Passive Adaptation:** ***Not my problem.*** | | |
| Total Number (and Percent) of Students at this Scale of CC | 13 (39%) | 11 (33%) |
| **Emotional Engagement:** ***Who is responsible?*** | | |
| Total Number (and Percent) of Students at this Scale of CC | 11 (33%) | 14 (42%) |
| **Cognitive Awakening:** ***Engineers are part of the problem.*** | | |
| Total Number (and Percent) of Students at this Scale of CC | 8 (24%) | 16 (48%) |
| **Intention to Act:** ***Engineers are part of the solution.*** | | |
| Total Number (and Percent) of Students at this Scale of CC | 1 (3%) | 12 (36%) |

In the first PBL unit, learners wrote about their understanding of the community stakeholders' needs as part of Deliverable 2 in mostly superficial ways. The HCD and DT processes necessitate as its first step that engineers *empathize* with users and stakeholders to inform the development of their engineering problem-solving efforts. Many students' writings reflected their use of empathy as a rote step in the design process, mostly striving to gain superficial information from stakeholders through rote interview efforts and information gathering exercises that simply treated the stakeholders as inputs to their problem-solving efforts. As an example, Ash (pseudonym) wrote in their response that "the engineering design process requires the understanding of stakeholders," which demonstrates Ash's characterization that understanding stakeholders is simply a necessary design step in their larger project efforts. This response along with other similar responses were characteristic of *passive adaptation*, where thirteen students expressed little to no interest in understanding stakeholders beyond what was minimally required to complete the assignment.

Very few learners in the first PBL unit used empathic efforts from the HCD and DT processes to gain insight from stakeholders or to imagine themselves as stakeholders subject to the consequences of their own engineering decisions, which is the inherent intent of the *empathize* step in DT. However, for the few students who did, they realized that the stakeholders themselves held opinions or viewpoints on the fictitious engineering project effort that differed from their own. Basil (pseudonym) wrote in their response that after they interviewed stakeholders, they "learned some people don't think the addition of a bridge in certain areas would be beneficial." Basil's response highlights that they gained information from the stakeholders that could have informed their engineering project effort, yet Basil did not incorporate this specific feedback into their engineering problem solving efforts. Eleven similar responses were characterized as *emotional engagement* because they revealed a minimally empathic tendency toward stakeholders without any of the gained information or insight being acted upon in the engineering problem solving efforts.

Eight students in the first PBL unit used their empathic efforts to change their perspective on the engineering problem solving effort in light of new information gained from the stakeholders. One student, Ella (pseudonym), wrote in their response that "the most eye-opening part of this project was how strongly the community members recommended a course of action that was not even considered in the initial stages of the project." Ella's realization that their own pre-conceived engineering solutions could be countered and shaped by community members input is a demonstration of *cognitive awakening* where it is implied that engineers may not necessarily be correct when proposing solutions without considering community input. Ella worked in a team that was the only team to ultimately incorporate stakeholder feedback into their final engineering solution as part of Deliverable 4 in the first PBL unit.

In short, the HCD and DT processes that the learners had used in a prerequisite engineering class and were now applying to a PBL unit focused on the design of a truss structure for a nearby community prompted mostly nascent or moderate forms of critical consciousness, where thirteen students were categorized in *passive adaptation*, eleven students were categorized in *emotional engagement*, eight students were categorized in *cognitive awakening*, and one student was categorized in *intentions to act* (see Table 4).

The instructor's formative feedback in Deliverables 2, 3, and 4 in the first PBL unit principally challenged students to avoid gathering information from stakeholders simply as a means of informing their engineering problem-solving efforts. For example, many teams in Deliverable 2 gauged stakeholder reactions to the placement of a new truss bridge without gauging the stakeholders' sentiments of the needs of the industrial area (an economic characteristic), the needs of the agricultural area (an environmental characteristic), nor the needs of the residential area (a social characteristic). The technical presentations in Deliverable 4 of the first PBL unit addressed some of the formative feedback provided by the instructor, yet nearly all student teams ultimately recommended the construction of a new truss bridge at any of the three candidate sites, without articulating how any of those bridge sites would impact community stakeholders. Only one student team raised a key point asking themselves whether a truss bridge in the community was even needed at all (i.e., an expression toward *intentions to act*), and they suggested the consideration of a new bridge site outside of the community that held the potential to alleviate regional traffic flow issues while minimizing direct impacts (e.g., increased traffic) to the community itself. This team included Ella who had expressed *cognitive awakening* early on during the first PBL unit efforts.

In the second PBL unit, the ill-structured characteristic was more acute by having three candidate sites for a new amusement park be located in suburban, moderately dense neighborhoods, which demanded a closer inspection of the economic, environmental, and social characteristics of each neighborhood. As a result, learners elaborated more in their written responses about the ways they considered the community stakeholders' needs as part of Deliverable 2. While there were still about the same number of students engaging in nascent forms of critical consciousness in the second PBL unit (eleven and fourteen) as compared to the first PBL unit (thirteen and eleven), there was a substantial increase in the number of learners engaging in strong forms of critical consciousness (sixteen and twelve) in the second PBL unit as opposed to the first PBL unit (eight and one) – see Table 4. This observation was an encouraging shift in learners' understanding of stakeholder needs and highlighted a richer array of critical perspectives articulated in response to the second PBL unit. Although student reflections were categorized into multiple categories which can skew direct comparisons, the increasing number of students demonstrating strong forms of critical consciousness in the second PBL unit compared to the first suggests a positive development in their critical awareness of the world around them.

Given the fictitious scenario of the second PBL unit, several students remarked in Deliverable 2 that it was impossible to make everyone happy given the constraints of the engineering project, with Shiloh (pseudonym) writing that "the land needed to build an amusement park is a very large area, and when placed in a populated area… it can be very hard to please everyone that would be affected." This response reveal's Shiloh's understanding that their engineering problem solving efforts will result in negative impacts for community members, yet they expressed no tendency to act with this information. This comment, among eleven like it, were characterized as *passive adaptation* in the second PBL unit because of the awareness each learner expressed that their decisions will have on others without expressing a propensity to change their course of action.

Yet, many of these same students elaborated in greater depth on their use of empathy in the second PBL unit, where many more opted to explore the impacts that their decisions would have on the community stakeholders. Sixteen student reflections in the second PBL unit elaborated about the inherent conflict with their own morality in weighing their decisions and realizing their hierarchal power as engineers over community stakeholders. Shiloh continued to write about their understanding of the fictitious scenario that "this is a tough situation because if there is a situation I am put in on a project I work on when I am an actual engineer, I do not know how to proceed in a way that is ethical, logical, and empathetic." While Shiloh had expressed earlier that the engineering project effort would result in negative impacts for community members and that the land was simply needed to build an amusement park, they were additionally expressing unease with their engineering decision and the impacts that it might have on others. While there remains no intention to act, this internal deliberation regarding not knowing how to proceed in a way that is justifiable to their own moral compass reveals moderate forms of critical consciousness – *cognitive awakening*.

Shiloh's extended response was representative of many other student responses, which led to student writings being categorized in more than one category, particularly in the second PBL unit.

Twelve students remarked how the engineering design process in the second PBL unit itself had strongly shaped their final outcome, which empowered them to question whether the standardized steps in engineering problem solving could be changed to create more holistic solutions. For example, Vesper (pseudonym) wrote in their response that "…exploring the sites and stakeholders has shown me that there are many aspects to consider during the engineering design process, and also the difference in outcome that will most likely occurring depending on the chosen design process." This comment reveals Vesper's insight that the selection of one design framework itself (i.e., HCD and DT versus ESJ) can inform the final outcome, which underpins how engineers can be part of cooperative solution-making with community partners – and reveals attitudes toward *intentions to act*, the strongest form of critical consciousness.

While some students persisted to argue in the second PBL unit that it was impossible to devise an engineering solution that could make all community stakeholders happy, about a quarter of the class was now expressing strong forms of critical consciousness, with sixteen being categorized in the *cognitive awakening* dimension and twelve being categorized in the *intentions to act* dimension (see Table 4).

The instructor's formative feedback in Deliverables 2, 3, and 4 in the second PBL unit principally challenged students to create an engineering solution that met the land developer's stated requirements while navigating the economic, environmental, and social considerations for each candidate site. Many student teams sought additional instructor feedback and guidance on what was 'allowable' for the assignment, mostly perceiving that it was an impossible task to raze any of the three existing neighborhoods without causing significant harm to the three community sites. The instructor guided students toward existing real-world examples where public-private-partnerships had developed new entertainment zones in smaller footprints, integrating more closely into the pre-existing community. Many student teams remarked to the instructor that they did not realize it was 'allowable' to consider alternate, outside solutions like this. The technical presentations in Deliverable 4 of the second PBL unit featured half of the student teams proposing alternative engineering solutions in lieu of a typical amusement park including an integrated nature park, a mix-used development entertainment zone, and revised amusement park boundaries to minimize razing of neighborhoods while increasing community-resources (e.g., new dog park, new walking trails, etc.). The other half of student teams proposed simply constructing an amusement park at any of the three sites that in their justification 'minimized' overall negative impacts among the three choices. The overall shift in nearly half the class having taken into account community stakeholder input into their engineering problem solving efforts suggests that critical consciousness was raised, where notions of *intentions to act* were increasingly manifested as part of Deliverable 4 in the second PBL unit.

In contrasting the two successive PBL units, there were more students who expressed higher stages of critical consciousness in the second PBL unit than in the first PBL unit, particularly as part of Deliverable 2 when the students generated reflective writing that was coded and analyzed (see Table 4). Moreover, of the twelve total student teams, only one team revised their engineering project effort in the first PBL unit whereas approximately half of the student teams revised their engineering project effort in the second PBL unit. After student teams had completed their technical presentation in the second PBL unit, the instructor queried the students on how they felt about the challenge or complexity in crafting a solution for the second PBL unit as opposed to the first PBL unit. First, many students pointed to the population density in the second PBL unit being an acute challenge – that there were 'more' people being affected by their recommended engineering solutions. This specific commentary by students strongly relates to one axis in Allford and Head's (2017) typology of "wicked" problems, whereby the increasing number of stakeholders who hold conflicting values and interests increases the perceived 'wickedness' or ill-structured characteristic of a problem. Second, student teams opined that if they were to redo the first PBL unit, they would seek to gather more input from stakeholders to inform their engineering problem solving efforts, particularly in determining whether a bridge is actually needed to solve the traffic congestion problem. This informal feedback suggests that there was a shift in the students' perspectives in considering social factors in their engineering problem solving efforts as a result of having engaged with the second PBL unit.

**Implications for Future Studies**

There are key interpretations of the study's findings that merit exploration in future studies. The use of human-centered design (HCD) and design thinking (DT) as engineering design processes in the first PBL unit ought to have generated *empathic* engineering project efforts, yet most students superficially used community-based input over the eight-week-long project period as a means to solve an engineering problem rather than treating the community as potential partners in problem solving. This shortcoming is further underscored by the fact that the students had completed a prerequisite, sophomore-year engineering design class emphasizing the HCD and DT processes, meaning that their prior exposure to these design frameworks did not necessarily enhance their capability to empathize with users and stakeholders in a future instance. This observation suggests that the mere adoption and use of HCD and DT as engineering design frameworks alone may be insufficient in cultivating the development of engineering learners' critical consciousness. The use of the engineering for social justice (ESJ) approach in the second PBL unit similarly ought to have generated *empathic* engineering project efforts. The introduction of this new design framework, particularly for its emphasis on exploring underlying (economic, environmental, and social) structural conditions as a key first step, was intended to be the catalyst for developing learner's critical consciousness. Yet, the adoption of ESJ as an engineering design framework similarly seemed insufficient in promoting engineering learners' critical consciousness as students did not point to the exploration of the underlying conditions at each community site as informative to their understanding of stakeholders' wants and needs.

In both the formal data (i.e., student reflections) and informal data (i.e., conversations with students), students repeatedly pointed to the ill-structured characteristic of the second PBL unit as the principal driver that enhanced their understanding of stakeholder wants and needs, providing valuable insights into the learning process. This key point suggests that, when desiring to develop engineering learners' critical consciousness, an instructor may consider adopting any engineering design framework as long as they give greater attention to the real-world setting and context of the problem-solving efforts to ensure an engineering tradeoff analysis by the student teams that addresses complex and competing matters across economic, environmental, and social dimensions. Further exploration of the specific instructional elements that contribute to the development of learners' critical consciousness is necessary so that engineering educators can create lasting positive impacts on the professional development of future engineers that will serve them throughout their careers. This study reveals how the ill-structured characteristic of engineering problem solving has the strong potential to benefit engineering learners in their future engineering practices.

Summarily, our findings suggest that the design of PBL units using culturally relevant pedagogy contributed toward the development of students' critical consciousness in the statics and dynamics class. Specifically, the scaffolded learning activities stemming from backwards-centered design enabled students to develop academic mastery of static and dynamic force systems. Moreover, the case-based learning activities and PBL units spurred opportunities for engineering learners to share, negotiate, and compromise their viewpoints on economic, environmental, and social tradeoffs in their team-based, engineering problem solving efforts, particularly in the second PBL unit which was deemed to be more "wicked" than the first PBL unit. As a result, more student teams developed holistic engineering solutions in the second PBL unit, and many students noted how they would revise their engineering problem solving approach for the first PBL unit given their newfound attitudes in engineering design methodologies.

**Limitations of the Study**

There are limitations in contrasting the two PBL units, which narrow the interpretation of the study's findings. First, the instructional design did not seek to establish a 'control group' to be measured against a 'variable group,' and additional quantitative comparisons regarding academic mastery (e.g., test performance) were not undertaken particularly for the study's relatively small sample size. Second, there is a possibility for students to have tailored their responses to the content that was introduced by the instructor. Third, several interconnected factors, such as instructor-student interactions, team dynamics, specific institutional contexts, and the hybrid learning environments created by the COVID-19 pandemic, are intricately linked to the study's findings and cannot be easily separated. These limitations prompt for future studies to understand more fully how specific instructional design strategies can be fine-tuned within an introductory engineering mechanics classroom context to promote the development of critical consciousness in engineering learners.

## CONCLUSION

Two successive project-based learning (PBL) units were designed to develop engineering learners' critical consciousness, particularly through the weighment of economic, environmental, and social impacts to three candidate sites where a fictitious engineering solution was being considered. Their learning was additionally supported through scaffolded instruction involving sociotechnical explorations in case study discussions and homework assignments. A thematic analysis of students' reflective writings at two distinct moments during the PBL units revealed that while both PBL units resulted in students manifesting nascent forms of critical consciousness, about a quarter of the class manifested moderate to high forms of critical consciousness in the second PBL unit. The observed increase can be attributed to a variety of factors, including regular instructor feedback challenging students to incorporate community stakeholders into their engineering problem solving efforts and the increasing complexity (i.e., ill-structured characteristic) of the problem at hand. Students reported that the increased number of people fictitiously affected played a role in their evolving attitude toward social factors in their engineering problem solving efforts.

Typical instruction of engineering mechanics (e.g., statics and dynamics) often overly focuses on technical concepts without exploring how those engineering concepts might have social consequences. That approach can reinforce to engineering learners that engineering problem solving efforts and design processes are devoid of social contexts, which can fuel asocial, apolitical, and apathetic attitudes in engineering at a time when engineers must tackle increasingly complex, sociotechnical problems in an increasing diverse society. The findings presented in this paper suggest that the careful design of instructional activities using culturally relevant pedagogy, with frequent instructor formative feedback, can promote engineering learners' critical consciousness in response to fictitious, ill-structured scenarios. These findings are valuable for engineering educators seeking to deploy new curricular interventions that are less resource intensive (e.g., monies, time, energy, etc.), equip the next generation of engineers with the skills necessary to devise solutions that meet the needs of our increasingly diverse nation and globalized economy, and have the potential to be adapted and explored in many other engineering mechanics classrooms and institutional contexts.

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