Board 141: Incorporating Sustainability into Engineering Curriculum Through Project-Based Learning (PBL)

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Climate change is one of the most pressing issues of the present time, and it has measurable and documented adverse effects on the well-being of the planet and society. As a result, there has been a widespread effort to improve environmental sustainability through rapid decarbonization efforts and a shift towards renewable energy sources. Thus, there will be considerable demand for future engineers to be aware of various novel emerging technologies to support multiple climate goals. Despite its importance, engineering students are not required to take coursework that introduces them to concepts aligned with environmental sustainability. Project-based learning (PBL) incorporated into core engineering classes can broaden the exposure of these topics to a larger group of engineering students, which improves environmental sustainability across several disciplines. Hence, we piloted PBL based on the Engineering for One Planet (EOP) framework into various core courses across several engineering disciplines (chemical and mechanical) at undergraduate and graduate levels at the University of Texas at Tyler. The students were provided reading materials, videos, and lectures on the core values of EOP, specifically focusing on systems thinking, environmental literacy, environmental impact assessment, materials selection, and design. After introducing the EOP concepts, three to five student teams were formed, and each group was tasked to pick an approved topic related to the specific classes. The deliverables for the assignment were a preliminary report, a final report, and an oral presentation to the peers. Finally, an anonymous survey was conducted to gauge the improvement in the student's understanding of the core EOP concepts and how it helped them improve their knowledge of environmental sustainability. Survey responses showed that the students had a more sustainable mindset after performing the PBL based on the EOP framework. Furthermore, the students also improved their technical communication and group work skills, which are critical for modern engineers.

1. Introduction

The atmospheric concentration of carbon dioxide (CO_2) was recorded as 424 parts per million (ppm) in May 2023, which represents an approximately 50% increase compared to the beginning of the Industrial Revolution[1]. This atmospheric CO_2 concentration is the highest value not seen for a long time period (Fig. 1). Carbon dioxide is a greenhouse gas (GHG) that results in global warming and adverse climatic changes. The effects of climate change are measurable and documented. For example, there were 25 confirmed weather/climate disaster events with losses exceeding $1 billion each to affect the United States in just 2023[2]. In a broader context, the CPI-adjusted cost of climate change-related natural disasters from 1980 to 2023 was US$ 2.657 Trillion, which also

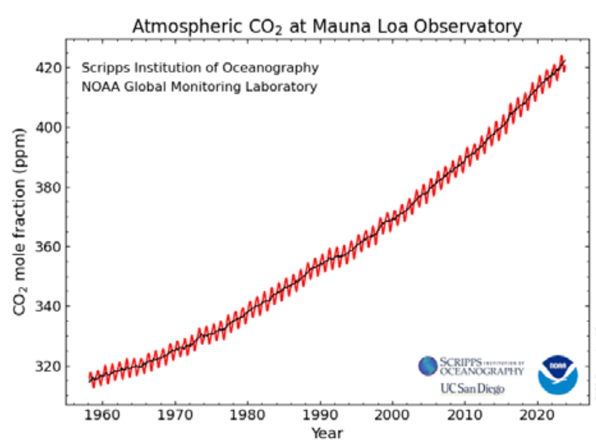


Figure. 1. Keeling graph showing the atmospheric concentration of CO2 at Mauna Loa Observatory, Hawaii [11].

resulted in around 16,340 deaths [2]. The Billion-dollar disasters, comprising drought, flooding, storms, cyclones, wildfires, and winter storms, have become more severe and frequent globally, causing irreparable harm to the natural ecosystem and human society worldwide. As the world's energy demand increases, there is a potential for a further rise in GHG in the atmosphere, leading to an increase in global temperature and catastrophic consequences. As a result, global efforts have been to reduce CO_2 emissions through a widespread push towards renewable energy sources to replace fossil fuels and increase fuel conservation/efficiency. For instance, at the 2023 UN Climate Change Conference (COP28), nearly 200 countries agreed to a "global stocktake" every five years to identify where the world stands on climate action and support, identify the gaps, and work together to chart a better course forward to accelerate climate action[3]. The overarching goal of the initiative is to limit the global temperature increase of 1.5°C compared to the preindustrial age through net zero emissions by the year 2050, which is critical to prevent the worsening and irreversible effects of climate change[4].

One of the major pillars of achieving this complex goal is through innovation and policy changes. Engineers and other technical professionals with a strong intuition and background in sustainability must innovate and improve our current energy production, storage, transportation, and other aspects to meet the climate goals. Hence, there is a critical need to include sustainability-related topics in the current undergraduate engineering curriculum to train future engineers who are well-versed in making climate-friendly choices once they graduate and enter the workforce. Although some engineering programs offer coursework that can prepare students on various topics related to green engineering, this method excludes a significant fraction of students who may not already be interested in those topics. Hence, it is critical to include topics that provide a broad overview of environmental sustainability in at least one core undergraduate class each engineering student takes before graduation. This approach introduces these critical topics to all graduating engineers, broadening the impacts across the overall engineering field. Hence, we implemented project-based learning (PBL) based on the framework proposed by Engineering for One Planet (EOP) for several undergraduate classes and one graduate class at the University of Texas at Tyler.

EOP, started by the Lemelson Foundation and VentureWell, is an initiative to transform engineering education to reflect the importance of sustainability in engineering education[5]. The goal of EOP is to ensure all future engineers across various disciplines learn the fundamental principles of social and environmental sustainability. Thus, we used the EOP framework, consisting of guide coursework and teaching tools, to introduce sustainability concepts using PBL in several core engineering classes. The EOP framework includes the following nine core values: Systems Thinking, Environmental Literacy, Social Responsibility, Responsible Business and Economy, Environmental Impact Measurement, Materials Choice, Design Mindsets, Critical Thinking, and Communication and Teamwork. One of the most important aspects of the EOP framework is that the topics covered can be used to assess various outcomes defined by the Accreditation Board for Engineering and Technology (ABET), which is critical to obtaining and maintaining accreditation. Hence, the EOP framework has already been adopted in numerous engineering departments across the United States. In this work, we present the results from our pilot implementation of the EOP framework across various chemical and mechanical engineering courses at undergraduate and graduate levels with a possible extension to electrical engineering courses. This paper is organized into four sections. Section 2 provides the materials and methods, including the course background used to implement EOP. Section 3 provides the results from student surveys, and the grades received. Finally, Section 4 contains concluding remarks.

2. Materials and Methods

2.1 Background

For the pilot study, we implemented the EOP framework as a PBL across four undergraduate classes and one graduate engineering class in the chemical and mechanical engineering departments in Fall 2023. The mechanical engineering courses were taught at two different locations in a combined mode of instruction – simultaneously online synchronous to the rural location (Tyler) and face-to-face in the urban location (Houston). In contrast, chemical engineering courses were only offered face-to-face in the rural area. These courses were selected for the pilot study as they focus on at least some aspects of energy generation, use, and efficiency. This approach would allow the student to choose intuitive projects that satisfy the course outcomes while focusing on the EOP framework. The courses where we piloted the EOP framework are summarized in Table 1.

Table 1: Summary of the Classes with EOP Implementation

Course Name	Course Number	Level*	Class Size
Thermodynamics II	CHEN 3302	UG	7
Chemical Engineering Laboratory I	CHEN 4320	UG	5
Introduction to Renewable Energy Systems	MENG 4349	UG	50
System Dynamics and Control	MENG 4312	UG	37
Process Control	MENG 5330	G	13

*UG: Undergraduate, G: Graduate

Student groups ranging from 2 to 5 randomly selected students were formed to work on a project. For a completion grade, the first assignment by each student group was submitting the project's title and a brief abstract to be approved by the instructor. The students were instructed to choose projects based on their relevance to the respective courses (Table 1). Some titles of the project selected by the students were:

1. Design of an Off-grid Solar EV Charging System
2. Design and Cost Analysis of a Solar PV Charging Station
3. Solar Energy for Mobile Off-Grid Applications
4. Wind Energy Project
5. Solar-Powered EV Charging Station
6. Hybrid Solar Power Hydrogen Fuel Cell Charging Station
7. Solar Power for Tomorrow Based on Efficiency and Sustainability in Photovoltaics
8. Solar Powered Trail Cameras
9. Hydrogen-Powered Mobility: Revolutionizing E-Scooter Charging Solutions
10. Optimizing the Sustainability of the Modern Smartphone
11. Application of Magnetism in Petroleum Clean-Up
12. The Sustainability of Lithium-Ion Batteries
13. Temperature and Humidity Control in an Evaporative Cooling-based AC System for Residential Applications

The students were then instructed to submit a graded preliminary report on their selected topic to receive feedback. The instructor provided opportunities for discussion on the initial report and detailed feedback so that the student groups could prepare the final report. At the end of the semester, each group needed to submit an 8 to 12-page report on the preapproved topics. Furthermore, the students also presented their findings as a group presentation to obtain the final grade for the project.

A standard rubric was used for grading the student work, with 60% of the grade assigned to the content (quality and depth of analysis) and including the major aspects of the EOP framework. The remaining 30% and 10% of the project grade were assigned for the presentation (clarity of expression, organization of ideas, and adherence to academic writing standards) and collaboration (peer evaluation of the group's collaborative effort, including communication, contribution, and teamwork), respectively. Furthermore, the students completed an indirect voluntary assessment using an anonymous survey concerning the EOP concepts. The survey was created and distributed by the instructor in Qualtrics, where the questions used a Likert scale for quantitative analysis while the comments were provided for qualitative analysis. Students were asked to rate the agreeability of their abilities after completing the project. The survey was distributed during the last week of classes in the Fall 2023 semester after being approved through the standard Institutional Review Board process. The survey included three sets of questions: the first was related to course outcomes, the second focused on the efficacy of the course project to learn and understand the course topics, and the third gauged the overall understanding of topics related to EOP[6]. The first set of questions, which were unique to each course, asked about the student's agreeability to meet outcomes defined in the course syllabus. The second and third sets of questions were based on a survey previously used in an EOP-based course[6]. After data collection, it was compiled and statistically analyzed by converting the Likert-type rating scales to numerical values as shown below, where 1 and 5 represent responses that strongly disagree (1) and strongly agree (5) with the presented sub-questions, respectively. Sustainability/EOP-related questions (Q. 2 and 3) related used in the survey are shown below:

Table 2: Question 2 - This second part of the survey aims to assess how the course project helped you in learning and applying course topics.

		1	2	3	4	5
a.	Helps you understand the concepts in this course					
b.	Allows you to implement concepts in real-life scenarios					
c.	Makes you aware of your responsibility in engineering					
d.	Confirms your future work is related to engineering					
e.	Is recommended for future students					

Table 3: Question 3 – The purpose of this third part of the survey is for you to evaluate the effectiveness of the course project in enhancing your understanding of different sustainability concepts.

		1	2	3	4	5
a.	Demonstrate whole system awareness with the ability to identify and understand interconnectedness.					
b.	Consider and understand tradeoffs and identify impacts between different parts of the system (i.e., environmental, economic, and social considerations).					
c.	Demonstrate awareness that all work is connected to other disciplines.					
d.	Understand when and how to collaborate and consult with others.					
e.	Demonstrates knowledge of the basic facts and ability to quantify data about important (current/past/future and local/regional/global) environmental issues (e.g., climate change).					
f.	Articulate and understand how engineering activities, directly and indirectly, cause positive and negative social/cultural impacts throughout the design life cycle, both to workers producing the products.					
g.	Forecast the near- and long-term costs and value of their work to the environment and society by efficiently using resources.					
h.	Be aware of the risks and opportunities related to changing environments in their work (e.g., extended costs, value, tradeoffs, partnerships, regulations, policies, etc.					
i.	Demonstrate knowledge of the basic facts and ability to quantify data about important (current/past/future and local/regional/global) environmental issues (e.g., climate change).					

j.	Be familiar with high-level environmental impact measurements (e.g., basic life-cycle assessments and hazards).
k.	Be aware of the potential impacts of the materials through the supply chain - from raw material extraction through manufacturing, use, reuse/recycling, and end-of-life.
l.	Set design goals and use technical analyses to choose strategies that minimize environmental impact.
m.	Define problems comprehensively with consideration of consequences, unintended and intended.

2.2 Integration of EOP Framework

Two 55-minute lectures were dedicated to briefly introducing the students to the major aspects of the EOP framework, which addresses the significant impact engineering has on the world, emphasizing the need for engineers to contribute to a sustainable solution for various environmental and societal problems. The EOP framework fills the gap and supplements the engineering curriculum by emphasizing sustainability-focused concepts, tools, and methodologies. The EOP Framework aims to equip engineers with the necessary skills and mindsets to ensure that today's solutions don't become tomorrow's problems and to work towards restoring and regenerating the environment while improving lives globally. It also stresses the importance of understanding and rectifying the history and implications of discriminatory practices in engineering and social systems, acknowledging the social and cultural impacts of engineering work, and promoting environmental justice. Additionally, the framework responds to the growing industry demand for professional preparation in sustainability. The EOP framework addresses all the ABET student learning outcomes and aligns with the 17 United Nations (UN) sustainable development goals[5,7].

The students were instructed to incorporate the following core learning outcomes in the projects as defined in the EOP Framework[5], which are briefly summarized below:

1. Systems Thinking

   Systems thinking includes explaining the interconnectedness of human actions and global environmental/social impacts. This concept is fundamental to help the students to think from an environmental and social perspective. Modern engineers must be able to think from the systems level so that sustainability can be applied within social and ecological borders within which the engineers operate.
2. Environmental Literacy

   The core learning outcome considered for this framework was the ability to recognize the social, economic, and environmental benefits of solving environmental challenges. Particular emphasis was placed on performing the life-cycle assessments (LCA) so that the impact of human activities may be minimized by improving the most energy-intensive aspect of the product life cycle. Finally, the assignment also focused on one specific environmental issue, such as climate change, energy, and water use, by clearly defining the project's scope.
3. Responsible Business and Economy

   This learning outcome was optional for the group project in implementing EOP. However, they were encouraged to consider it for bonus points. In the future, implementation will also consider this learning outcome, which focuses on opportunities and demands for more inclusive and sustainable business practices.
4. Social Responsibility

   This learning outcome was optional for the group project in implementing EOP. However, they were encouraged to consider it for bonus points. Future implementation will also consider this learning outcome, which focuses on identifying the UN SDGs and how to implement them in engineering practices effectively.

5. Environmental Impact Measurement

   This learning outcome aims to interpret broader environmental implications of engineering work, including energy, climate, water, and pollution concerns, by conducting basic assessments like LCAs and evaluating carbon footprints. Furthermore, it stresses the importance of questioning complex information and considering various tradeoffs, especially regarding costs, impacts, and the inclusion of marginalized communities in decision-making processes.

6. Materials Selection

   This learning outcome considers minimizing the negative impacts of material selection on the environment and society. The students were encouraged to consider different materials for design alternatives that ensure long functional lifetimes, net zero greenhouse gas emissions, and minimal environmental and social harm.

7. Design

   This learning outcome focuses on environmentally and socially responsible design strategies in engineering to select strategies that both maximize positive impacts and minimize negative environmental and social impacts in achieving design goals. Techniques such as lightweighting, repairability, durability, upgradeability, disassembly, flexibility, reuse, and recovery of parts or whole products were emphasized.

8. Critical Thinking

   This learning outcome considers holistic consideration of problems, considering both intended and unintended consequences. The students were instructed to critically defend several choices and their role in improving their idea's overall sustainability.

9. Communication and Teamwork

   This learning outcome focuses on teamwork and communication through written reports and oral presentations. The teamwork was also evaluated by using peer evaluations of each member working on the group project.

As this is the first implementation of the EOP framework in the respective classes, only a small subset of the core values was emphasized, as described above. The students were also provided with references, websites, and other resources to help them understand different aspects of the EOP framework[5].

2.3 Implementation of PBL

We used Project-based learning (PBL) in our courses to implement various aspects of the EOP framework. Project-based learning (PBL) is an increasingly common feature in many engineering courses, including introduction to engineering courses and senior design projects across universities in the United States[8]. PBL has been shown to significantly impact students learning and retention[9]. PBL can further be enhanced by consisting of these components relevant to engineering education:

1. making clear the PBL goals for knowledge, understanding, and skills,
2. providing engaging problems at a suitable level of challenge and open-endedness to motivate students,
3. allowing for sufficient time for students to explore and learn new topics in terms of breadth and depth,
4. motivating students by relating to real-world problems to allow for authentic learning,
5. providing mentorship, not supervising, as students choose objectives, methods, and testing and assessment process of their project,
6. enabling students to reflect on what they learned from their projects and how these projects relate to the real world through surveys and open discussions,
7. having consistent follow-up through scaffolded PBL assignments, as well as providing formative feedback for improvement and

8. making projects prepared and presented for external audiences to motivate student accomplishment[9].

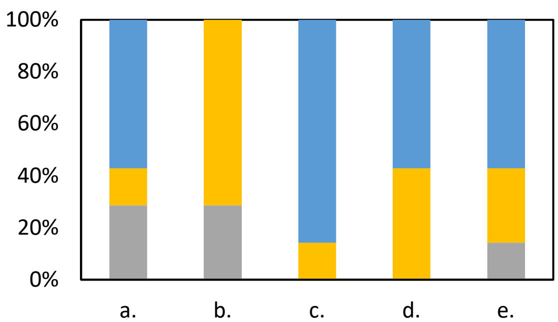
Implementing the EOP framework in the existing courses can be effectively done through PBL to help students learn new concepts without disrupting the core components each student needs to learn to succeed in upcoming classes. The PBL approach also promotes essential skills such as leadership, team building, ethical behavior, creativity, critical thinking, and problem-solving.

3. Results and Discussion

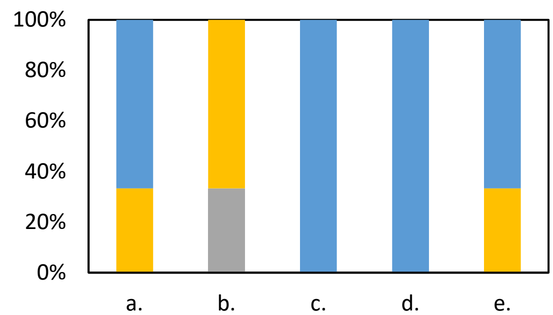
The post-completion survey for the course was completed by 75 out of 112 students across all the classes (Table 4). The highest fraction of completion (100%) was observed for Thermodynamics II (CHEN 3302). In contrast, only 60% of the students completed the survey for Chemical Engineering Laboratory I and Introduction to Renewable Energy Systems (MENG 4349). Figure 3 shows the survey results related to question 2 for the CHEN and MENG classes. Most of the students (88.6%) across all the classes strongly agreed or somewhat agreed that the project helped them learn and apply course topics. An average Likert score of 4.14 was observed across all the classes. The highest scores of 4.27 and 4.19 were observed for the questions "c. Makes you aware of your responsibility in engineering" and "a. Helps you understand the concepts in this course," respectively. The lowest score was obtained for the question "e. Is recommended for future students," with an average score of 3.88.

Table 4: Number of responses to survey for each class

Course Number	Class Size	Participation
CHEN 3320	7	7 (100%)
CHEN 4320	5	3 (60%)
MENG 4439	50	30 (60%)
MENG 4312	37	23 (62%)
MENG 5330	13	12 (92%)



(A)



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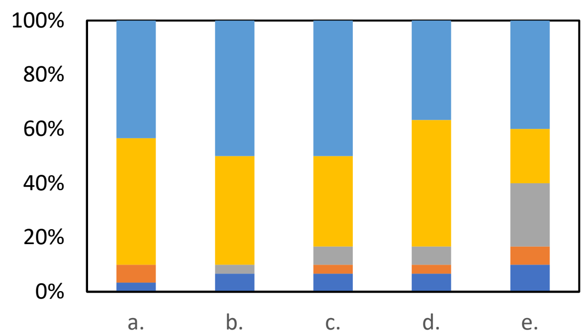

(C)

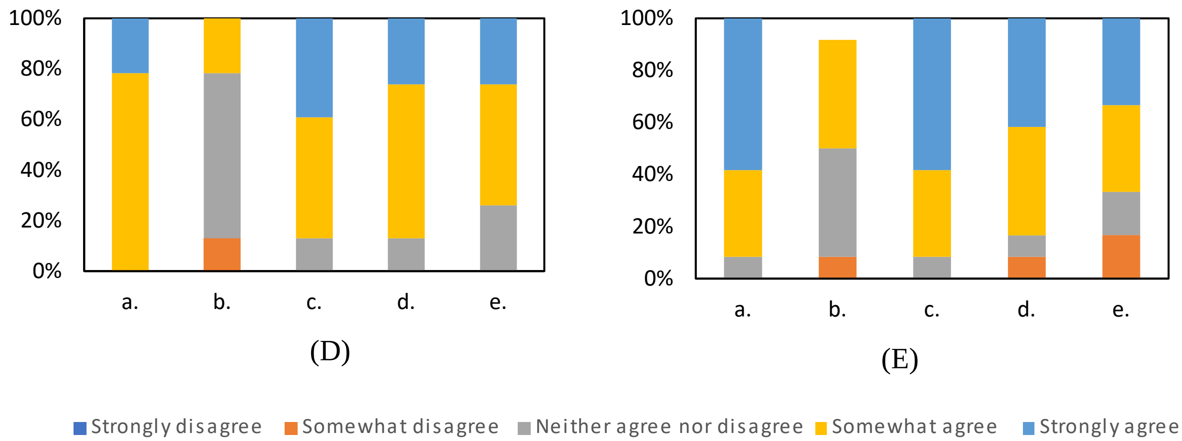

Figure 2. The student responses for the sub-questions of Question 2 (Table 2) for (A) CHEN 3302 (B) CHEN 4320 (C) MENG 4349 (D) MENG 4312 (E) MENG 5330

Next, we evaluated the responses for Q3, which gauged the students' understanding of the concepts related to sustainability in engineering. The descriptive statistics for each course are summarized in Table 5. The first row with numerical data (italicized) in Table 5 is the mean and the standard deviation of the combined Likert scores for each question. The scores for each course question are shown in the subsequent rows. Table 5 shows that the overall Likert score when the responses from each course are combined is 3.40. This score indicates that most students who took the courses and the survey found it to help introduce various sustainability concepts in engineering.

Table 5: The summary of Likert scores from student surveys across various classes

Course→	**CHEN 3302**		**CHEN 4320**		**MENG 4349**		**MENG 4312**		**MENG 5330**		**Overall↓**	
	n = 7		n = 3		n = 30		n = 23		n = 12		N =75	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{X}$	S
	3.69	*1.55*	*4.74*	*0.25*	*3.38*	*1.47*	*3.33*	*1.47*	*3.05*	*1.45*	*3.40*	*1.49*
Q*↓												
a.	3.57	1.50	4.33	0.47	3.30	1.46	3.35	1.46	2.83	1.34	3.31	1.45
b.	3.57	1.68	4.67	0.47	3.40	1.52	3.22	1.41	3.00	1.35	3.35	1.48
c.	3.71	1.75	5.00	0.00	3.47	1.50	3.30	1.54	3.25	1.64	3.47	1.57
d.	3.71	1.58	5.00	0.00	3.40	1.58	3.43	1.53	3.17	1.62	3.47	1.58
e.	3.71	1.48	5.00	0.00	3.50	1.45	3.30	1.46	2.75	1.48	3.40	1.50
f.	3.57	1.68	4.67	0.47	3.40	1.43	3.35	1.46	3.00	1.58	3.39	1.50
g.	3.71	1.48	4.33	0.47	3.60	1.28	3.35	1.40	2.83	1.40	3.44	1.38
h.	3.86	1.36	5.00	0.00	3.33	1.49	3.39	1.44	3.00	1.35	3.41	1.46
i.	3.57	1.68	4.67	0.47	3.33	1.45	3.30	1.54	*2.92*	1.55	3.33	1.53
j.	3.71	1.48	4.67	0.47	3.30	1.49	3.30	1.52	3.17	1.14	3.37	1.45
k.	3.86	1.55	5.00	0.00	3.43	1.50	3.35	1.40	3.08	1.32	3.45	1.46
l.	3.71	1.48	5.00	0.00	3.30	1.42	3.35	1.55	3.33	1.43	3.43	1.48
m.	3.71	1.48	4.33	0.47	3.23	1.54	3.35	1.43	3.33	1.60	3.37	1.50

*Q = Questions from Table 3

We also performed an upper-tailed t-test[10] to evaluate the average rating provided by the students taking the course by assuming the following hypothesis:

$$H_0: \mu \leq 3$$
$$H_a: \mu > 3$$

The null hypothesis (H_0) assumes that the students had a negative outlook toward the benefit of PBL based on EOP to understand various sustainability concepts. However, rejecting the null hypothesis will lead us to accept the alternate hypothesis (H_a) that the students agreed that PBL based on EOP positively impacted their understanding of sustainability concepts applicable to various engineering courses. The significance level (α) of 0.05 was used for the hypothesis test. Table 6 shows the *t-value*, *P-value*, and conclusion from the t-test. In all the cases, the calculated *P-value* is significantly smaller than 0.05, which means we reject the null hypothesis in each case.

Table 6: Results from the hypothesis test for overall responses and for each question

	***t*-value**	***P-value*** **($\alpha = 0.05$)**	**Conclusion**
Overall→	2.32	0.011	Reject H_0
Q*↓			
a.	1.85	0.034	Reject H_0
b.	2.05	0.022	Reject H_0
c.	2.59	0.006	Reject H_0
d.	2.58	0.006	Reject H_0
e.	2.31	0.012	Reject H_0
f.	2.25	0.014	Reject H_0
g.	2.76	0.004	Reject H_0
h.	2.43	0.009	Reject H_0
i.	1.87	0.033	Reject H_0
j.	2.21	0.015	Reject H_0
k.	2.67	0.005	Reject H_0
l.	2.52	0.007	Reject H_0
m.	2.14	0.018	Reject H_0

*Q = Questions from Table 3

However, it should be noted that when the test is performed on a course basis, we fail to reject the null hypothesis for all courses(at α =0.05) except for CHEN 3302. The most significant p-value of 0.45 on a course basis was observed for MENG 5330, a graduate process controls class. This observation could mean that the PBL based on EOP may not be effective in graduate classes. However, this assertion will be tested by implementing this project in future graduate-level courses.

Figure 3 shows the instructor's evaluation of the student project for each class. Across several courses, the average grade distribution fell between C (70- 79, satisfactory) and B (80 -89, good). For the classes with an average grade of C, few students failed to submit the completed assignments. This grade distribution is promising for pilot implementation, and we hope it will improve with future iterations.

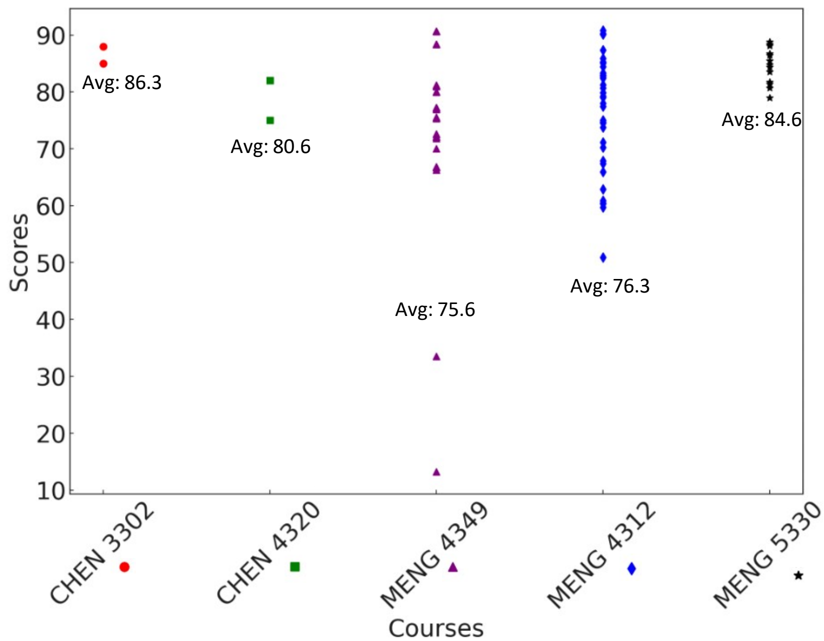

Figure 3. Instructor grade for projects across different classes.

4. Summary and Conclusion

This paper presents results from a pilot study where EOP was implemented using PBL in various chemical and mechanical engineering courses. The students were introduced to the different EOP concepts and were assigned an open-ended project related to the respective courses. After completing the project, the students were asked to complete two questionnaires to gauge their perception of the project's benefit on understanding the course topics and sustainability. Based on the student responses, it was observed that the PBL based on the EOP framework helped the students learn and apply course topics. Furthermore, based on the statistical analysis of the collected data, students agreed that the project helped them better understand various sustainability concepts. This conclusion was also supported by the instructors' evaluation of student work, which showed a good understanding and implementation of EOP concepts. However, some student groups lacked a clear understanding of complex topics such as life-cycle assessment. Future implementation would benefit from additional structured lectures on complex topics with mini assignments. This change will enhance student learning and retention compared to the self-study approach implemented in the current courses. However, as this project is being implemented in the core classes, some modifications to the topics covered in the classes may be required. The PBL approach, based on the EOP framework implemented in the CHEN and MENG courses, has the potential to be implemented in other engineering disciplines. Future studies will involve classes in electrical engineering. The findings from this study show that implementing EOP frameworks in engineering curricula can be used to instill sustainable thinking in future engineers.

Acknowledgments

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