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Integrating Sustainable Practices into Lean Engineering: Applying the Engineering for One Planet Framework in Manufacturing Engineering Technology Education

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Abstract

A growing number of manufacturers are recognizing the significant financial and environmental benefits of adopting sustainable business practices. Sustainable manufacturing refers to producing goods through processes that are economically sound, minimize environmental impact, and conserve energy and natural resources. Lean engineering, a comprehensive approach to decision-making and leadership within manufacturing organizations, has proven effective in promoting sustainable practices. Core principles of lean engineering, such as waste elimination, value identification, value stream mapping, and continuous improvement, align closely with sustainability objectives. Both lean principles and sustainability emphasize waste reduction, including the seven types of waste: transport, inventory, motion, waiting, over-processing, overproduction, and defects. Reducing waste enhances operational efficiency and minimizes the environmental footprint of manufacturing processes. In this study, the Engineering for One Planet (EOP) framework was embedded into the Lean Engineering course within the Engineering Technology Department's Manufacturing Engineering Technology Program. The curriculum revision focused on two key topics from the EOP framework: Environmental Literacy and Responsible Business and Economy. Through this integration, students were introduced to sustainability principles such as whole life cycle thinking, closed-loop systems, and inclusive business models that prioritize product durability, ethical practices, and responsiveness to evolving social, economic, and environmental demands. Retrospective pre- and post-course evaluations revealed significant improvements in students' understanding of sustainability concepts. These improvements were demonstrated by their ability to recognize opportunities for addressing environmental challenges and assess risks and trade-offs in sustainable business models. Qualitative findings further highlighted an increased awareness among students of how lean engineering can be leveraged to achieve long-term environmental and economic benefits, aligning with the goals of sustainable manufacturing. This paper presents the methodology, outcomes, and implications of integrating the EOP framework into lean engineering education, contributing to the preparation of engineers for addressing complex sustainability challenges in manufacturing industries.

Keywords: Sustainable Manufacturing, Lean Engineering, Engineering for One Planet Framework, Environmental Literacy, Responsible Business and Economy.

Introduction

Modern manufacturing organizations acknowledge lean manufacturing as a key approach to eliminating waste, streamlining processes, and enhancing value while simultaneously prioritizing eco-friendly products and processes, positioning lean as a pathway to sustainable benefits; this paper offers a state-of-the-art review of lean and sustainable manufacturing [1]. The main idea of lean manufacturing is the reducing the waste in manufacturing processes and optimization of resources that are used in manufacturing processes through concepts such as resource allocation planning with discrete event simulation in small furniture companies [2, 3].

Numerous pieces of evidence indicate that Lean significantly benefits sustainable manufacturing, particularly from environmental and economic perspective [4]. Sustainable manufacturing practices are based on the Toyota Production System which identifies eight types of waste: overproduction, which refers to creating more than necessary, and underutilized human resources, which involves not leveraging employees' skills and ideas. Additional wastes include excessive transportation of materials, surplus inventory (such as unfinished or finished goods), inefficient movements of people, rework or corrections, over-processing beyond what is required, and delays caused by waiting for materials, information, or people [2]. Even though Total Productive Maintenance and lean manufacturing practices can positively impact environmental sustainability, their influence varies across specific environmental performance indicators, suggesting limits to their effectiveness and emphasizing the need for targeted approaches in their implementation [5].

Therefore, students need to learn these concepts to effectively introduce lean and green principles, enabling them to address environmental impacts, improve value streams, and drive continuous improvement in manufacturing environments, aligning with industry trends and sustainability goals [6]. Also, students have to be aware that their future role in manufacturing industry will be also related to different aspects of social impact, economic performance, and environmental impact of manufacturing processes [7]. Furthermore, they need to understand which tools can assist them in embedding lean manufacturing processes to support sustainable activities in their organization [8]. The introduction of the EOP framework into a Lean Engineering course could address gap in engineering education and prepare undergraduate students enrolled in Manufacturing Engineering Technology program to be better prepared to tackle future sustainability challenges.

Background

The Engineering for One Planet (EOP) framework is a sustainability-driven approach in engineering education and practice. It emphasizes incorporating environmental, social, and economic sustainability into engineering design and decision-making. The framework encourages engineers to consider the entire life cycle of products, systems, and processes, with a focus on minimizing environmental impact while promoting responsible business practices and long-term economic sustainability. It also fosters inclusivity, ethical behavior, and adaptability to global challenges, preparing engineers to tackle complex sustainability issues across industries.

Introducing sustainability into engineering curricula, particularly in manufacturing engineering technology, faces challenges such as balancing technical skills with sustainability concepts, which may require significant curriculum redesign. To reinforce the sustainability principles, the course incorporated real-world case studies on companies implementing lean and green manufacturing. Activities included analyzing Toyota's waste reduction strategies, evaluating closed-loop systems in electronics manufacturing, and engaging in lifecycle assessments of common consumer products. These examples provided students with tangible applications of lean engineering in sustainability-driven industries.

Additionally, there is a need for instructors to stay current with rapidly evolving sustainability practices and to equip students with the interdisciplinary knowledge necessary for addressing complex environmental and social issues in manufacturing. The How Learning Works framework serves as the foundation for the study design, providing a research-based approach to understanding how students learn and guiding the development of effective educational strategies.

Methodology

This study employed a mixed-methods approach to evaluate the integration of the EOP framework into the Lean Engineering course. Both quantitative and qualitative methods were used to assess changes in student learning outcomes and explore their experiences with the revised curriculum. The study involved nine participants enrolled in the Lean Engineering course. The course had 11 students in total, nine of whom participated in the study. The demographic breakdown included two female and nine male students. All nine participants completed the retrospective survey. Additionally, students submitted a total of two photo-voice assignments, which were analyzed to identify emerging sustainability themes. Students participated in hands-on activities such as value stream mapping exercises to identify waste reduction opportunities in simulated manufacturing processes. Additionally, case studies on sustainable business models, such as Patagonia's repair and resale initiative, were discussed to highlight real-world applications of responsible business practices. These activities allowed students to critically assess how lean engineering principles can support sustainable decision-making.

Class sessions were interactive, with discussions, case studies, and applied exercises such as value stream mapping and life cycle assessments. A flipped classroom approach was incorporated for select topics, requiring students to engage with pre-class readings and videos, followed by in-class problem-solving exercises. At the end of the course, participants completed a retrospective survey to measure self-reported learning gains. The survey used a Likert scale ranging from 1 ("strongly disagree") to 5 ("strongly agree") and included questions aligned with the course's learning outcomes. The survey assessed students' ability to recognize opportunities to address environmental challenges, understand whole life cycle and closed-loop systems, evaluate risks and opportunities related to sustainable business models, and assess the impact of economic, social, and environmental systems on their work. Survey responses were analyzed using descriptive statistics, calculating the mean and standard deviation of self-reported proficiency levels before and after the course.

The study focused on two key EOP topics: Environmental Literacy (EL) and Responsible Business and Economy (RBE), which were integrated into the course to enhance students' understanding of sustainability principles. These topics were aligned with specific learning outcomes, as outlined in Table 1, to ensure students developed competencies in recognizing environmental challenges, applying whole life cycle thinking, and assessing inclusive and sustainable business models.

Throughout the course, participants completed photo-voice assignments to reflect their understanding of the EOP topics. The photo-voice assignments required students to submit an image that represented a sustainability concept discussed in class and to write a short narrative explaining its relevance. The assignment prompt encouraged students to connect their selected images to lean engineering principles, environmental sustainability, and responsible business practices. By requiring students to relate concepts to real-world applications, the assignment aimed to assess not just recall but deeper understanding and application of sustainability principles in engineering contexts.

Table 1. The EOP topics and the core learning outcomes chosen for the course

EOP Topics	Learning Outcomes
Environmental Literacy (EL)	**Core Outcome 1:** Recognize opportunities (i.e., social, economic, and environmental benefits, etc.) to solve environmental challenges
	Core Outcome 2: Explain whole life cycle and closed-loop systems thinking as related to the impact of their work (e.g., understanding of life-cycle burdens of design alternatives)
Responsible Business and Economy (MS)	**Core Outcome 1:** Recognize opportunities and demand for more inclusive and sustainable business models, such as models that leverage product durability (e.g., renting, upgradeability, repairability, modularity, resale, etc.), protect consumers and their privacy, reflect the interests and needs of diverse users and consumers, and reflect ethical considerations.
	Core Outcome 6: Examine risks and opportunities related to changing social, economic, political, and ecological systems on their work (e.g., extended costs, value, trade-offs, partnerships, regulations, policies, etc.).

The qualitative component also included open-ended questions to explore students' perceptions of the course. These questions prompted participants to reflect on the role of engineers in sustainable decision-making, areas for improvement in the curriculum, essential sustainability skills for professionals, and how the course could better prepare students for environmental and economic challenges.

Thematic analysis was applied to the photo-voice assignments and open-ended responses to identify recurring themes related to the EOP topics. This analysis was guided by the *How Learning Works* framework Ambrose [9], emphasizing motivation, prior knowledge, and skill mastery. Thematic analysis was conducted using an inductive coding approach. First, all student responses were open-coded to identify key concepts. Inclusion criteria for themes required that a concept appeared in at least 50% of responses and aligned with lean engineering and sustainability principles discussed in the course. Codes were grouped into broader themes based on frequency and conceptual similarity. The three primary themes; Seeing Value, Supportive Environment, and Student Efficacy, emerged as the most prevalent across student reflections.

Figure 1 the study flow, beginning with the integration of the EOP framework into the course. Students then completed Photo-Voice assignments reflecting on their learning. These reflections were analyzed using the How Learning Works framework, guiding the thematic coding process, which identified three primary themes: Seeing Value, Supportive Environment, and Student Efficacy.

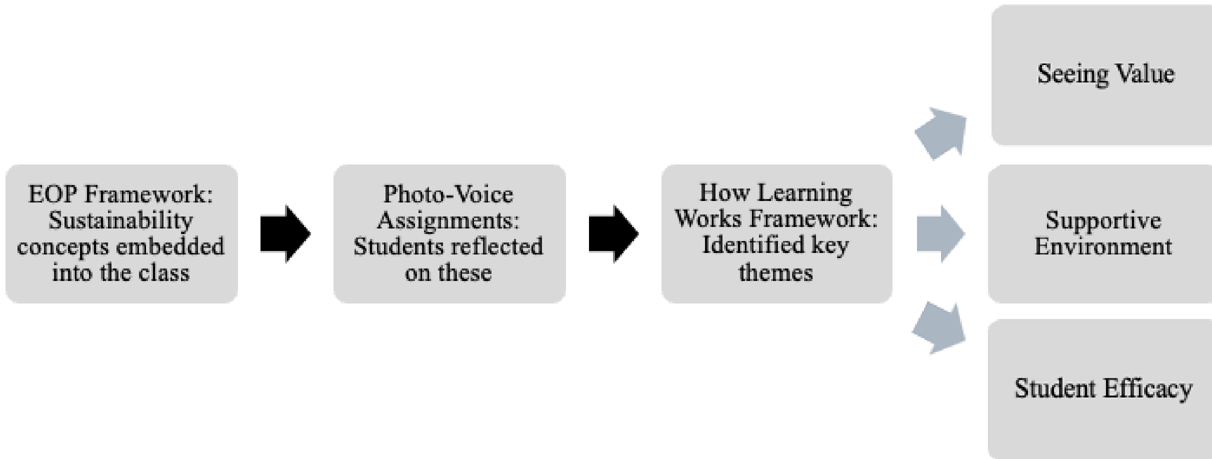

Figure 1. Study Flow: Introduction of EOP, Phot-voice Assignments, and Thematic Coding

Results

Quantitative Results

The analysis of students' self-reported proficiency in EOP learning outcomes, as illustrated in Figure 1, indicates significant improvements across all measured dimensions after completing the course. The following observations summarize the key findings:

1. Environmental Literacy (EL: CO1)**:**
   Students' ability to recognize opportunities to address environmental challenges improved from a mean score of 3.78 before the course to 4.44 afterward, reflecting a substantial gain in comprehension.
2. Environmental Literacy (EL: CO2)**:**
   The understanding of whole life cycle and closed-loop systems thinking increased from 3.67 to 4.56, highlighting enhanced awareness of the environmental impact of their work.
3. Responsible Business and Economy (RBE: CO1)**:**
   Students demonstrated an improved ability to recognize opportunities for inclusive and sustainable business models, with scores rising from 3.67 to 4.33.
4. Responsible Business and Economy (RBE: CO2)**:**
   The ability to assess risks and opportunities related to changing social, economic, and environmental systems improved from 3.89 to 4.33.

Qualitative Results

The qualitative analysis of photo-voice assignments revealed three key themes: Seeing Value, Supportive Environment, and Student Efficacy. These themes, derived from student reflections and informed by the *How Learning Works* framework, provide valuable insights into how the course facilitated a deeper understanding of sustainability principles and their application in engineering. The *How Learning Works* framework emphasizes the interplay of motivation, prior knowledge, and mastery in fostering meaningful learning experiences, and evidence of these principles emerged across student responses.

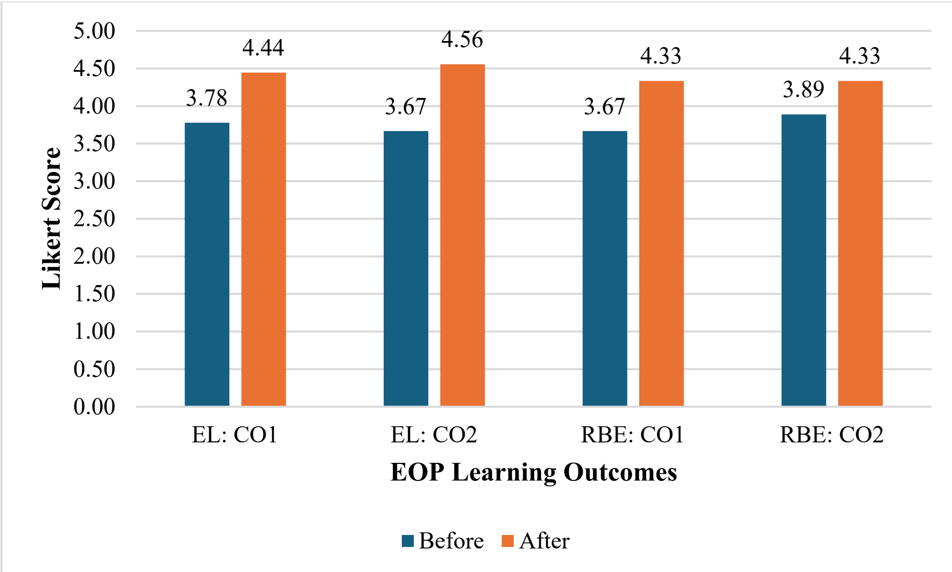

Figure 2. Comparison of students' self-reported proficiency in EOP learning outcomes before and after the course.

Theme 1: Seeing Value

Students highlighted the importance of sustainability in engineering, demonstrating a growing awareness of the broader implications of their decisions. For instance, one student noted, *"Environmental literacy is critical for understanding how human actions impact the environment and how these effects extend across global ecosystems."* This reflection highlights the necessity of understanding environmental impacts to make informed, responsible decisions. Another student emphasized the proactive role engineers play in adopting renewable energy technologies, stating, *"The installation of solar panels highlights the shift toward renewable energy. Engineers play a crucial role in reducing reliance on fossil fuels by integrating sustainable technologies into infrastructure."* Such insights reflect a recognition of engineering as a driver of sustainable change.

Theme 2: Supportive Environment

The course fostered a learning environment that encouraged students to explore creative and practical sustainability solutions. One student remarked, *"By understanding the ecological impacts of land use, engineers can design projects that minimize habitat destruction."* This observation highlights the integration of ecological considerations into engineering practices, fostering designs that balance human and environmental needs. Another student reflected on the importance of product lifecycle thinking, stating, *"We need to consider the ending life cycle of our product designs, ensuring they are biodegradable, so they don't harm wildlife."* This perspective demonstrates an understanding of sustainability beyond immediate design goals, extending to long-term environmental impacts.

Theme 3: Student Efficacy

The assignments also enhanced students' confidence in their ability to implement sustainable engineering practices. One student explained, *"By integrating ethical, environmental, and social values into decision-making, engineers can create solutions that benefit both businesses and the communities they serve."* This statement illustrates a sense of empowerment in addressing sustainability challenges holistically. Another student highlighted their responsibility to drive sustainable practices, stating, *"Sustainability is continually being called into question when the effects of non-sustainable practices are felt or seen. It is important for modern engineers to take action."* This reflection emphasizes the students' growing sense of agency and their commitment to fostering positive change.

Word Cloud Analysis

The word cloud (Figure 2) visually represents the key concepts and themes emphasized by students in their responses during the course.

Figure 2. Word Cloud Representing Key Sustainability and Engineering Themes

The most prominent terms, such as "sustainability," "sustainable", "engineering," and "environmental," reflect the central focus of the course on integrating sustainability principles into engineering practices. These terms highlight students' awareness and engagement with the overarching goals of the curriculum. Other significant terms, such as "skills," "solutions," "practices," and "decisions," emphasize the practical and action-oriented nature of the course. Students consistently linked sustainability concepts to their ability to make informed decisions in real-world scenarios. Words like "lean," process," and "principles" indicate that students recognized the integration of lean engineering concepts with sustainability goals. The presence of terms such as "energy," "environment," and "waste" aligns with the Environmental Literacy (EL) component of the curriculum, which focuses on life cycle thinking and closed-loop systems. Additionally, the inclusion of "students," "learning," and "skills" suggests that the course successfully fostered a learner-centered environment, enhancing student engagement and understanding of sustainability challenges. Finally, terms like "engineers," "companies," and "solutions" highlight the real-world applicability of the concepts taught, emphasizing the course's focus on preparing students for sustainable decision-making in professional engineering roles.

The word cloud was generated specifically from open-ended survey responses and represents the most frequently occurring words used by students. It does not directly map onto the three themes (Seeing Value, Supportive Environment, and Student Efficacy) because these themes were identified through thematic analysis of meaning, rather than the presence of specific words. For example, a student might describe how sustainability creates business opportunities, which aligns with 'Seeing Value,' but they may not explicitly use the words 'value' or 'seeing value' in their response. Thus, while the word cloud reflects dominant terminology used by students, the qualitative themes were developed through an interpretive process that considered the context and meaning of student reflections rather than just word frequency.

Discussion

Enhanced Learning Outcomes

The quantitative results highlight significant improvements in students' self-reported proficiency across all EL and RBE learning outcomes. These improvements reflect the success of the curriculum in developing critical competencies, such as recognizing opportunities to address environmental challenges and understanding the whole life cycle and closed-loop systems. For example, the notable increase in EL: CO2 scores (3.67 to 4.56) suggests that the course was particularly effective in teaching systems thinking and life-cycle considerations. This aligns with the broader goal of enabling students to design solutions that minimize environmental impacts while considering economic and social trade-offs.

The findings for RBE learning outcomes further emphasize the development of skills related to sustainable business models and risk assessment. The increased ability to assess risks and opportunities (RBE: CO2) demonstrates that students are better equipped to navigate the complexities of sustainability within dynamic social, economic, and ecological systems. These outcomes suggest that the course effectively prepared students to introduce sustainability principles into professional engineering practices.

Student Engagement and Depth of Understanding

The qualitative results reveal deeper insights into how students internalized and applied the course content. Each theme was constructed from a set of specific codes: 'Seeing Value' included references to sustainability's importance in engineering decision-making, 'Supportive Environment' captured reflections on how the course encouraged engagement and application, and 'Student Efficacy' encompassed statements about personal responsibility and agency in sustainable engineering practices. The three themes highlight the interplay between motivation, prior knowledge, and mastery, as outlined in the *How Learning Works* framework.

- **Seeing Value**: Students' reflections highlighted their recognition of the broader implications of sustainability in engineering. Their ability to connect sustainability principles with real-world engineering challenges, such as renewable energy adoption and life cycle thinking, demonstrates the motivational impact of the curriculum. This is consistent with the *How Learning Works* framework, which emphasizes the importance of perceived relevance in fostering deep engagement with learning material.
- **Supportive Environment**: The course's structure, which included hands-on projects and real-world examples, provided students with a supportive environment to explore sustainability concepts. Responses indicated that students valued opportunities to apply theoretical knowledge to practical problems, such as designing biodegradable products or minimizing habitat destruction. These findings suggest that the course effectively bridged the gap between abstract principles and tangible applications, enhancing students' ability to innovate within sustainability-focused frameworks.
- **Student Efficacy**: The theme of efficacy highlights the confidence students gained in applying sustainability principles to their work. To mitigate response bias, students were prompted to provide real-world examples in their reflections, rather than restating course content. Open-ended questions encouraged students to apply sustainability concepts to scenarios beyond those explicitly covered in class. While some responses echoed course discussions, others introduced unique insights and personal experiences, suggesting genuine engagement rather than rote repetition. Future studies could incorporate additional verification methods, such as follow-up interviews, to further assess student comprehension and application of these themes. Reflections on ethical, environmental, and social values in engineering decisions illustrate a strong sense of empowerment. Students' acknowledgment of their responsibility to drive sustainable practices aligns with the *How Learning Works* principle of mastery, which is critical for sustained application of learning in professional contexts.

Implications for Curriculum Design

The findings also highlight opportunities for further refinement of sustainability-focused curricula in engineering education. Students consistently emphasized the value of case studies, interdisciplinary collaboration, and exposure to real-world sustainability challenges. These insights suggest that incorporating more experiential learning opportunities, such as industry partnerships, site visits, and collaborative projects, could further enhance student engagement and understanding. Additionally, the emphasis on lifecycle thinking and stakeholder engagement highlights the importance of teaching students to approach engineering challenges from a holistic perspective.

Word Cloud Analysis and Real-World Relevance

The word cloud analysis reinforces the findings from the quantitative and qualitative results, emphasizing students' focus on terms like "sustainability," "engineering," and "environmental." These keywords reflect the central themes of the course, demonstrating that students internalized its primary objectives. The prominence of terms such as "skills," "solutions," and "decisions" indicates that students recognized the practical applicability of sustainability concepts in engineering. Moreover, the inclusion of terms like 'lean,' 'process,' and 'principles' provides evidence that students became more aware of how sustainability concepts relate to lean engineering methodologies, indicating a strengthened connection between these topics in their learning process.

Conclusion

This study highlights the effectiveness of integrating the EOP framework into a Lean Engineering course to enhance students' understanding and application of sustainability principles. The findings demonstrate that the course significantly improved students' self-reported proficiency in Environmental Literacy (EL) and Responsible Business and Economy (RBE) learning outcomes. Students exhibited a greater ability to recognize opportunities for addressing environmental challenges, apply whole life cycle and closed-loop systems thinking, and assess risks and opportunities related to sustainable business models.

The qualitative analysis provided further depth, showcasing students' growing recognition of the value of sustainability in engineering, their appreciation for a supportive learning environment, and their confidence in applying sustainable practices. These themes, informed by the *How Learning Works* framework, reveal the course's success in fostering motivation, linking prior knowledge to new concepts, and promoting mastery of sustainability-focused skills.

This work demonstrates the importance of embedding sustainability principles into engineering education. By equipping students with the tools to address global environmental, social, and economic challenges, the course prepares future engineers to create innovative, sustainable solutions that benefit both society and the planet. Future efforts can build on this success by incorporating additional experiential learning opportunities, interdisciplinary projects, and industry partnerships to further enhance student engagement and real-world application. The integration of the EOP framework serves as a model for sustainable engineering education, highlighting the potential for curricula to not only improve technical proficiency but also instill a commitment to ethical and sustainable practices in the next generation of engineers.

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