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Effects of Using Computer-Aided Drawing Programs to Implement Sustainable Engineering Design Principles on First-Year Engineering Students

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Abstract:

Amidst the increasing importance of sustainability in engineering, our study at Penn State Abington aimed to integrate sustainability into first-year engineering design classes. We developed and implemented modules using computer-aided drawing (CAD) tools and problem-based learning and assessed their effectiveness through pre and post surveys. The findings revealed a significant shift in students' understanding of sustainability: from limited initial knowledge and general perspectives to a focused and nuanced comprehension, especially regarding environmental impacts and sustainable design principles. Notably, prior knowledge of sustainability did not predict performance on sustainability assignments, suggesting that our modules effectively enhanced understanding regardless of students' starting points. The study also indicated that these modules have a lasting impact on students' attitudes towards sustainability, inspiring them to incorporate these principles in subsequent projects. This highlights the value of integrating sustainability early in the engineering curriculum, shaping students' perceptions of its importance and preparing them for future challenges in the field.

Introduction

The integration of sustainability into engineering education at the higher education level has seen limited progress since the 1992 United Nations World Summit on Sustainable Development [1] Recognizing the role of engineers in achieving the United Nations Sustainable Development Goals by 2030 [2] and the emphasis by the Accreditation Board for Engineering and Technology (ABET) [3] on sustainability in engineering designs, there is a growing need to educate engineering students in sustainable and green engineering. Despite the growing number of papers and discussions in academic forums like the American Society for Engineering Education (ASEE), there is no universally accepted strategy for integrating sustainability into the engineering curriculum.

In efforts to integrate sustainability into undergraduate engineering curricula, various strategies and pedagogies are explored, but a universally accepted approach is yet to be established. Sustainability initiatives can be implemented at different levels within educational institutions, including departmental, individual, school, or university-wide strategies. This study focuses on individual-level efforts and adopts an integrated approach, which is widely considered preferable, to incorporate sustainability into existing engineering courses. Specifically targeting first-year engineering students, our methodology combines LCA with computer-aided design tools and problem- and project-based learning (PBL). We aim to address critical learning objectives and instructional techniques that prepare students for advanced studies and careers. This paper not only presents our findings and an example lecture module but also evaluates the effectiveness of these methods through student surveys. The goal is to contribute to the development of sustainable engineering education and provide a practical guide for educators in effectively integrating sustainability at the course level.

Research Aims and Questions

The literature on engineering and design education demonstrates how problem-based learning techniques may increase the participation of students and aid in the integration of core ideas, useful and technical skills, and subject-specific information. This indicates that a PBL-based module can be effective in teaching the principles for sustainability, life-cycle assessment. Furthermore, previous studies have also shown the integration of computer aid programs in teaching sustainability in various engineering courses[4]. This paper's objective is to detail the creation and application of a brand-new sustainable engineering design module for our first-year engineering students at Penn State Abington. The aim is to enhance the comprehension of students regarding sustainable engineering design and assist them in incorporating it into their mini and final design projects that they work on throughout a semester. An anonymous survey is used to evaluate how the modules affected students' perceptions and engagement about sustainable engineering design before and after it. Moreover, we hope that the modules we have created will help engineering students regardless of their intended major type of engineering: (1) gain a sufficient level of comprehension of sustainability concepts; (2) enhance their ability to evaluate project components for sustainability; (3) increase their ability to propose mitigation strategies for lowering negative impacts; and (4) provide opportunities for students to apply their knowledge of sustainability to real-world problems and projects. It's noteworthy that there is a paucity of comprehensive publications on integrating education for sustainable development into engineering design studies [5]. Hence, this study serves as a valuable resource for educators seeking to apply sustainability education into their curricula. Furthermore, it stands as a reference highlighting the potential benefits of problem-based learning, particularly during the foundational years of an engineering degree.

Technical Background

Life Cycle Assessment (LCA) is a comprehensive method used to evaluate the environmental impacts of product systems, from raw material procurement to waste management[6]. It involves a four-step framework[6]: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation. These steps help to quantify the inputs, outputs, and environmental impacts of a product system throughout its life cycle. The International Organization for Standardization's standards ISO 14040 and 14044 guide the LCA process.

LCA is pivotal in sustainability education, especially at the undergraduate level, for fostering an understanding of the holistic impacts of products and processes on the environment[7], [8]. It promotes cradle-to-cradle thinking, encouraging students to consider the full environmental consequences of different materials and technologies [8]. This approach is crucial for preparing students for the green job market [9],[10], as it equips them with the skills to address contemporary sustainability challenges [7] in business, politics, and society.

Teaching sustainability through LCA involves introducing students to life cycle/systems thinking, enabling a comprehensive understanding of sustainability evaluation components. This educational approach prepares students to tackle complex sustainability problems [11]. Various pedagogical methods, including project-based learning[12], [13], [14], [15], [16], inquiry-based learning [17], digital game-based learning [18], and problem-based learning[19], have been applied to teach LCA and sustainability concepts effectively. These methods aim to engage students actively, promote deep learning, and develop professional skills.

In engineering design, LCA is invaluable for its holistic evaluation[20] of environmental, social, and economic impacts, supporting the integration of sustainability into design processes [21]. It aids in decision-making [21], regulatory compliance [22], risk reduction [23], product innovation, consumer awareness [24], and resource efficiency [25]. By applying LCA, engineers can identify more sustainable materials, processes, and technologies, ensuring that their designs minimize negative impacts while meeting consumer and regulatory demands.

Methodology

Evaluation of Sustainability Knowledge and Attitudes

In this study, we employed a mixed-method approach[26], combining both qualitative and quantitative methods. This approach was chosen to mitigate the inherent weaknesses of each individual method. In employing a mixed methods approach to comprehensively assess students' knowledge and attitudes about sustainability in engineering design, we employed three distinct methods: self-developed questions and assignments. The survey, initiated with a statement securing participants' consent, focused on demographic details before delving into six open-ended questions gauging perspectives on sustainability, life cycle assessment (LCA), and sustainable design.

Furthermore, the LCA reflection assignment served as a valuable component, providing direct evidence of students' understanding of the significance of Life Cycle Assessment (LCA) in engineering designs. The thorough assessment of assignments focused on aspects such as the product's lifespan and its broader impacts, encompassing environmental, economic, and social considerations. The evaluation process included a scoring rubric [27] (Appendix C Table 1) for case study discussions and an assessment of LCA reports generated using SolidWorks. The students' ability to conduct LCA assessments via SolidWorks was determined by their capacity to produce reports, evaluated using the criteria in Appendix C Table 2. Additionally, understanding of LCA was assessed by examining their conclusions regarding the selection of environmentally friendly materials. Importantly, students, even in assignments not explicitly requiring LCA assessments or sustainability considerations, voluntarily incorporated sustainability discussions, as exemplified in the final design project report. This mixed methods methodology, blending quantitative and qualitative measures, provided a holistic understanding of students' sustainability literacy and its application in engineering education.

First-Year Engineering Design Course

In their first two years, all PSU Abington engineering students had to take a three-credit introductory course in engineering design. Throughout the course of the 15-week semester, these three-credit classes met for 150 minutes each week. This course provides students with a foundation for engineering design through hands-on team projects that address specified design opportunities. Through this course, students recognize the role that engineering, and design have in improving the health, safety, and welfare of the global community, as well as identifying when a solution is technically feasible, economically viable, and desirable. Students use a range of design tools and techniques to carry out and communicate their design processes as applied to their projects. Additionally, students develop and practice professional skills, such as communication, teamwork, and ethical decision making. Students must comprehend the notion of sustainability and how it applies to engineering design in order to teach designs that enhance the health, safety, and welfare of the global community. As a result, we include modules in this course to assist students in understanding and putting the notion of sustainability into practice.

In this course, students turn in electronic files of their homework for grading to a learning management system called Canvas. We use this platform to communicate readings, assignments, and lecture slides with the students. The demographics of the students on the courses are summarized in Figure 1. The data highlights a homogenous composition, with all individuals in the sampled population identified as freshmen. In terms of gender distribution, the data shows that 31.03% (9 individuals) are female, while 68.97% (20 individuals) are male. In comparison to national data for engineering majors in the United States, which show that 28.7% of all engineers are minorities and 13.7% of all women are engineers, the percentage of minority students (51.63%) and female students (31%) in these first-year engineering design classes is greater [28]. There is no effort made to find statistically significant disparities for minority students in the courses due to the extremely low numbers of these students. This comprehensive representation of both gender and racial demographics provides a nuanced understanding of the diverse composition within the freshman cohort.

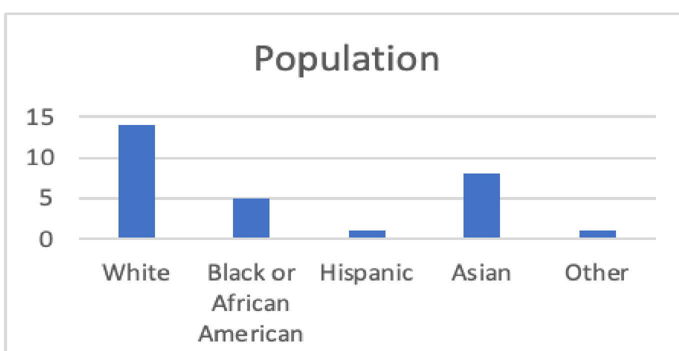

Figure 1. Demographic distribution of the survey participants.

Sustainability Module

In the fall of 2022, Author 1 implemented sustainability modules into an introductory engineering design course, starting from the sixth week of the semester. This initiative aims to elevate students' understanding and application of sustainability concepts within engineering contexts.

The curriculum covers various topics, such as systems thinking[29], definitions of sustainability [30], LCA, and the engineers' code of ethics[31]. It also addresses grand challenges like water scarcity and solar energy. In week 6, students complete an individual reflection assignment after watching videos on lifecycle thinking and LCA[32], and reading the Executive Summary of a Nestle study comparing environmental impacts of tap water versus bottled water and other beverages. This setup encourages students to ponder the importance of LCA in engineering design.

Class discussions facilitated by Author 1 and centered around the environmental and health impacts of engineering designs, provide a platform for deep engagement with the concept of LCA. The Nestle study serves as a case study to illustrate the application of LCA, showing the broader environmental impacts of various consumer choices beyond tap versus bottled water. The course employes problem-based learning, where students critically examined the Nestle LCA report, identifying overlooked aspects such as the health effects of beverages and the environmental impact of bottled water waste. This analysis led to brainstorming sessions where students propose solutions to the issues highlighted in the report.

Additionally, students gain hands-on experience with SolidWorks (SWs) LCA Sustainability tool during a tutorial. They apply their knowledge to a homework assignment that involves conducting an LCA on a 3D bottle design, comparing different materials, and presenting their findings in a professional email format.

The learning experience culminates in a micro design project where students constructed a derrick tower, applying alternative materials and sustainability analysis to minimize environmental impact. The semester concludes with a five-week final design assignment, where students are encouraged to incorporate sustainability analysis, optionally presenting their LCA results in their final report.

Findings and Discussions

The research findings are categorized into two main segments: qualitative and quantitative results. This section initially covers a summary and discussion of the qualitative survey findings, followed by the outcomes of the students' sustainability projects and other assignments that incorporate sustainability elements. After the qualitative part, the section continues with an explanation and discussion on the quantitative survey findings.

1. Qualitative Part:

The results of the qualitative evaluation included an analysis of the questions created specifically for this assessment. This section features a table summarizing select responses to each question. Subsequently, the outcomes before and after the assessment are presented. Lastly, a discussion on the amalgamation of these results is provided.

1.1. Evolution of Perceptions on Sustainability

Table 1 Showcases participants' initial and final responses to the query, "What is sustainability?"

Quotes from pre-analysis	**Quotes from post-analysis**
"Sustainability is fulfilling our own needs consistently."	*"The ability to not harm the environment after the original job is done."*
"Being able to be stable, the ability to last."	*"Sustainability is the ability for something to not harm the environment while also can last for a long time."*
"It is not overworking the land and destroying the world we live in."	*"The ability to regenerate resources as fast or faster than we are using them."*
"Sustainability describes how an object or a system affects the things around it."	*"The environmental impact of producing, transporting a product."*

1.1.1. Before Results: Diverse Perspectives and Definitions

The initial findings before the teaching method were used reveal a rich tapestry of perspectives on sustainability. Participants articulated sustainability as a multifaceted concept, encompassing the ability to fulfill needs consistently, maintaining stability, and innovating without harm to the environment. Participants acknowledged the importance of conserving the environment, meeting present needs without sacrificing the future, and saving the environment for future generations.

However, uncertainty was evident in responses marked by phrases like "I don't know," reflecting the complexity of the concept.

1.1.2. After Results: A Focus on Environmental Impact and Regeneration

Post-analysis reveals a shift toward a more focused and nuanced understanding of sustainability, particularly in the context of environmental impact and regeneration. Participants now emphasize the conservation of resources, highlighting the characteristics of sustainability as it relates to systems or products. The awareness of not harming the environment, both during and after a task, emerged as a recurrent theme. A notable evolution is evident in the acknowledgment of the need to regenerate resources at a rate equal to or faster than consumption, underscoring the interconnectedness of sustainability with resource management.

While the responses evolved, some common threads persisted. The emphasis on stability, lasting impact, and the ability to be maintained at a certain rate or level remained consistent. Both sets of responses recognized the critical link between sustainability and the environment, with participants highlighting the importance of not negatively affecting ecosystems. The comparison demonstrates a maturation in participants' comprehension of sustainability, transitioning from a varied collection of definitions to a more focused recognition of environmental impact and resource regeneration. The evolving perceptions indicate a deeper awareness of the intricate balance required for sustainable practices, emphasizing the need for holistic approaches that consider long-term consequences on the environment and resources.

1.2. Perceptions of Sustainability

Table 2 Showcases participants' initial and final responses to the query, " Does sustainability matter?”

Quotes from pre-analysis	**Quotes from post-analysis**
"Yes, because consistency will always be important."	*"Yes, sustainability matters because running out of something that we are using currently will spell danger for the future generations."*
"Yes, because it determines whether or not these limited resources can still be replenished for future use."	*"Yes, sustainability does matter because current generations should save resources for future generations."*
"Yes, sustainability matters because we want future generations to live on this earth."	*"Absolutely! Sustainability improves the quality of our lives."*

"Sustainability is extremely important, especially in a school or work setting because it allows students or employees to get accustomed to a certain habit or lifestyle, and stick with it to be successful in the future."	*"Sustainability is extremely important for production because it allows the production team to analyze the project and identify what they need to change in order to satisfy their needs."*

1.2.1. Before Results: A Shared Understanding of Importance

The responses before the test reflect a collective recognition of the significance of sustainability. Participants express agreement on the importance of sustainability, citing reasons such as the need for consistency, ties to efficiency and environmentally friendly practices, and the necessity of replenishing limited resources for the well-being of future generations. There is a prevalent sentiment of responsibility towards the environment and a consideration of the long-term impact of human activities.

Common Themes in Before Test Responses:

Consistency and Efficiency: Participants emphasized that sustainability matters due to its link to consistency and efficiency, indicating an understanding that sustainable practices contribute to long-term stability.

Environmental Responsibility: A prevailing theme is the understanding that sustainability is closely tied to environmentally friendly practices. Respondents highlighted the significance of considering the impact of actions on the environment, with an emphasis on resource replenishment.

Concern for Future Generations: Many participants expressed a sense of responsibility toward future generations. The idea that sustainability is crucial for ensuring a healthy and habitable planet for the coming generations has emerged consistently.

Long-Term Perspective: The concept of sustainability was not merely seen as a short-term goal; participants recognized its value in creating habits and lifestyles that contribute to long-term success, particularly in educational and professional settings.

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1.2.2. After Test: Continuation of Recognition

The responses after the test indicate a consistent acknowledgment of the importance of sustainability. Participants continue to affirm that sustainability matters, with reasons ranging from the reduction of environmental impacts to improving the quality of life. There is a notable emphasis on the long-term effects of sustainability, both in terms of resource conservation and the well-being of future generations.

Common Themes in After Test Responses:

Environmental Impact Reduction: Participants recognize sustainability as a means to reduce the environmental impacts of products and processes. The focus is on mitigating harm and adopting practices that are less detrimental to the Earth.

Long-Term Considerations: There is a consistent emphasis on the long-term implications of sustainability, highlighting the importance of preserving resources for future generations and ensuring a better quality of life.

Responsibility and Improvement: Sustainability is viewed as a responsibility, not only to the environment but also to current and future generations. Participants see it as a pathway to improve lives and the overall quality of life.

The qualitative analysis of responses before and after the test reveals a continuity in participants' recognition of the importance of sustainability. Whether considering it from the lens of consistency, environmental responsibility, or long-term impact, participants consistently affirm that sustainability matters. This shared understanding underscores the enduring importance of adopting sustainable practices for the benefit of the environment and future generations.

1.3. Designing for Sustainability Pre-test and Post-test Perspectives

Table 3 Showcases participants' initial and final responses to the query, " How can you design for sustainability? “

Quotes from pre-analysis	**Quotes from post-analysis**
"By starting a business or side hustle to have a consistent income."	*"Being mindful of the way your design affects the world around it."*
"Make use of every output; minimize waste."	*"Design a project that can still be used after finishing its original purpose."*

"Using materials that are known for their ability to last over long periods of time."	*"Use renewable energy sources to ensure that whatever is being created currently can continue to be made infinitely in the future."*

1.3.1. Pre-test: Initial Understanding and Varied Perspectives

Responses before the test showcase a range of initial perspectives on designing for sustainability. Participants express uncertainty in some cases but also offer insightful views. Some focus on economic sustainability, linking it to income and expenses, while others emphasize learning from past mistakes and minimizing waste. The importance of considering the environmental impact of materials and resources is a recurring theme, and participants highlight the role of renewable resources, eco-friendly materials, and longevity in sustainable design. The idea of repetition as a means of building sustainability habits is also mentioned.

Common Themes in Pre-test Responses:

Economic Sustainability: Some participants connect sustainability to financial stability, emphasizing the importance of consistent income.

Environmental Considerations: Many participants recognize the significance of choosing materials and resources that have minimal environmental impact and designing products that can be recycled or converted without leaving damaging waste.

Longevity and Renewable Resources: The concept of designing for longevity and using renewable resources emerges consistently as a key aspect of sustainable design.

Learning from the Past: Several participants stress the importance of learning from past mistakes and planning for the future in the design process.

1.3.2. Post-test: Evolved Perspectives with Emphasis on Consequences and Conscious Design

After the test, participants exhibit an evolved understanding of designing for sustainability. There is a consistent emphasis on being mindful of the consequences of design choices on the world and the environment. The importance of reusability and the reduction of environmental impact through material choices and manufacturing processes is highlighted. Renewable resources and energy efficiency remain central themes, with a specific mention of conserving water. The idea of meeting customer needs while following sustainable practices is also emphasized.

Common Themes in Post-test Responses:

Conscious Design: Participants stress the need to be mindful of the impact a design has on the world and its users, emphasizing the importance of considering consequences.

Reusability and Reduction: Designing for sustainability is seen as creating products that can be reused, with an emphasis on using less material and environmentally friendly materials and manufacturing techniques.

Renewable Resources and Energy Efficiency: Participants continue to emphasize the use of renewable resources and energy-efficient processes as integral to sustainable design.

Customer-Centric Design: Designing with sustainability involves aligning with customer needs and ensuring the longevity and functionality of products.

The comparison between pre-test and post-test responses reveals an evolution in participants' perspectives on designing for sustainability. While initial responses included varied viewpoints, post-test responses exhibit a more refined and conscious understanding of the consequences of design choices, the importance of reusability, and the role of renewable resources in creating sustainable products. The emphasis on being customer-centric and considering the long-term impact of design choices reflects a more holistic and informed approach to sustainability.

1.4. How do products make environmental impacts?

Table 4 Showcases participants' initial and final responses to the query, "How do products make environmental impacts?"

Quotes from pre-analysis	**Quotes from post-analysis**
"Products impact the environment when they are mass produced."	*"Products make environmental impacts by the waste that they produce if they are thrown away."*
"Certain products can either help or harm the environment, for example, plastic can have negative environmental impacts."	*"Products make an environmental impact by either how the product is used or how it affects the environment after being thrown out."*
"Products make environmental impacts by causing some sort of effect which harms the environment in some way."	*"Many products make environmental impacts, especially depending on the material they are made of."*

1.4.1. Pre-test: Initial Perspectives on Product Environmental Impacts

Before the test, participants presented varied perspectives on how products make environmental impacts. There was an initial recognition that the materials used, waste production, and mass production processes contribute to environmental impacts. Some participants associated products with positive effects, suggesting that they can make life easier and more organized. However, there was also acknowledgment of negative impacts, particularly regarding pollution, emissions, and the improper disposal of products.

Common Themes in Pre-test Responses:

Waste Production and Disposal: Participants recognized that the waste produced during the manufacturing process and the improper disposal of products contribute to environmental impacts.

Mass Production and Pollution: The mass production of products was highlighted as a factor leading to pollution, both in terms of waste and emissions.

Material Choices: The materials used in products were identified as a significant factor, with some recognizing the potential harm caused by certain materials, such as plastics.

Positive and Negative Effects: Participants acknowledged that products can have both positive and negative effects on the environment, depending on their design, materials, and usage.

1.4.2. Post-test: Enhanced Awareness of Environmental Impact Factors

After the test, participants exhibited a more nuanced and comprehensive understanding of how products make environmental impacts. The emphasis shifted towards specific aspects such as material choice, waste production, transportation, and end-of-life disposal. There was a heightened awareness of the consequences of improper waste disposal, the harmful effects of certain materials (e.g., plastic), and the role of non-renewable resources. Some participants highlighted the importance of analyzing products for better material choices to prevent negative environmental impacts.

Common Themes in Post-test Responses:

Waste Production and Disposal: Participants continued to emphasize the impact of waste production during the manufacturing process and the potential harm caused by improper product disposal.

Material Choices: The importance of material choices in product design was reiterated, with an increased focus on selecting materials that are less harmful to the environment.

Transportation: The environmental impact of transportation, including the gas used for transportation, emerged as a key factor influencing a product's environmental footprint.

Positive and Negative Effects: Participants continued to recognize that products can have both positive and negative effects on the environment, with an increased emphasis on the need for better material analysis.

The comparison between pre-test and post-test responses indicates an evolving awareness of the factors contributing to product environmental impacts. While initial responses touched on general concepts, post-test responses demonstrated a more detailed understanding of specific elements, such as material choices, transportation, and end-of-life considerations. The participants exhibited an enhanced awareness of the potential environmental consequences of product design and usage, emphasizing the need for sustainable practices and responsible decision-making throughout a product's life cycle.

1.5. What is a life cycle assessment?

Table 4 Showcases participants' initial and final responses to the query, " What is life cycle assessment?"

Quotes from pre-analysis	Quotes from post-analysis
"My guess is that it's a cycle, a chain of some sort that has a continuous rotation."	*"LCA is a way for producers to calculate the environmental impact their product will have."*
"I'd assume that it refers to making and analyzing a chart of the processes a product goes through."	*"Measuring the environmental impact of a product or the material in the product."*
"LCA is the overview of the sustainability of a certain 'thing.'"	*"The LCA is a way to measure the impact a product has throughout its life span on the environment."*

1.5.1. Pre-test: Initial Perceptions and Varied Understandings

Participants' responses before the test indicated a range of perceptions and uncertainties regarding what LCA entails. Some participants associated it with a cyclical process, while others speculated about its connection to the time span between product launch and end-of-life status. There were guesses about analyzing charts, considering sustainability, and assessing the positive and negative effects of a product throughout its life span.

Common Themes in Pre-test Responses:

***Cyclical Process*:** Some participants associated LCA with a cyclical or chain-like process, but the specifics were unclear.

Time Span and Sustainability: Speculation about the time span between product launch and end-of-life status, with an emphasis on sustainability.

Analysis and Assessment: The notion of analyzing charts, assessing positive and negative effects, and recognizing problems in the environment was present in some responses.

1.5.2. Post-test:

After the test, participants demonstrated a more clarified and informed understanding of LCA. The majority of responses correctly identified it as an assessment of the environmental impacts a product has throughout its entire life span. The emphasis was on measuring the positive and negative effects, analyzing stages from production to end-of-life, and calculating the overall impact on the environment. There was recognition of LCA as a tool used by producers to assess the environmental impact of their products.

Common Themes in Post-test Responses:

Environmental Impact Assessment: Participants recognized LCA as a method for assessing the environmental impacts of products.

Full Life Span Analysis: There was an emphasis on analyzing a product's entire life span, including stages from production to end-of-life.

Producer's Tool: Participants acknowledged LCA as a tool used by producers to calculate and measure the environmental impact of their products.

The comparison between pre-test and post-test responses indicates an evolution in participants' understanding of LCA. While initial perceptions were varied and uncertain, post-test responses demonstrated a more accurate and informed comprehension of LCA as a tool for assessing the environmental impacts of products throughout their entire life span. Participants recognized the importance of considering the full life cycle, analyzing stages, and calculating the overall impact on the environment.

1.6. What are the factors used to measure the environmental impacts?

In an effort to gauge the awareness and comprehension of environmental impact factors, students were asked to provide their perspectives. The objective was to capture their understanding of what contributes to the measurement of environmental impacts and to identify recurring themes in their responses.

Key Findings:

Land Usage and Emissions: A recurring theme among students was the acknowledgment of the impact of land usage and emissions on environmental sustainability. Many students recognized that factors such as carbon footprint contribute significantly to ecological considerations.

Life Cycle Considerations: A significant number of students demonstrated an awareness of LCA, emphasizing the importance of evaluating a product's impact throughout its entire life span. This holistic approach resonated well with the participants.

Energy Utilization: Students expressed a clear understanding of the role of energy consumption in environmental impact. They recognized that energy usage, from resource extraction to product usage, is a critical factor in sustainability assessments.

Chemical and Atmospheric Impacts: A subset of students identified chemical impacts, such as acidification and eutrophication, as well as atmospheric temperature rise, as crucial considerations in assessing environmental health.

Resource Availability and Environmental Diversity: Several students underscored the importance of considering resource availability, encompassing energy, land, water, and clean air. Additionally, they recognized the significance of maintaining environmental diversity for sustainable practices.

Mathematical Equations in Environmental Impact Assessment: While not universally emphasized, a notable portion of students acknowledged the use of mathematical equations to quantify environmental impacts. Resource availability, energy usage, and environmental diversity were identified as key variables in these equations.

Specific Metrics: Students highlighted specific metrics like CO2 emissions and factory waste as integral to environmental impact assessments. The importance of sustainability reports in disseminating such information was also recognized.

Human Welfare and Safety: A noteworthy insight was the recognition among students that sustainability extends beyond environmental considerations to encompass human welfare and safety. This human-centric approach aligns with broader sustainable development goals.

Toxic Gas Emissions and Decomposition: Some students honed in on specific environmental concerns, including toxic gas emissions, the duration of product decomposition, and the product's lifecycle utility. These factors were identified as crucial in evaluating overall environmental impact.

The results indicate a commendable level of understanding among students regarding factors influencing environmental impact measurements. Their insights reflect a holistic comprehension that extends beyond ecological considerations to encompass human welfare and safety. These findings suggest a promising foundation for instilling sustainable practices and awareness among the younger generation. Further educational initiatives can build upon these insights to foster a deeper understanding of environmental stewardship.

2. Sustainability Assignment

The LCA reflection assignment, focusing on the significance of LCA in engineering design, revealed a varied depth of understanding among students, with the majority covering key aspects (refer to Fig. 5). However, a common deficiency in students' comprehension of the importance of LCA in design was observed, particularly regarding the social, economic, and life span aspects of LCA assessment.

During the class sessions where students evaluated LCA reports using SolidWorks, it became apparent that the SolidWorks LCA report has limited capabilities in assessing economic impacts and lacks the ability to evaluate social impacts. Consequently, students tended to pay less attention to these aspects compared to the environmental aspect. The prevailing sentiment among students was that LCA is essential in design primarily to mitigate the negative environmental impact of the design.

In summary, while there was a reasonable understanding of the basic importance of LCA in engineering design, the reflection assignment highlighted a need for a more comprehensive understanding, especially concerning the social, economic, and life span dimensions of LCA assessment.

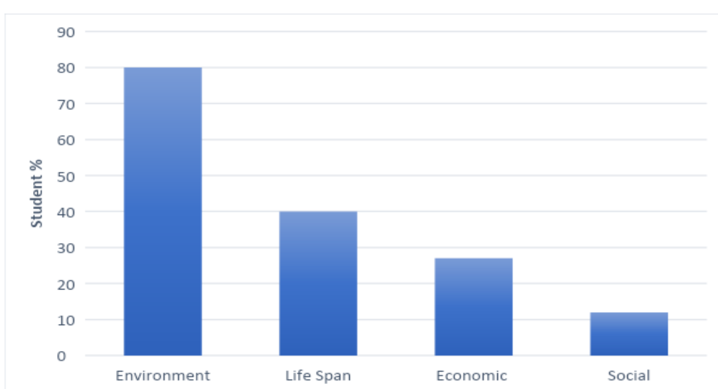

Figure 7: Proportion of students incorporating different elements in their discourse on the significance of LCA in engineering design.

Throughout the class session, all students managed to generate the LCA report from SolidWorks with the aid of the tutorial. However, certain students encountered technical challenges, specifically related to identifying the appropriate buttons to press and locating information mentioned in the tutorial. Interestingly, the instructor observed that the questions raised by students did not pertain to the LCA or sustainability aspects, such as understanding how parameters influenced their assessments.

The instructor perceived a lack of enthusiasm among students for learning about the LCA itself; instead, their primary focus seemed to be on the technical aspects of executing the LCA within SolidWorks. This observation led to the impression that students were more concerned with the operational aspects of running the LCA in SolidWorks rather than delving into the substantive aspects of LCA and sustainability. Nevertheless, this assignment demonstrated that every student in the class is capable of generating LCA reports in SolidWorks.

In the assessment of the LCA for the provided water bottle design, the calculated average grade was 71.25%. Considering that this was the first instance of students undertaking such an assignment, the average can be deemed relatively high. The distribution of student performances, illustrated in Figure 8 as a pie chart, indicated that (58%) successfully completed this assignment.

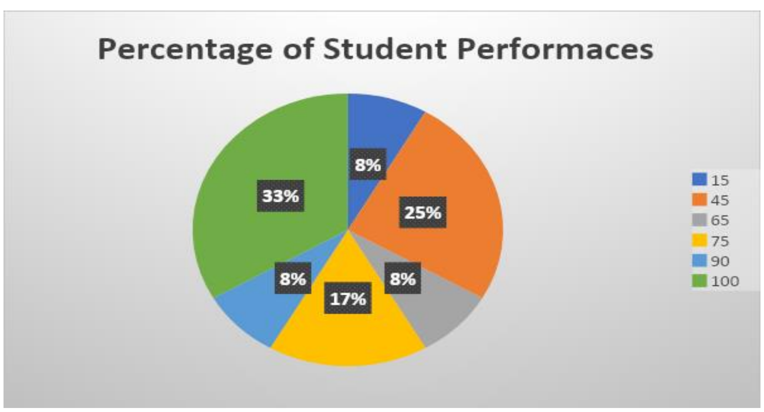

Figure 8: Student performance distribution in the water bottle LCA report evaluation assignment

The majority of students (92%) successfully generated the LCA report using SolidWorks. Even among the groups that did not complete the report, they managed to create a summary table and spreadsheet to assess the LCA report, leveraging reports from other groups. When asked to explain their inability to create the LCA report, these groups attributed it to a lack of time. Remarkably, all groups, regardless of their completion status, successfully developed a spreadsheet summarizing their findings and facilitating the identification of the most sustainable material among various options. A significant portion (58%) of students drew conclusions from their spreadsheets and LCA reports. Among these conclusions, 41% correctly identified the best sustainable material. However, only 33% of these students, who had the correct answer, provided a comprehensive and thorough elucidation of their conclusion. The primary cause of this disparity (8%) was not linked to the students' inability to articulate conclusions but rather their insufficient understanding of how to employ weight factors to derive a conclusion.

In summary, more than half of the students demonstrated some level of understanding of the LCA report, with 33% having a thorough comprehension of the concept. However, a small percentage (8%) of the overall students had difficulty interpreting the data correctly or lacked an understanding of how to do so.

3. Other Course Assignments

In the derrick design project, where identifying sustainable materials was a requisite, all students created an LCA report to determine a sustainable material for their designs. However, variations emerged in the explanations behind their material choices. While the majority of groups assessed their designs primarily in terms of air pollution, only 16% of students made decisions based on multiple environmental factors. Merely 8% of students discussed the cost implications of the chosen material.

The observed trend indicated a lack of motivation among students to conduct a thorough analysis and discuss the LCA of their designs. Overall, students faced challenges in articulating their reasoning, even after practicing with previous assignments like the bottle water task. Notably, 20% of students demonstrated improvement in the number of sentences used to explain their LCA reports.

Only a minority of students, specifically 26%, incorporated sustainability considerations into their final design project, which revolved around constructing solar panel-powered cars. This suggests a natural alignment of sustainability with the project topic. While all groups acknowledged sustainability during the problem definition and design explanation phases, the focus tended to be on the material aspect. It is noteworthy that the understanding of sustainability was limited to the material perspective, indicating a narrow scope.

Interestingly, none of the student groups utilized LCA to determine the most suitable material for their actual design. One group acknowledged the importance of designing a sustainable product but failed to implement sustainable practices. Another group went a step further by employing the Analytic Hierarchy Process (AHP) to assess the value of sustainability in their design. However, despite recognizing its importance, this group ultimately chose to prioritize other values over creating a sustainable design.

4. Quantitative Part:

This study assesses the impact of an educational intervention focused on sustainability, utilizing SolidWorks for simulation-based learning. The findings, categorized into four key areas—Learning Environment Perception, Engagement and Interaction, Future Application and Utility, and Perceived Value and Personal Projection—reveal diverse perspectives on the effectiveness and future application of sustainability education.

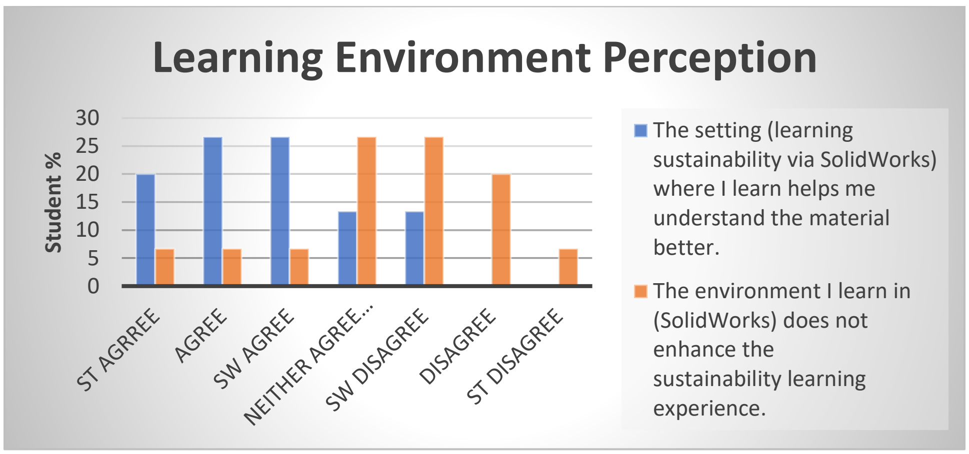

Figure 2. Summary of participants' perceptions on their learning environment.

The summary of participants' perceptions reveals mixed feelings about the learning environment provided by SolidWorks for sustainability education. While nearly half of the participants (46.67%) see a positive impact on their understanding of the material, with a combined 46.67% expressing agreement to strong agreement, there's a significant portion (46.67%) displaying neutral to negative views on how much SolidWorks enhances their sustainability learning experience. This division highlights the need for adjustments and improvements within the SolidWorks learning environment to better serve sustainability education goals. Optimizing and addressing specific elements to enhance the learning experience could lead to a more effective and satisfying educational journey for participants.

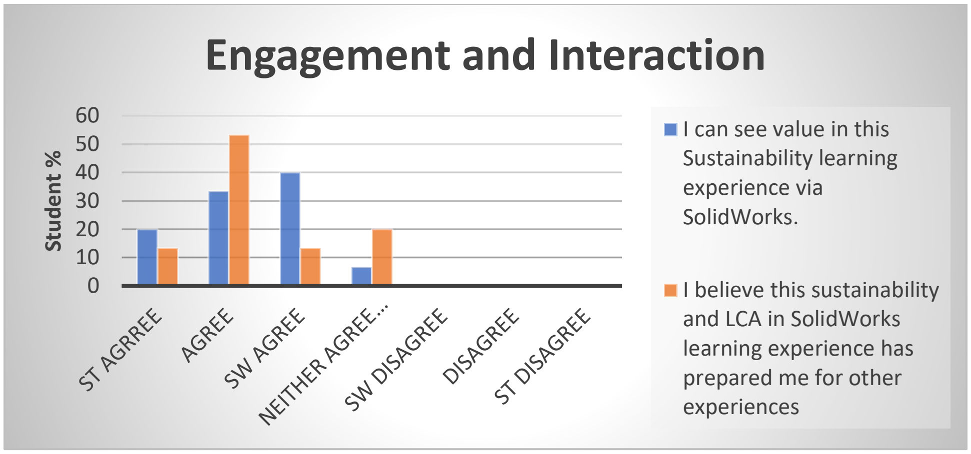

Figure 3. Summary of participant responses on engagement and interaction in sustainability and LCA.

The summary of participants' expectations for their sustainability learning experience highlights a clear anticipation for tackling real-world problems, with nearly half (46.67%) expecting to face practical challenges. This consensus suggests a proactive desire among participants to apply their learning in authentic scenarios. Additionally, there's a recognition of the value in interacting with a wider range of individuals beyond the conventional educational roles, seen in the majority (53.33%) who agree to the importance of such interactions. Despite this, a notable portion (26.67%) expresses reservations, pointing to the need for acknowledging diverse viewpoints within the learning process. These insights underscore the significance of practical engagement and broad interpersonal communication as essential elements of effective sustainability education.

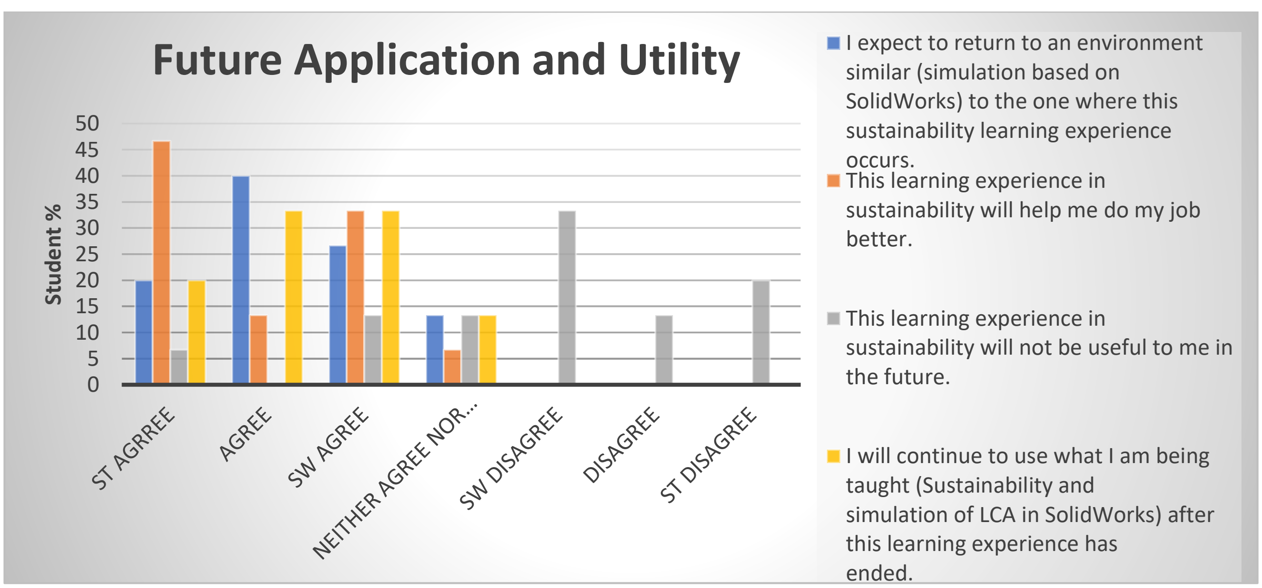

Figure 4. Summary of participant responses on future applications of sustainability and LCA.

The summary of participants' expectations and perceptions regarding the SolidWorks-based sustainability learning experience shows a mix of optimism and skepticism. Sixty percent of participants anticipate revisiting a similar simulation-based learning environment, indicating a positive view towards such educational settings. Almost half (46.67%) strongly feel that the experience will positively impact their job performance, highlighting the relevance and practical applicability of the knowledge gained. However, there is a significant level of skepticism about the long-term value of this learning, with 40.00% expressing doubts about its future usefulness. Despite these varying viewpoints, a majority (53.33%) plan to apply the sustainability and LCA knowledge they have acquired, demonstrating a commitment to integrating these lessons into their future endeavors. This blend of views underscores the nuanced nature of participants' attitudes towards sustainability education, revealing both the perceived benefits and the challenges of ensuring its relevance and applicability.

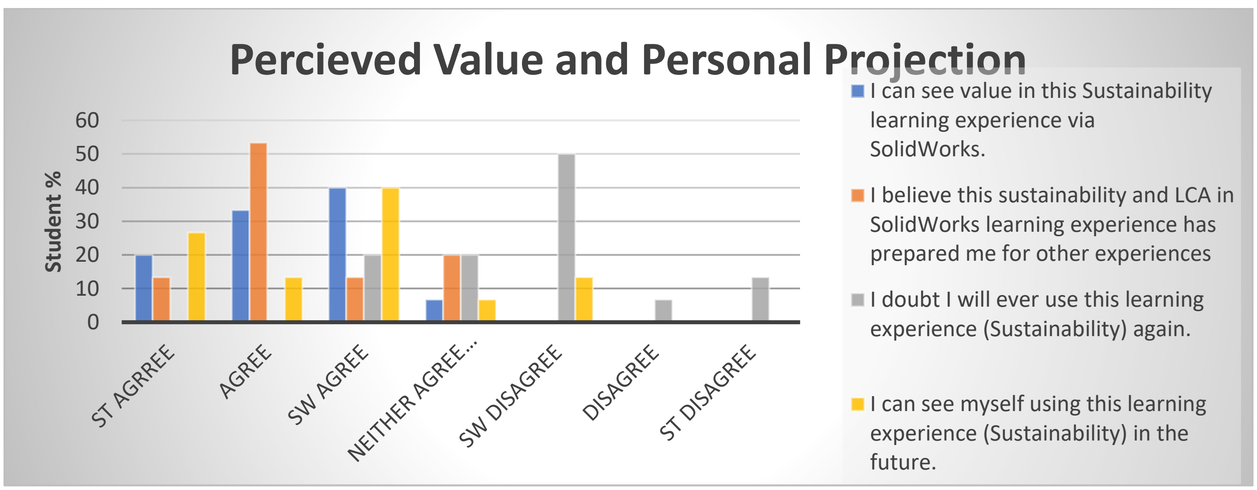

Figure 5. Summary of participant responses on perceived value and personal projection in sustainability and LCA.

The summary of participants' perceptions on the value and future application of the sustainability learning experience through SolidWorks reveals a complex picture of attitudes and expectations. Sixty percent acknowledge the value of the learning experience, with a split between those somewhat agreeing (40%) and fully agreeing (20%) on its inherent benefits. A significant majority (66.67%) feel prepared for future challenges, indicating a strong sense of confidence in the skills and knowledge acquired. However, there's a notable level of skepticism regarding the actual future use of this learning, with 60% expressing doubts, split between somewhat disagree (40%) and disagree (20%). Despite these reservations, a majority (66.67%) remain optimistic about applying sustainability and LCA knowledge in future contexts, suggesting a positive view on the long-term relevance of their education. This blend of recognition, confidence, skepticism, and optimism underscores the multifaceted impact of sustainability education in a SolidWorks environment, reflecting varied expectations about its practical utility and applicability in real-world scenarios.

Summary and Conclusions

This research study has provided insightful findings in understanding students' perceptions and awareness of sustainability concepts through both qualitative and quantitative assessments. The study's approach, encompassing qualitative analysis of student responses and quantitative data from survey results, revealed a multifaceted view of sustainability education and its impact.

The qualitative analysis highlighted a significant evolution in students' understanding of sustainability. Initially, students exhibited diverse perspectives and definitions of sustainability, with varying levels of depth and clarity. As the course progressed, a notable shift occurred towards a more focused and nuanced comprehension, particularly in aspects like environmental impact, resource regeneration, and sustainable design principles.

Students' responses evolved from general notions of sustainability to more specific and impactful understandings. This evolution was evident in their perceptions of sustainability's importance, the environmental impacts of products, and approaches to designing for sustainability. The study underscores a maturation in comprehension, with students moving towards a holistic recognition of sustainability's interconnectedness with environmental and resource management.

Quantitative data from the surveys reflected positive trends in students' engagement with and understanding of sustainability. A majority of students recognized the value of the learning experience and expressed a willingness to apply the knowledge in future contexts. However, there were indications of skepticism about the long-term utility of the learning experience and varying expectations regarding its application.

The assignment results further revealed a decent grasp of LCA concepts, although there were gaps in students' ability to comprehensively apply these concepts in practical scenarios. While many students successfully generated LCA reports and identified sustainable materials, there was a noticeable lack of depth in analyzing and articulating the reasoning behind their choices.

The study's findings suggest that while there is an overall positive trajectory in sustainability education, there is a need for more comprehensive and integrated approaches. Educators should focus on reinforcing the connection between theoretical knowledge and practical application, encouraging students to critically analyze and articulate their understanding of sustainability in diverse contexts.

Incorporating more interactive, real-world problem-solving activities could enhance student engagement and deepen their understanding. Emphasizing the social and economic dimensions of sustainability, in addition to environmental aspects, would provide a more rounded education. Continuous assessment and adaptation of teaching methodologies are crucial to keep pace with evolving concepts and practices in sustainability.

In conclusion, the study demonstrates the effectiveness of sustainability education in enhancing students' understanding and awareness, while also highlighting areas for further improvement. The insights gained can guide future efforts in sustainability education, aiming for a more comprehensive and impactful learning experience that equips students with the necessary skills and knowledge to address the challenges of sustainable development.

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Appendix A

Table 1: The summary table of the SW LCA assessments created by the students.

	Baseline	Option 1	Option 2
	PE High Density	PET	PP Copolymer
Carbon Footprint (kg CO_{2e})	1	2.2	1.1
Total Energy Consumed (MJ)	25	42	24
Air Acidification (kg SO_{2e})	3.80E-03	7.80E-03	4.50E-03

Water Eutrophication (kg PO_{4e})	4.10E-04	7.40E-04	4.20E-04

Figure 1: An example spreadsheet image that students expected to create.

	Baseline	Option 1	Option 2	Baseline = 1	Option 1 Relative to Baseline	Option 2 Relative to Baseline	Weight Factor
	PE High Den	PET	PP Copolymer	PE High Density	PET	PP Copolymer	
Carbon Footprint (kg CO_{2e})	1	2.2	1.1	1	2.20	1.10	1
Total Energy Consumed (MJ)	25	42	24	1	1.68	0.96	10
Air Acidification (kg SO_{2e})	3.80E-03	7.80E-03	4.50E-03	1	2.05	1.18	1
Water Eutrophication (kg PO_{4e})	4.10E-04	7.40E-04	4.20E-04	1	1.80	1.02	1
		Arithmetic Average		1.00	1.93	1.07	
		Weighted Average		**1.00**	**1.76**	**0.99**	

Appendix B

Email template that was given as homework after the second lecture about LCA.

<u>**Template:**</u>

To: [Send it to your instructor in this case]

cc: [Copy your teammates, and maybe the student grader if there is one]

From: [Team - One teammate should send the email, but all should contribute to it, and review it for quality and completeness.]

Subject: [Keep this short and descriptive, and include your team name, e.g. Innitech's LCA results for part X.]

Body of email:

Salutation: [Put the name and title of the person, or persons, the email is directed to: this should be all of the people in the To: address, but not those cc'd, e.g. Prof. Carly Brownstein, or Jeff Abram, Engineering Director.]

Brief Introduction: [State the purpose and any necessary background of the report – keep it as brief as possible, but use complete formal sentences and no abbreviations.]

Bad examples:

Yo man, here's the rept.

Whatup? Heres the assignment.

Good example:

Team Wazoo has completed the LCA of our water container and recommend the use of HDPE (high density polyethylene).

Rationale: [Explain how you arrived at your decision and refer to the LCA report from SW that you will attach to the report. If you prepare any additional spreadsheet or analysis, include that either as an attachment or in the body of the email. Sometimes, one material will be better than alternatives in every aspect of the LCA. More commonly though, some aspects will be better, and some will be worse. You may have to prepare your own matrix, possibly with weighting factors. A table and/or graph can be helpful here, and can be copied and pasted from the attachment(s). Whatever logic you use should be clearly and succinctly explained here. This should be a few paragraphs with about 200-300 words. You must demonstrate that you have considered the LCA results and how they led you to choose your material.]

Closing: [List your team name and the names of all of the member's first and last names]

Attachment(s): [The SW LCA report should be attached as a PDF file, with all the form entries filled in. Also attach any other analysis you do such as a spreadsheet.]

Appendix C

Table 1: Scoring Rubric Used to Evaluate LCA Reflection Homework Assignment

Dimension	**No Evidence (0 Points)**	**Weak Discussion (5 points)**	**Good Example Provided (10 points**
Environment	Lacked any mention of environmental. impacts	Discussed environmental elements in the conversation without providing specific examples, highlighting the importance of	Notable illustrations of how design influences the environment include instances where the

		considering them in the design process.	environmental impact is evident.
Product's Life Span	Lacked any mention of duration of the effects	Referenced the product's life span without specifying the components or factors encompassed within this duration.	Effective illustrations of various stages in the life of design and their corresponding effects.
Economics	Lacked any mention of cost, local economic benefits, etc.	Referenced cost or economics without elaborating on its significance in the context of design.	Effective instances of how design influences the economy and incurs costs.
Social	Lacked any mention of social benefits	Referenced social benefits without providing an explanation of their importance in the context of design.	Notable instances of how design influences and leaves an impact on society.

Table 2. Scoring Rubric Used to Evaluate LCA Report Creation and Discussion of Finding the Most Sustainable Material for Bottled Water Homework Assignment for

SolidWorks LCA	**The spreadsheet can be successfully generated.**	**A conclusion**	**The accurate conclusion can be deduced.**	**A comprehensive and through elucidation can be provided**

Report Created		**can be inferred.**		
Successfully created: 30 points	Successfully Created: 15 points	Created :20 points	Only the correct option present:15	Correct option was chosen, and explanation for it was correct: 20 points
Not created: 0 Points	Successfully created with minor mistakes: 10 points	Not created: 0 Points	Multiple options including the correct option present:10	Correct option was chosen with room for improvement in the explanation :15 points
	Created with major mistakes : 5 points		Correct option not present: 0 points	Correct answer was not present, but a correct justification for the wrong answer: 10 points
	Not Created: 0 Points			Correct answer was not present, and justification for the wrong answer was inaccurate:0 points