2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #37482

Designing and Innovating Sustainable Products, Services and Systems: Infusing the Entrepreneurial Mindset in Undergraduate and Graduate Industrial Engineering Training

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Abstract

A typical IE course in sustainability engineering introduces students to engineering design, manufacturing, supply, and systems aspects while highlighting global sustainability, energy management, and life cycle analysis. Although such courses provide students with the knowledge required to assess the environmental impacts of existing products, services, and systems, they suffer from a few common weaknesses: (1) they focus more on analysis and much less on front-end design of environmentally sound products; (2) in many IE curricula, these are only elective courses; and (3) students tend to treat sustainability courses as a one-off class, and often lack a vision and clear next steps toward a career path in designing and innovating around sustainable products.

To address the challenges above and to improve the skills and competency of engineering students, we have introduced in our sustainability course two additional sets of training – one on innovation and product design principles, practices, and methods and one on the entrepreneurial mindset. These additional training sets aim to: (1) encourage constant curiosity among students about our changing world and anticipate the challenges of currently accepted solutions; (2) make connections from many resources to intersect ideas; and (3) develop product designs that create environmental, economic, and social value. We also present insights into ISE curriculum changes that can strengthen these sustainability training elements. This effort would create entrepreneurs with engineering training who can innovate and design sustainable products and systems for the future. We are presently implementing this effort in our sustainability course and will share results from ongoing student projects and student surveys about their attitudes, skills, confidence, and viability for sustainability engineering as a career path.

Background

As environmental awareness in the general populace grows, to capitalize on an emerging market in sustainably and responsibly designed and produced products and services, and to stay competitive, industries have begun to focus more attention on redesigning their end-user products and production processes [1]. Furthermore, global competitive pressures, government regulations, and new environmental policies are forcing industries to comply with and align their products, services, and processes with emerging environmental standards [2].

These market and regulatory forces have necessitated a revisit of what we teach our future engineers and how we train them to think about sustainability engineering and design. While operating under new sustainability constraints and fewer resources to meet customer and market demands. The instructor for the Sustainability Engineering course at the Industrial Manufacturing and Systems Engineering Department at the University of The University of Texas at El Paso, with support from faculty from the Department of Engineering Management at Rose-Hulman Institute of Technology, recently redesigned a Sustainability Engineering course taught to industrial engineering students. Traditionally, the course only included modules on sustainability engineering and life cycle analyses (LCA) along with hands-on laboratory activities and a class project using software tools for life cycle analyses, but the redesigned course implemented this past Fall also incorporated lectures and discussions in the principles of entrepreneurial-minded learning, and in the principles, tools, and methods for consumer product design. Students incorporated ideas and concepts from these two additional sets of learning materials in their course projects and analyses. The goals of the redesigned course elements were to provide engineering students the knowledge and tools needed for thinking with an entrepreneurial mindset when designing sustainable products, and for following a structured product design process for generating and evaluating the designs. The rationale for including entrepreneurial-minded learning and product design principles and methods in the course was three-fold: (1) to encourage constant curiosity among students about the changing priorities in sustainable and responsible design in the world in general and industries they will work for in particular, and anticipate the challenges involved in designing and implementing acceptable solutions; (2) to make connections from many information resources to intersect ideas, particularly by using structured methods for generating concept designs for their ideas on sustainable products and services; and (3) to develop product designs that create environmental, economic, and social value. Student teams completed a design project incorporating these new learning materials. This paper provides an outline of the various lecture modules in the course with a brief description of the module contents. The paper also illustrates the integration of life cycle analyses, entrepreneurial-minded learning principles [3], and structured product design methods with an example student-generated project in the course.

A brief overview of Entrepreneurial-Minded Learning (EML)

Entrepreneurial-minded learning (EML) is a pedagogical approach aimed toward developing the mindset of Curiosity (discovery), Connection (identifying unexpected opportunities), and Creating value (for stakeholders) as known as the 3Cs. The EML needs to be coupled with engineering thought and action expressed through collaboration and communication, and founded on character (Hylton, 2019). The entrepreneurial mindset allows students to think broadly and deeply about how their ideas fit into their environment (Hylton, 2019). As such, it is a suitable approach for bridging the gap between theoretical analyses that designing sustainable products might entail, and the front-end design process and the practical vision toward designing sustainable products.

The EML framework was developed and improved through the Kern Entrepreneurial Engineering Network (KEEN) [4].KEEN is a network of currently 4,000 engineering faculty and staff with a shared mission to graduate engineers with an entrepreneurial mindset so they can create personal, economic, and societal value through a lifetime of meaningful work [5]. More information is available on the Engineering Unleashed website hosted by the Kern Entrepreneurial Engineering Network (KEEN) (https://engineeringunleashed.com).

Course modules and a brief description of the content

The goal of the redesigned course was to bridge the gap between the skills and training in designing sustainable products and services, and training to think with an entrepreneurial mindset – we represent the interplay between the skillsets and mindsets required for these learning goals with the enmeshing of the cogs in the skillsets and mindsets wheels as seen in

Figure 1. Typically, the product design skillsets are taught isolated from sustainability engineering and analysis skillsets; engineering classes seldom integrate these, particularly with mindset changes needed to think entrepreneurially.

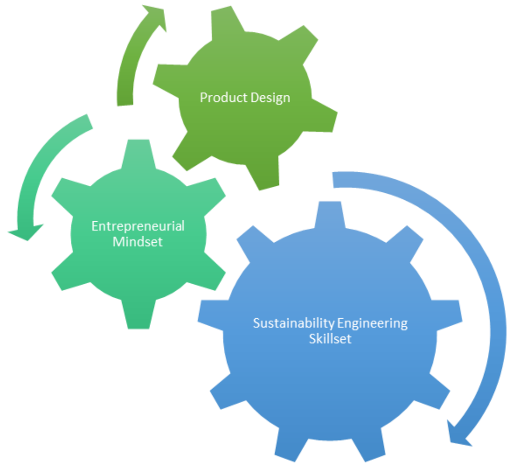

Figure 1. The intermeshing of product design and sustainability engineering and analysis skillsets with an entrepreneurial-minded learning mindset.

Students in the course acquired the knowledge and skillsets about sustainability engineering principles and practices through a series of lectures, discussions, and hands-on laboratory activities. Sustainability engineering and analysis skillsets are taught in a series of 8 modules (described in 1 through 8 below).

Structured steps in designing a product and how to think like an entrepreneur (for cultivating an entrepreneurial mindset in students) were introduced to students via two separate lecture modules. Module 9 introduces the design requirements and outlines the structured steps involved in designing a product that addresses the sustainability concerns discussed in the first eight modules. Module 10 introduces the principles behind an entrepreneurial mindset and entrepreneurial learning by which students metacognate and discuss how entrepreneurs learn. The module also covers the content on how students can stay motivated, how they develop and strengthen their entrepreneurial mindset (i.e., curiosity, connections, and creation of value), and how they cultivate their entrepreneurial attitude. Module 10 ends with a structured way to think about how to identify opportunities to innovate and create value for various stakeholders (customers, users, organizations, and society).

Module 1: Introduction to Sustainability and Global Warming

We begin the course by discussing "The Tragedy of the Commons" by Garrett Hardin [6]. The objective is that students recognize the conflict between individual interests and the common good. We also define sustainability as "meeting the needs of the present without comprising the ability of future generations to meet their own needs.". The objective is that students understand that the three main pillars of sustainability (environment, economic and social) must be considered to develop a sustainable system.

We define Global Warming and the Greenhouse Gas Effect in this module. Here, we present historical data on the anthropogenic concentration levels of CO2, CH4, and N2O, and population growth and how these are associated with the global rising temperatures. The objective is to provide students with scientific evidence that human activities are changing the climate and how climate change can significantly impact our lives.

We end this module by defining Carbon Footprint and begin introducing its characterization factor, impact category, impact indicators, and impact indicator results. The objective is to introduce students to how to quantify the impact of greenhouse gases in terms of Global Warming Potential.

Module 2: Carbon footprint

In this module, we review Global Warming Potential (GWP) values for a 100-year time horizon according to the Intergovernmental Panel on Climate Change's (IPCC) second, fourth, and fifth assessment reports [7]. Additionally, we define the following terms:

- Carbon Dioxide (CO2)
- Carbon Dioxide equivalent (CO2 eq)
- Carbon Neutral
- Carbon Offset
- Carbon Offset Project

We also provide and discuss examples of global companies going carbon neutral and review the specifications for demonstrating carbon neutrality according to the PAS 2060:2014 standards [8]. This module aims to present students with the steps organizations must take to demonstrate the carbon neutrality of a specific product, entity, or activity.

Module 3: Types of Carbon Footprints and Environmental Standards

In this module, we define several types of carbon footprints: (1) Organizational footprint; (2) Supply chain footprint; and (3) Product carbon footprint. Furthermore, we review the following environmental standards:

- Greenhouse Gas (GHG) Emissions Protocol
- ISO 14000 (ISO's environmental management system standards)
- European Commission Organizational Environmental Footprint
- PAS 2050 (Product carbon footprinting standard)
- International Reference Life Cycle Data Systems Handbook
- Global Water Footprint Assessment Standard
- BS EN 15978:211 (standard to assess the environmental performance of buildings)
- EN 15804 (environmental product declaration for construction works and services)

The objective is to provide students with the fundamentals of accounting for Greenhouse Gases. The main topics students discuss include what GHG accounting is, why account for GHG gases, standards and protocols used, sources of GHGs (6 GHGs covered by *Kyoto Protocol*), global warming potential (GWP), and setting boundaries and reduction targets.

Module 4: *Life Cycle Assessment*

These modules teach students every phase of the Life Cycle Assessment, including goal definition and scoping, inventory analysis, impact assessment, and interpretation of the analysis results. The instructions include detailed steps required in every phase, examples, and exercises.

Module 5: Biofuels & Lab 1: GREET

We begin this module by defining biofuels and reviewing current biofuel trends, applications of biofuels, and methods for producing biofuels from biomass. We compare biofuel's energy content versus its counterparts. For instance, the energy content of biodiesel is about 90% of its counterpart, petroleum diesel, the energy content of butanol is about 80% of that of gasoline, and the energy content of ethanol is about 50% of that of gasoline. We also describe biofuel types and their classification and provide the following examples:

First generation

- Corn
- Sugarcane
- Soybeans
- Jatropha and other seed crops

Second generation

- Waste Vegetable Oil
- Non-Woody Biomass: Grasses
- Non-Woody Biomass: Municipal Solid Waste

Third generation

- Algae

For each example, we review regions suitable for cultivation, advantages, and disadvantages.

The objective is that students learn about the benefits of biofuels and understand why, despite these benefits, they have not been successful in replacing conventional fuels.

We also include a laboratory activity on Greenhouse Gas Regulated Emissions and Energy Use in Transportation (GREET). This lab aims to train students to evaluate the energy and emission impacts of advanced and new transportation fuels and evaluate different vehicles and fuel combinations by using GREET's current fuel and vehicle pathways or by creating a new pathway.

Module 6: Energy & Lab 2: HOMER

In this module, we review non-renewable and renewable energy and discuss the following examples

Non-renewable

- Coal
- Petroleum
- Natural Gas
- Nuclear Power

Renewable

- Solar Power
- Wind Power
- Biofuels
- Hydro Power

For each example, we discuss the advantages and disadvantages.

The objective is to have students learn about the energy ecosystem, how they are created, and their capacities, and understand the challenges of shifting from non-renewable to renewable energy sources. We also include a hands-on laboratory activity on the HOMER energy software. The objective is to have students learn how to design and optimize microgrids and distributed generation systems.

Module 7: GaBi Education

These labs are dedicated to the GaBi Education software. The objective is to have students apply the knowledge acquired from the Lifecycle Analysis lecture modules to quantify the environmental impacts associated with a product, process, or service using GaBi's database or developing processes from scratch.

Module 8: SimaPro

These labs are dedicated to using the SimaPro software. The objective is for students to apply the knowledge of life cycle analyses to quantify the environmental impacts associated with a product, process, or service.

Module 9: Product Design

In this module, students are exposed to the structured steps in the product design process [9]. These steps include (a) customer needs identification, (b) generating target product specifications with measurable metrics and how to translate customer needs into engineering specifications, (c) how to then systematically generate concepts using concept generation and ideation techniques such as external searches including benchmarking, patent searches, talking with experts, and internal search methods including creative brainstorming and ideation, and concept sketching; (d) how to generate alternative concepts for their sketches and how to relate them to target product specifications; (e) how to systematically rate and rank concepts and select promising concepts for further development using techniques such as Pugh's selection method; and (f) how to develop visual prototypes for concepts using the software.

Module 10: Entrepreneurial Mindset

Module 10 involves a lecture/discussion of the elements of an entrepreneurial mindset and how to cultivate and sustain one. The principles of entrepreneurial-minded learning, including curiosity, making connections, and creating value are emphasized through class discussions. The goal of this module is for students to become curious about their changing world, explore various solutions, search for, and integrate design information from various sources such as competitor benchmarks and patents and make appropriate connections to their design solutions, and identify opportunities for creating value in the sustainability engineering and design space. After the completion of this module, students integrate the sustainability engineering and analysis skills learned in the course with product design principles and steps, and entrepreneurial mindset principles in a final design project. Students are encouraged (by offering extra credits) to integrate the knowledge from sustainability engineering, product design, and entrepreneurial mindset to propose a solution to a defined problem statement.

Results

Students who took this class in the Fall of 2022 conducted a final project to apply the new skills and tools learned. This project aimed to propose an innovative product design that would potentially reduce the environmental load of a commonly used product. The project consisted of (1) Identifying a conventional product; (2) Identifying its environmental performance in the literature; (3) Propose at least two product designs that would potentially reduce the environmental performance of the current product; and (4) Performing the LCA's of the proposed designs. Furthermore, the projects must be submitted in a document report and presented to the class and guest faculty.

The example below is one of the students' artifacts integrating the instruction, including the sustainability engineering skillset, product design, and entrepreneurial mindset. In this project, the students proposed substituting charcoal made from burning wood, a traditional grilling method since the industrial revolution with many deforestation concerns, for charcoal made from bamboo. As required, the students conducted a comparative analysis based on the LCA methodology in GaBi between wood and bamboo designs (figures 2 and 3).

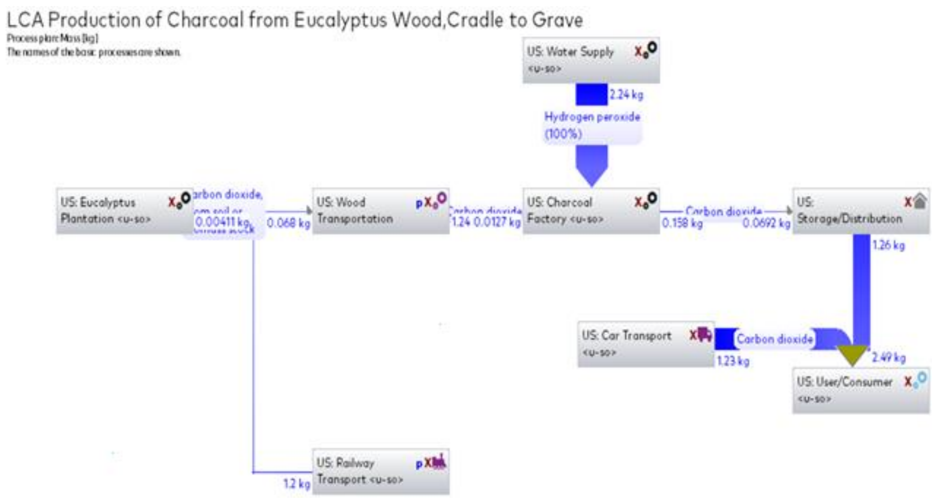

Figure 2. LCA of Charcoal Production from Eucalyptus Wood (GaBi)

Figure 3. LCA of Charcoal Production from Bamboo (GaBi)

Their results were based on TRACI 2.1, which indicated that producing charcoal from eucalyptus wood had higher Global Warming Potential and acidification potential than charcoal produced from bamboo. Based on the analysis, students concluded that the design substitution was a viable option since bamboo has faster-growing capabilities and uses fewer natural resources for its growth, reducing deforestation while effectively reducing CO2 emissions. In addition to their life cycle analysis study, students proposed three different product designs to accommodate the different styles of charcoal-burning grills, where some might accommodate circular logs or rectangular logs to fit correctly in the grill. Furthermore, they included a hollow hole in the middle of the design to allow better heat distribution throughout the log for equal burning (figure 4).

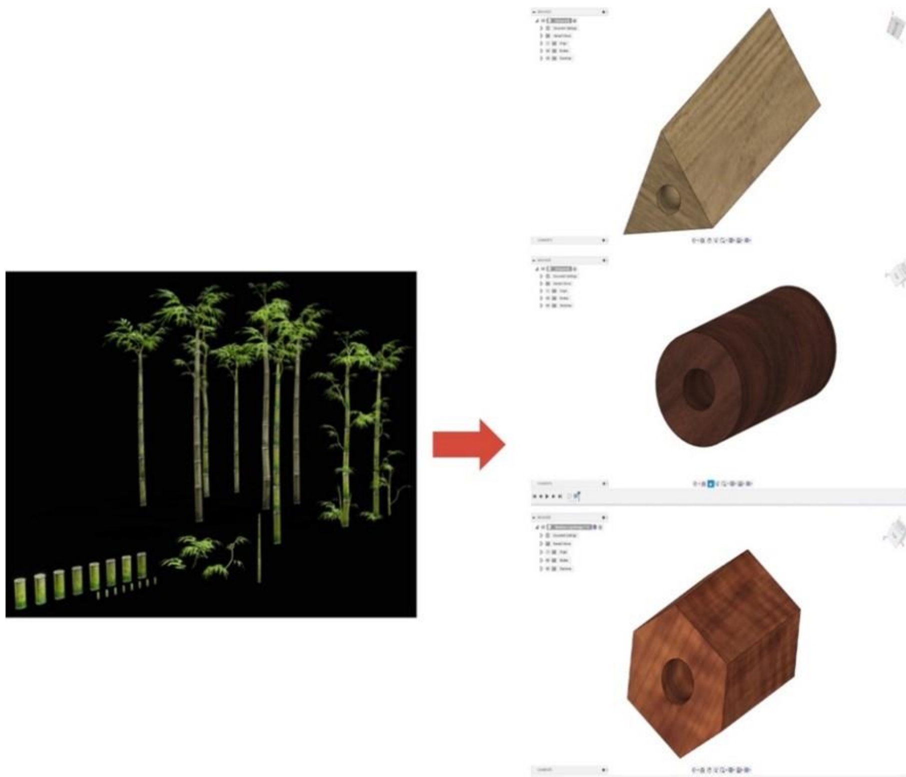

Figure 4. CAD Model Design of Bamboo Wood to Final Design Models

In order to quantify the effectiveness of the training sets described, the final projects were graded on the following criteria: (1) Relevance; (2) Degree of difficulty; (3) Project justification; (4) Digital product design prototypes (at least two); (5) Properly documenting the steps taken in the design development; (6) Perform LCAs of the product designs; (7) Properly documenting the steps taken in the development of the LCAs; (8) Quality of the report; and, (9) Verbal communication. The results of these evaluations are presented in Figure 5. Because of the nature of the projects, three teams did not produce a digital product design. However, they did comply with the rest of the project's requirements. Overall, students demonstrated their ability to apply the skills learned in this course, providing alternative solutions that can potentially reduce environmental loads.

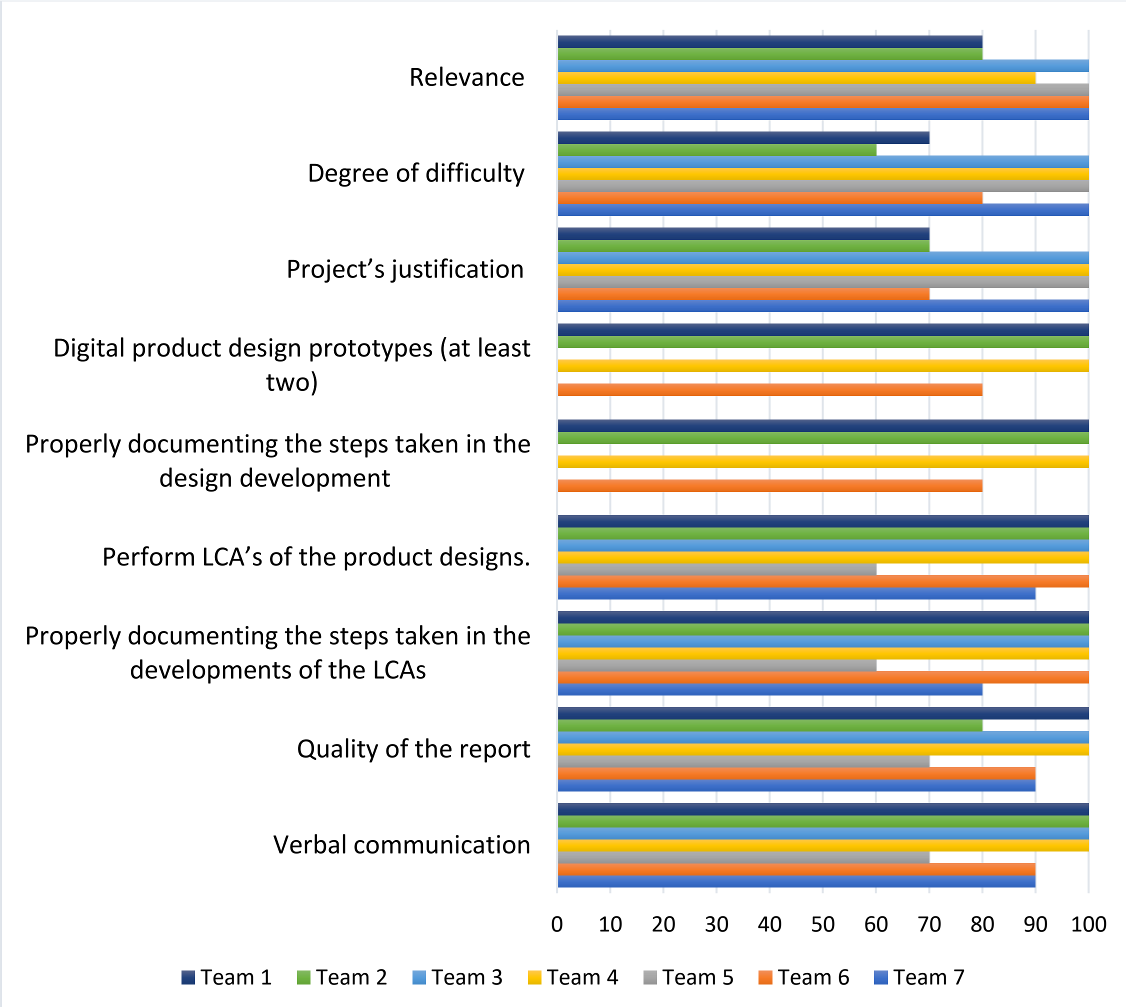

Figure 5. Evaluations of Final Projects

The perceived efficiency of this course was measured through a student survey conducted at the end of this course. This survey consisted of 8 questions developed to identify areas of opportunity for course improvement. The answers to the questions on this survey were anonymous, allowing students to respond truthfully. Figure 6 shows the statistical results that address the student's knowledge about climate change and the effects of human activities (a) before and (b) after taking this course. As the results show, students' general knowledge of climate change increased significantly after completing the course.

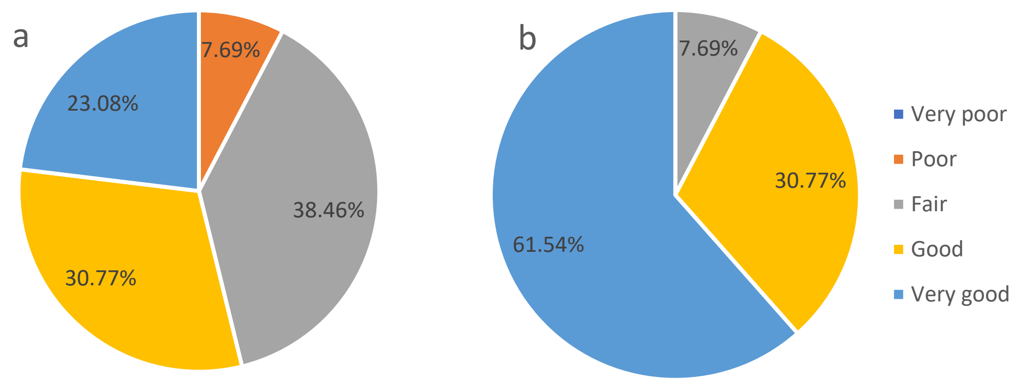

Figure 6. Survey results on knowledge about climate change

Figure 7. shows the statistical results that address the student's understanding of LCA (a) before and (b) after taking the course. The results indicate that the student's knowledge of LCA and environmental impacts has largely increased after taking the course.

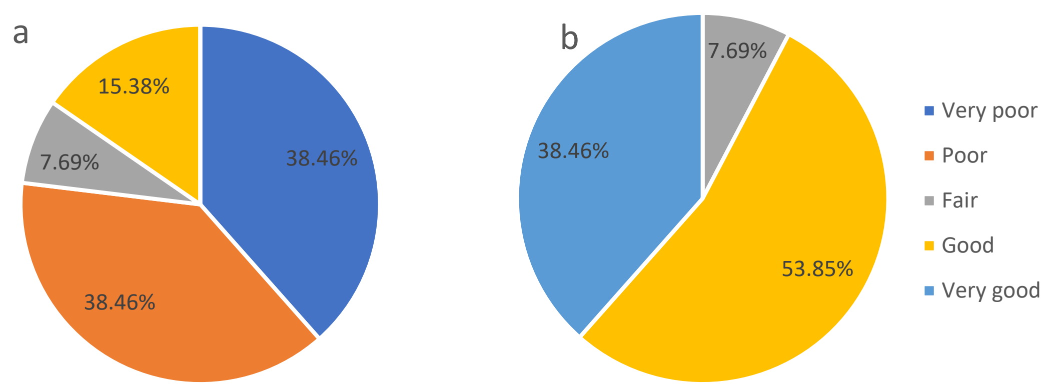

Figure 7. Survey Results on Knowledge of Life Cycle Assessment

Figure 8. shows the statistical results regarding the increase in student interest in sustainable products. The results indicate a significant positive interest after taking the course.

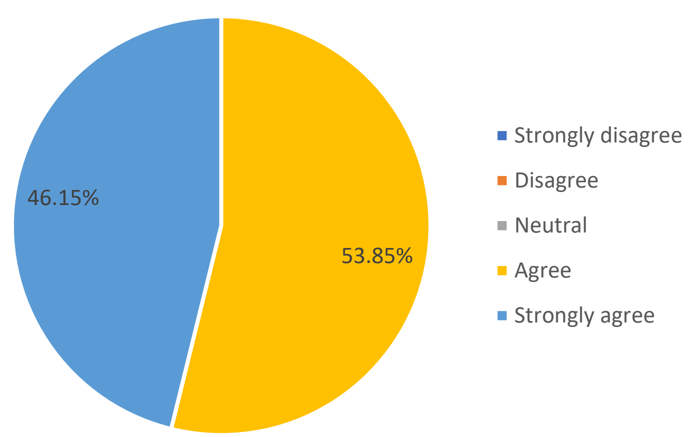

Figure 8. Interest in Sustainable Products

Figure 9. shows the statistical results regarding the perceived importance of designing and developing sustainable products. The results also show a significant positive interest in sustainable product design, which was one of the additional training sets.

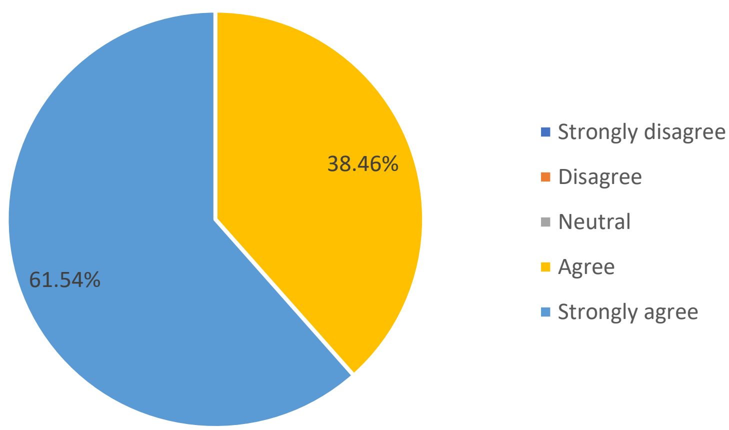

Figure 9. Perceived Importance of Sustainable Product Development

Figure 10. shows the statistical results on the perceived impact of entrepreneurial thinking and risk-taking. Based on this survey, the students show that this additional training set helped them increase their confidence in how they can impact sustainability by applying entrepreneurial thinking.

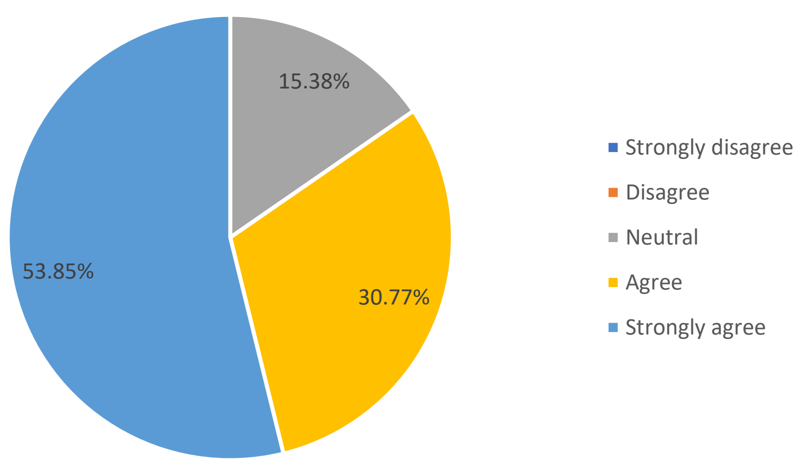

Figure 10. Perceived impact of entrepreneurial thinking and risk-taking

The statistical results in Figure 11 show how likely students are to employ the skill sets learned in this course in their professional careers. The results indicate that all students sense that the skill sets learned in this course are highly applicable in the workforce.

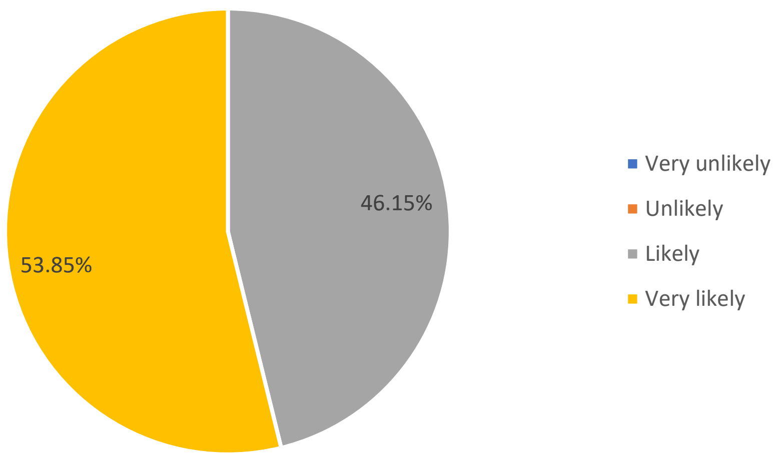

Figure 11. Perceived applicability of skill sets learned.

In general, the survey shows satisfactory results on the reconfiguration of this class. Overall, the objective of bridging gaps between the skills and training in designing sustainable products, systems, and services was met. However, we identified several areas of opportunity for improvement, such as increasing student engagement to improve their understanding of topics of climate change, LCA, and entrepreneurial mindset.

Conclusions

This work was prompted by the need to inculcate in engineering students, not just the skillsets for designing sustainable products, services, and systems, but also to impress upon them the need to think entrepreneurially about sustainability engineering so that, as future engineers, they would be equipped with the tools and the thinking necessary to venture into creating environmentally responsible businesses themselves or to influence their employers into adopting sustainable practices in their industries. Early interventions in the engineering curriculum to include what we term *micro-doses* of sustainability and entrepreneurial thinking, particularly in courses where design concepts are introduced to students or where students conduct engineering analyses would increase student awareness and interest in this important topic. Integrating these micro-doses into the engineering curriculum will not only create the sustainability entrepreneur mindset in students but also make the sustainable design truly sustainable in the future. Additionally, opportunities to collaborate with the colleges of business (with their infrastructure for teaching entrepreneurship) should be explored to fully realize the potential for creating sustainable products, services, and businesses in the near future.

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