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Work-In-Progress: Holistic, Multi-disciplinary Systems Approach to Teaching Sustainable and Contextual Engineering Concepts for Undergraduate Students

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ABSTRACT

The urgent global need for sustainable engineering solutions necessitates a paradigm shift in engineering education. This work-in-progress advocates for a comprehensive, multi-disciplinary approach in teaching sustainable and contextual engineering to undergraduate students. The multidimensional challenges of sustainable development require engineers to understand the complex interplay of ecological, social, economic, and ethical factors. This paper highlights the imperative of embracing a holistic pedagogical framework that combines engineering fundamentals with knowledge from diverse disciplines. Specifically, this paper will discuss how two universities implemented sustainable, contextual learning opportunities for their undergraduate students from an interdisciplinary perspective and from disciplines not typically involved in sustainable education pedagogy such as Chemical and Electrical Engineering. This paper provides examples on how contextual learning opportunities could be implemented with a range of types of assignments with various time commitments. Through our educational approaches to implementing contextual engineering learning opportunities, we aim to cultivate a new generation of engineers capable of devising innovative, sustainable, and contextually relevant solutions that positively impact society and the environment.

Introduction and Motivation

In the face of escalating global challenges, the demand for sustainable engineering solutions has never been more pressing [1]. The imperative to address complex issues such as climate change, resource depletion, and social inequality necessitates a fundamental reorientation in how we educate the engineers of tomorrow. This paper underscores the urgency of this paradigm shift, advocating for a holistic, multi-disciplinary approach in engineering education that goes beyond traditional boundaries.

The urgency of sustainable development requires engineers to navigate an intricate web of ecological, social, economic, and ethical factors. In fact, ABET accreditation criteria specifically require all engineering undergraduate programs to address ethical, global, cultural, social, environmental, and economic impacts [2]. Despite this requirement for all of engineering, such a holistic approach is often associated with Civil Engineering or Environmental Engineering [e.g., 3, 4, 5] more than other engineering disciplines. Recognizing this imperative, in this paper, we strive to motivate a comprehensive pedagogical framework that transcends disciplinary silos. By delving into the experiences of two universities, we explore how sustainable, contextual learning opportunities were integrated into the undergraduate engineering curriculum, specifically drawing insights from disciplines not conventionally associated with sustainability education, such as Chemical and Electrical Engineering.

We provide tangible examples from two different universities of implementing contextual learning through diverse assignments, accommodating varying time commitments from a one class module to a month-long international course. We do acknowledge that not all students may have the ability to participate in international experiences, therefore we provide a variety of implementation examples for both international and traditional course learning opportunities. Our core argument revolves around the belief that exposing undergraduate engineering students to this holistic approach equips them with the indispensable skills, perspectives, and critical thinking abilities required to effectively address sustainability challenges that are important for all engineering students to consider.

Examples

Chemical Engineering at Northeastern University

An international, interdisciplinary, month-long, faculty-led program in Brazil, focused on sustainable energy was designed to provide experiential learning opportunities to discuss technical engineering concepts in relation to social, cultural, and environmental issues. A holistic pedagogical framework was used to develop the program's deliverables and educational content. The three main program elements are course content, company/government/community visits, and a company project. The pedagogical elements were combined and scaffolded to ensure that the learning outcomes from the courses connected to the site visits and were applied to design a sustainable action plan for a company in Brazil. Two second year courses, General Engineering *Energy Systems* and Chemical Engineering *Conservation Principles,* were taught to provide background knowledge of how energy systems work, concepts of material and energy balances, and how chemical reactions can be manipulated in processes for sustainability and energy efficiency purposes. These courses were taught to provide an understanding of systems learning as it related to sustainability from multiple engineering disciplinary viewpoints. There were lectures and readings to help students learn how sustainable technologies are implemented and regulated in Brazil. The learning of these concepts was strengthened by interactions and visits to companies, government agencies, and/or communities to discuss how they implement technologies, policies, and/or engage in entrepreneurial activities to implement sustainable technologies. Some examples of visits include a sugarcane ethanol production plant, a biogas-producing landfill to produce energy, and the largest electricity producing hydroelectric plant in the world, Itapúa.

Project Requirements

The objective of the project is to apply theoretical knowledge in a practical setting through a hands-on, month-long project. Multi-disciplinary teams were formed which included American and Brazilian University students from a variety of different engineering majors, such as electrical, mechanical, and mechatronic. For the project, each team is required to do research on the background of their project problem statement and develop proposed solutions taking into consideration the social, environmental, and economic needs and policies in Brazil. They are required to write and present a proposed detailed action plan to the company supervisor detailing innovative ideas and designs for how the company can be more sustainable for their assigned problem. Students validated the lessened environmental impact of their designs by calculating reduction of fossil fuel use, greenhouse gas (GHG) emissions, and raw material consumption through material and energy balances. These calculations directly correlate to the technical course content which provides real-world examples of how sustainability can be measured. They are asked to incorporate efficiency and saving techniques to reduce energy and material consumption and provide drawings illustrating the implementation of proposed technologies and designs.

Another important pedagogical component of this project is effective cross-cultural teamwork which provided the US-Brazilian teams an opportunity to learn how to work together through communication and perspective-taking. This was facilitated by the cross-cultural teams working together to develop a written team agreement at the beginning of the project to discuss communication, team dynamics, expectations for the project, and project management. Each project team had a company mentor that they also communicated with about project details and answered questions.

Project example 1:

In 2022, a project was developed where students worked in interdisciplinary teams with Brazilian university students alongside a Brazilian energy technology company, CPFL Energia. CPFL Renováveis is a company of the CPFL Energia group and explores opportunities in the Brazilian market for generating electricity from renewable sources. During this 5 week-long project, the students were asked to design improvements for CPFL to be more sustainable in four sectors/processes by reducing the company's energy and material usage [6]. These four sectors and project teams were:

1. Develop an integrated model of management and operational control of aquatic macrophytes, to promote cost reduction, optimization of water areas for the community, and potential use of plant biomass.
2. Propose sustainable sources for green hydrogen, specifically to foster Brazilian perspective and opportunities in this market.
3. Define a viable destination/reuse solution for tree pruning residue, analyzing effects to communities and propose alternatives for destinating those residues.
4. Propose alternatives for the noble disposal/reuse of waste from packaging, in order to reuse it in its entirety and avoid disposal in landfills or inappropriate formations.

Reflecting on the program and the project, one student commented: *Overall, I learned a lot through these projects. I will make sure to be thinking about sustainability in my future career, making sure the products I design will have a sustainable life cycle and will not negatively impact society. I learned a lot from both my peers and the Brazilian students.*

Two students who participated in the program in 2022 wrote a paper discussing their learning experience in this program [7].

Project example 2:

In 2020, the students worked with Brazilian engineering students to perform a project in collaboration with Suzano, a sustainable paper pulp company located in Brazil. Suzano provided five areas the company would like to improve their sustainable practices. The students were split into five teams, each focused on a certain sector of their business: (1) Inlet raw material transportation, (2) Outlet product pulp transportation, (3) Energy consumption and efficiency of mill, (4) Alternative fuel sources for lime kiln process, and (5) Heat energy and water efficiency pulp plant [8].

The students' comments on the program echo the importance of cultural understanding in engineering education. *"The global aspects of the project and working with Brazilian students has truly been a valuable cultural experience for me. This experience has shown me nuances within the United States' and Brazilian cultures, and others' perspectives and knowledge as a result of their environment. From subtle things such as punctuation for large numbers to differences in world history and cultural understandings, working with Brazilian students has been both enjoyable and educational. Overall, I am very grateful for this experience with Suzano and my teammates and walk away from this program with newfound knowledge and cultural understanding."*

Overall Program Impact

The implementation of the holistic pedagogical framework in the development and execution of this interdisciplinary, international program demonstrated its value in a few ways. First it fostered cross-cultural collaboration while acknowledging and addressing differences in communication, team dynamics, and project management. It cultivated engineers capable of devising sustainable solutions, positively impacting society, and the environment. The emphasis on experiential learning provided authentic learning experiences through visits, projects, and interdisciplinary collaboration. Lastly, it provided a global perspective for real-world problems that equip students to approach engineering problems with a nuanced understanding of broader systems and contexts.

Electrical Engineering at the University of San Diego (USD)

We recognize that an international experience requires resources that not all students may have access to. The international experience is incredibly valuable but not the only way that this holistic approach can be implemented in engineering classes. This approach has been used in Electrical Engineering in the *Introduction to Circuits* class with modules in required classes. This class is typically the first course in electrical engineering for majors and a required course for other engineers. It is often taken in the second year of the curriculum. One of the authors has incorporated modules on conflict minerals, sustainable innovation, electronics recycling, and fitness trackers. These are typically one or two class periods and follow the guidelines suggested in [9] and described below.

Pedagogical Guidelines

Adopting this holistic contextual approach can be challenging. Instructors need to have some degree of comfort in dealing with ambiguity in an interdisciplinary space which is different from how most technical work is taught. For example, there is a “right” answer to the voltage at a node in a circuit but no “right” answer to “should I get a new cell phone every year now that I know the impact on people’s lives?” This work must be done using discussions and active learning. It is not possible to learn these concepts by doing only mathematical problems. It is also important for instructors to follow good pedagogical practices including having clear learning objectives and assessments.

1. Identify possible sociotechnical collaborators
2. Identify a salient course topic that has broader social and environmental implications
3. Identify, add or update existing course learning objectives and/or ABET student outcome that this sociotechnical course topic aligns with
4. Create learning objectives for specific sociotechnical modules
5. Create modules by designing activities for homework before and/or after class session(s) as well as class session(s) that integrate technical content and calculations students are familiar with and social and environmental context
6. Include low stakes assessment for module (e.g., homework) and consider including sociotechnical questions on exams
7. Conduct formative assessment and/or engineering education research on sociotechnical modules to get student input and improve module offerings in the future.
8. Refine modules and identify possible sociotechnical collaborators for the next course offering

Course module 1: Conflict Minerals

Lord, Przestrzelski, & Reddy [10] incorporated a module on conflict minerals into the *Introduction to Circuits* course. Conflict minerals are minerals such as tantalum, tin, tungsten, and gold that are mined in areas such as the Democratic Republic of the Congo (DRC) where the money from their production supports armed conflict. The module was designed to connect the ethical implications of conflict minerals to capacitors which are typically a topic in this course. Learning objectives included:

- Analyze capacitors as electrical devices
- Define conflict minerals and describe at least 2 social issues surrounding them
- Describe where conflict minerals are used
- Describe potential options for engineers concerned with societal implications of conflict minerals

Before the module, students completed calculations about tantalum (Ta) in capacitors and cell phones and identified where Ta is mined. During the in-class module, the instructor defined and introduced some history about conflict minerals. Students discussed conflict minerals and their societal implications and brainstormed about ways to reduce reliance on conflict minerals as engineers. For homework after the module, student teams were each assigned a well-known company. They conducted research on the conflict minerals’ policies of the company and presented that to their classmates.

Students were asked to highlight social implications and concerns about these strategies.

When the larger context is tied to the technical content, students describe the modules as “real world” engineering and beneficial for their learning. For example, after the conflict minerals module, students participated in surveys and interviews [11, 12]. In the survey, all students who responded said the topic mattered to them as an engineer. Several students pointed out that these topics were not typical for engineering classes, that they found them engaging, and they would like to see more of this.

I thought it was a really interesting topic that has larger social consequences. It was cool to get away from the stigma of engineers only worrying about math and showing that engineering is able to have effect in other disciplines.

I think it was addressed well, and I'm really glad you did, it really sparked my interest in issues like that and how we can affect them from an engineering standpoint!

It was well done, it engaged the students into the topic, A topic similar [sic] must be a larger part of the engineering classes.

In the interviews, students indicated that they found modules to be well-integrated into the class. When asked about engineering as a field, every student brought up the modules emphasizing that they saw the social context as important for developing their sense of engineering in the real world and its potential although it might challenge their definition of “engineering”.

Well, I think all the things we did, including conflict minerals, … circuits in front of us was like, ‘This is the real world.’

Obviously, we looked at a lot of stuff that wasn’t engineering including the conflict minerals …which I thought was really cool. And that was very clearly…I mean it was engineering but at the same time it was very clearly like looking at it from different angles.

One student thought the modules were useful and that they should be expanded.

for me they [the modules] helped like further my learning a lot with just real examples of how the things worked.

Course module 2: Fitness Trackers

A module on fitness trackers was incorporated into an introduction to electrical engineering class for second-year undergraduate engineering students [13]. The instructors identified four topics related to fitness trackers that intersected with broader sociotechnical themes including data privacy, the workplace, health insurance companies, and sustainability. This project was designed to help students achieve two course learning objectives:

1) Describe two examples of how electrical engineering topics from this course relate to their everyday lives.

2) Describe an example of how engineers might consider social context in electrical engineering applications and why this is important.

In teams, students researched the social and environmental impacts of fitness trackers for their topic and gave a presentation to the class including leading a discussion. The instructors gave each team suggested readings to start their research. Students were creative in how they encouraged their classmates to participate including using Zoom polls, Kahoot, and breakout rooms. Students' responses to survey questions demonstrate that they learned about the sociotechnical nature of engineering, believed the project topics mattered to them as engineers, and these topics were relevant to their majors. Students cited the environmental, social, and legal aspects of the project as most interesting to them as engineers.

Students were interested in a variety of aspects of the project. When asked what aspect(s) of their topic they were most interested in, the largest number of students (10 out of 13 respondents) said environmental including sustainability closely followed (7 responses each) by legal and social. Six said technical and five said economic. In other work, we have seen that technical and environmental are given top priority [9, 13, 14]. This result is encouraging since it suggests that this project integrated these aspects effectively and was interesting to the students.

Student response to this module was positive overall. When asked "What was the most interesting part of this assignment?", students had a variety of responses. Several emphasized sustainability and valuing interdisciplinary perspectives:

Looking at the companies and the real issues they face with sustainability, data privacy, and more

I appreciated that the topics was relevant in our lives even though we might not have had fitness trackers because the issues relate to other devices in our lives, mainly smartphones.

Seeing all the different types of engineering that can analyze a product/their perspectives

When asked to cite the most important takeaways, students connected technical, social, environmental, economic, and legal aspects of engineering. For example, "*As engineers, we always have to look at larger perspective and outcomes of new technology*." and "*Fitness trackers have implications in various fields such as social, economic, technical, and legal.*" Issues related to data privacy and environmental impact came up several times. For example, one student said "*Fitness trackers can be counted towards our ewaste problem and that our data can be used in ways we are unaware of.*"

Discussion

The introduction of a holistic, multi-disciplinary approach in engineering education, as outlined in this paper, addresses the critical need for sustainable engineering solutions in the face of global challenges. The motivation behind this educational reorientation is rooted in the recognition that traditional boundaries in engineering education are insufficient to address issues such as climate change, resource depletion, and social inequality effectively.

The examples provided, from two universities, showcase how sustainable, contextual learning opportunities have been integrated into the undergraduate engineering curriculum. Drawing insights from Chemical and Electrical engineering which are not typically associated with sustainability, the holistic educational framework aims to equip students with essential skills, perspectives, and critical thinking abilities necessary for addressing sustainability challenges. Real-world case studies, interdisciplinary collaboration, ethical considerations, and experiential learning opportunities are emphasized as key components to empower students with a nuanced understanding of broader systems and contexts.

The Chemical Engineering examples from the program in Brazil exemplifies the practical implementation of a holistic pedagogical framework. Through course content, company/government/community visits, and a company project, students engage in experiential learning, applying theoretical knowledge to real-world scenarios. The project requirements emphasize teamwork, effective cross-cultural collaboration, and the development of detailed action plans. The emphasis on sustainability influenced students' perspectives on engineering, encouraging a commitment to incorporating sustainability into their future careers. The collaboration with Brazilian students fosters cultural understanding, enhancing the educational experience beyond technical knowledge. Furthermore, the application of the holistic approach in Electrical Engineering classes, specifically in the Introduction to Circuits course, illustrated the learning of core concepts. Modules on conflict minerals and fitness trackers have been incorporated to align technical content with broader social and environmental implications. The pedagogical guidelines provide a structured approach for instructors to integrate sociotechnical topics effectively. The incorporation of real-world examples and active learning enhances students' understanding of the societal impact of engineering decisions. The positive responses indicate a shift toward recognizing the importance of considering broader contexts in engineering education.

Conclusions

In this paper, we have explored a holistic, multi-disciplinary approach in engineering education and showcased its effectiveness in addressing the pressing need for sustainable solutions. Through tangible examples in Chemical and Electrical Engineering, we demonstrated the successful integration of sociotechnical modules, experiential learning, and collaborative projects. The overall impact on students' perspectives, cultural understanding, and commitment to sustainability aligns with the authors' goal of cultivating a new generation of engineers capable of positively impacting society and the environment. The pedagogical framework serves as a valuable model for institutions aiming to adapt their engineering education to meet the challenges of the 21st century. This framework can be used in both on campus and in international educational settings to provide students opportunities to understand the complexities of a systems approach to sustainability topics.

Through real-world case studies, interdisciplinary collaboration, ethical considerations, and experiential learning opportunities, our educational approach aims to empower students to approach engineering problems with a nuanced understanding of broader systems and contexts. Ultimately, our goal is to cultivate a new generation of engineers capable of devising innovative, sustainable, and contextually relevant solutions that positively impact both society and the environment.

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