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Utilizing transdisciplinary project-based learning in undergraduate engineering education

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Abstract

Transdisciplinary project-based learning is an opportunity for undergraduate engineering students to acquire valuable skills in translating individual knowledge to other disciplines and interacting with non-academic stakeholders. In the authors' project-based education experience, these skills have been developed in both course-based and co-curricular learning contexts. A necessary foundation for implementing transdisciplinary projects in education includes introducing students to constructive collaboration across engineering disciplines and with stakeholders, consumers, and users. Furthermore, students must engage problem-solving techniques that account for emergent system behaviors during project development. Emergent behaviors are inherent to complex real-world problems. Engineering students benefit from the opportunity to respond to evolving project requirements and goals in low-risk, academic settings prior to enduring these challenges at the career level. This active learning approach can increase student agency and diversity as students work in multi-disciplinary teams on relevant problems, drawing from previous experiences. Additionally, students learn the value of qualitative data for characterizing priorities of stakeholders, consumers, and users that are often unavailable from quantitative data. Students participating in transdisciplinary project-based learning gain agency and develop a skillset for investigating the cross disciplinary implications and sociotechnical contexts of real world problems, as well as integrating quantitative engineering analyses with qualitative stakeholder needs.

Keywords: engineering education, project-based learning, collaborative design decisions, managing emergent behavior, understanding stakeholder and user needs.

1. Introduction

Engineering education curriculum standards currently emphasized at universities intend to improve the quality of engineering education to keep up with the pressing complex problems that have surfaced globally, especially those experienced in the COVID-19 pandemic. The skills obtained from implementing these objectives prepare graduates to enter the professional practice of engineering with the abilities to apply both hard engineering science as well as professional and social contextualized critical thinking independently and in collaboration with multidisciplined team members, stakeholders, consumers, and users (ABET, 2022). Building on the traditional development of disciplinary curriculum standards, the transdisciplinary engineering environment aims to exchange diverse knowledge and experiences in diversified teams of technical and social experts to generate approaches to real world complex engineering problems.

In the context of this paper, complex engineering problems are defined as situations requiring engineering design innovations that are ill-defined, cross-disciplinary, and lack an obvious or singular "best" solution. Engineering design is defined as an iterative, creative, and decision-making process that balances science, mathematics, and engineering with constraints from stakeholders and users such as cost, sustainability, and usability (ABET, 2022; Rouse, 1991). Current engineering education curriculum in the United States most often includes (a) standard science and math courses, (b) engineering theory-based courses, (c) a broad education component that complements the technical component, and (d) an engineering design component that incorporates constraints for students to apply knowledge and skills acquired from prerequisite coursework (ABET, 2022). Additionally, (e) a professional engineering education component is proposed that promotes diversity, equity, and inclusion awareness (ABET, 2022). The content of the complementary components (c-e) in the curriculum can be interpretated by accredited universities in a variety of ways. Acknowledging social contexts is not required, and are often separated from technical contexts, in traditional engineering problem statements and approaches. Students in such settings are tasked with coming to a single "best" option defined by numerical optimization methods such as minimizing cost

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and time to build (Wickerson, 2022). This instills a belief that decision-making is purely objective and based on "optimized" quantitative values from math and science.

The effectiveness of these complementary components is influenced by the students' motivation, resources available, and supporting faculty. Creating an immersive learning experience in coursework or co-curricular activities has a positive impact on a student's agency and identity as an engineer. In a study on college student success, it was found that their learning experience and persistence to complete their degree was directly influenced by programs for active and collaborative learning with students and faculty in an inclusive environment (Xu, 2016; Crawley et al., 2007). One approach to creating this environment is project-based learning. Project-based learning shows students how to explore a problem space with real world context through inquiries as well as collaborating and sharing knowledge with peers, stakeholders, and users to develop a feasible solution space (Kokotsaki et al., 2016). For engineering students, the projects provide context for the theories learned in formal STEM courses and engage students in realistic and relevant problems. Applying the concept of transdisciplinary engineering (TE) to project-based learning emphasizes collaboration between students from various degree studies, backgrounds, and personal experiences to generate holistic solution spaces. It is critical that students graduate from engineering programs understanding how to cooperate in diverse teams. Students working in TE project groups learn how to process information and make decisions towards a shared goal while considering the impacts on others. Drawing from published studies and course frameworks, as well as the authors' student experiential perspectives, understanding what effective TE project-based complementary experiences are and how they shape engineering undergraduate students as cross-disciplinary, holistic problem-solvers are the primary emphases of this paper.

2. Complementing formal STEM theory through TE project-based learning

Undergraduate engineering education should prepare students for the changing world where user and stakeholder responsiveness and sustainability is as critical as technical feasibility in problem solving. To keep up with the demand for well-rounded design thinkers, universities in the United States and abroad have integrated active learning approaches in both the classroom and co-curricular activities. This type of education produces career-ready engineers with skills in cross-disciplinary communication, teamwork, and holistic problem-solving methods. Holistic problem-solving explicates the problematic situation into all of its contextual parts: user community, cultural values, economics, environmental, and social impacts. Current and emerging world engineering problems are inherent to these contextual parts evolving and new behaviors surfacing. Managing these complexities requires exploration outside the boundaries of the original problem and practice in doing so. Types of TE project-based learning programs that address these complex contextual parts include industry sponsored projects, local environmental and social engineering, and bi-national service engineering.

The following examples are published studies and course frameworks from a selection of universities that offer TE education courses and co-curricular programs which support the authors' student experiences. The examples depict the current state of TE project-based learning in education and illustrate the benefits of continuing these projects for future students. The universities emphasized in this paper are Washington State University Everett (WSU), University of Texas El Paso (UTEP), University of Southern California (USC) in the United States, Technical University of Madrid (UPM) in Spain, and Linköping University (LiU) in Sweden. These universities are some examples of institutions that emphasize the internal connectedness between disciplines and departments as well as external connections with other universities and industries. Another catalyst for TE projects is study abroad programs. Bi-national collaborations teach students how to collaborate with students from different countries who may not share the same education background, values, or language. Together these students not only learn how to balance community needs with engineering innovation but also how to work within an internationally diversified team.

2.1. Industry sponsored projects

In 2019 a group of professors in engineering, business management, and communications departments at Washington State University Everett (WSU) launched a course that teamed students from the three academic disciplines to work on industry-sponsored projects from Boeing, Fluke, and other companies in the Seattle area (Murray et al., 2020). One purpose of this course was to introduce students to approaching problems with an Aristotelian model: the whole is greater than the sum of the parts. The second purpose was to create a roadmap to guide students through interdisciplinary teamwork (Murray et al., 2020). The project deliverables included a project vision, project description and significance, a business pitch to a broad audience, and a final product pitch and media release. Apart from team-based, hard deliverables for the course, students had individual tasks to reflect on their values, expectations towards cross-disciplinary collaboration, and lessons learned (Murray et al., 2020). The organization of this course is a foundation for individual and interdisciplinary team growth. This course gives students an opportunity to think about their own motivations and identify what strengths they bring to a team. In addition, students consider what assumptions or biases are held by themselves and team members. As part of the learning objectives, students practice balancing individual values and develop an interdisciplinary mindset for future projects.

The Spanish User Support and Operations Center (E-USOC) is a center at the Technical University of Madrid (UPM) assigned by the European Space Agency (ESA) to support the operations of scientific experiments on board the International Space Station (Crawley et al., 2007). Using this center, a study was conducted from 2009 to 2014 to examine the outcomes of project-based learning in higher education. Students were in their last semester of higher education and had not been exposed to project-based learning up to this point. Using the E-USOC labs, students were given the opportunity to learn about and consider aspects of the whole spacecraft design lifecycle from decomposing requirements to the integration and validation phases. Students were also required to present the work performed and submit technical documents (Rodríguez et al., 2015). The driver behind studying project-based learning is to increase active learning by students engaging in a project with other students in a collaborative environment. Graduating students are expected to have the skills to design and operate complex engineering systems in a team. When entering their careers, students should especially possess soft skills such as teamwork, leadership, and communication. Feedback was received at the conclusion of the project from instructors and students provided on workload, skills learned, and motivation/interest in the topics. Instructors and students both expressed that project-based learning required more effort than the traditional theory-based methods (Rodríguez et al., 2015). However, students also described feeling more confident about their technical knowledge and transversal skills. Students also reported an increase in their motivation and interest from active participation in real projects (Rodríguez et al., 2015).

2.2. Local environmental and social engineering

The University of Southern California (USC) Viterbi School of Engineering is addressing the complex transdisciplinary issues in its Los Angeles (LA) community. As a diverse major city, LA serves as a lab space for transdisciplinary research and innovation to help with urbanization, sustainability, equity, and health needs of the communities. In 2018, Project SUNRISE was launched to bring together undergraduate and graduate students at USC to address healthcare challenges faced in LA county. Project SUNRISE is a USC sponsored program that highlights humanitarian engineering and shows students to leverage technology and entrepreneurship in an effort to solve real-world healthcare problems, particularly in underserved communities (Ballon, 2021). The project partnered with LA County Department of Health Services for advisement on relevant healthcare challenges like improving the patient portal, engagement between patients and care providers, and increasing screening rates for colon and cervical cancers (Ballon, 2021). The work at Project SUNRISE combined social entrepreneurship, customer and problem discovery, and generating resources by applying for grants. Customer and problem discovery was done by interviewing physicians and nurses at Harbor-UCLA and nonprofit leaders at the LAC+USC Wellness Center to learn about pain points and identify problem spaces (Ballon, 2021). At the end of the academic year, students displayed prototypes, business models, and software at a public showcase. Over the year, Project SUNRISE showed promise in helping engineering students obtain human-centered design and social entrepreneurship skills from real-world problems.

Linköping University (LiU) in Sweden is organized differently than most other European universities. LiU supports large multidisciplinary departments that merge adjacent disciplines in order to facilitate communication across the traditional confines between disciplines. LiU is part of the European Consortium of Innovative Universities (ECIU), a network of universities united in the idea of connecting cities and businesses with learners and researchers to solve multidisciplinary societal challenges (European Consortium of Innovative Universities, 2022a). A course offered at LiU titled “inGenious – Cross Disciplinary Project” gives students the opportunity to collaborate with other students across departments on a chosen problem from inGenious (Linköping University, 2022). To understand what problems and values were centralized to the student teams, an interview was conducted with the course supervisor, Charlotte Norrman. Norrman shared that the course is run in cooperation with inGenious, a platform that connects multi-disciplinary teams with real-life problematic situations brought forward by companies or public organizations in the EU (European Consortium of Innovative Universities, 2022c). Students are supported by both Norrman and coaches from inGenious. Norrman described the course as challenge-based learning where students take on a challenge posted on ingenious and deliver a solution to what they have defined within the challenge. In the past, challenges have been about environmental and social efforts such as sustainable cities and communities, reducing inequality, and climate action (European Consortium of Innovative Universities, 2022b). Students obtain cross disciplinary and professional communication skills from working in diversified teams and presenting solutions to the real stakeholders.

2.3. Bi-national service engineering

At the University of Texas El Paso (UTEP) there are global programs where faculty and students engage with students at Latin American universities on sustainability projects in poor communities. In UTEP's college of engineering students can apply to projects with Czech Technical University, Pontifical Catholic University of Parana in Brazil, University of Rosario in Argentina, University of Piura in Peru, and Costa Rica (University of Texas at El Paso, 2022). In an interview with the previous program coordinator, Luisa Ruiz Arvizu, the global program at UTEP was described as a unique opportunity to introduce students to what engineering in education and in practice was like in other countries. There were barriers UTEP students did not expect upon beginning the program. UTEP has a student body that is over 80% Hispanic and the global partnerships were with Latin American universities; however, even students who were bilingual struggled to communicate and understand technical engineering terms in Spanish. The primary goals of the trips focus on solving a problem that local poor communities face and producing a prototype of the solution given a $100 budget. For this project teams were made up of both cross-disciplinary and bi-national students. The teams were told to consider the location, resources, and users in their prototypes. There were two challenges that came with this project: (1) creating a solution feasible for poor families to implement themselves, and (2) acquiring materials for the design (UTEP students felt lost at first when they learned there was no Home Depot nearby).

Arvizu also spoke of the lasting impacts of the global program when students returned back to the States. She explained that the study abroad program helped with student retention as they became more confident in their culture, experiences, and ideas. When asked how well she thought these kinds of programs prepare students for their careers, she stated that the program gives the students hands-on engineering skills, professional skills, and increased their technical communication abilities both in English and Spanish.

3. Valuable skills for career readiness

Engineering undergraduate education should help students obtain valuable skills for tackling realistic, complex engineering problems in the world. The examples above demonstrate how TE project-based learning as complementary components to engineering education is a robust method for achieving this goal. Project-based learning with real world problems require the use of scaffolding instructional techniques to help students connect their technical knowledge to the economic, environmental, and social context (Nelson, 2012). Scaffolding in education is directly related to a construct in Vygotsky's theory of learning known as the zone of proximal development, which defines the range of tasks that can be performed with help or guidance but not yet independently (Vygotsky, 1978). With the use of scaffolding techniques in the design process to introduce complex problems and strategies, students can progress from being overloaded by seemingly unsolvable problems to confidently implementing these strategies and capturing the problem contexts as the supports are reduced. Additionally, students have the opportunity to practice these strategies in a supportive and low-risk academic environment. Students learn from a balanced ratio of successes to productive failures and analyzing why mistakes occurred in the process (Fisher & Frey, 2010). In the TE project and course examples described above, scheduled milestones in the process allowed teams and individuals to reflect on missteps and assumptions that led to less desireable design decisions.

Industry sponsored projects give students the opportunity to practice interacting with industry partners and mentors, real-world users, and non-academic stakeholders, consumers, and users (SCUs). Local environmental and social engineering projects focus on user-centered design methods. Students at USC interviewed actors directly involved with the healthcare challenges to learn areas of frustration and listen to suggestions for changes these actors would like to see (Ballon, 2021). Students practiced qualitative data collection methods to gather enthographic information and discover stakeholder and user exigencies that otherwise would have been missed in quantitative data. Bi-national service engineering projects not only exposed students to translating knowledge across disciplines but translating needs, values, and ideas to another language. The students at UTEP in collaboration with students abroad applied holistic problem-solving approaches to generate solutions using available resources and simple assemblies for poor families in the local communities.

Overall, TE projects that balance SCU needs challenge students to consider creative solutions that adapt to and manage emergent behavior. For complex engineering problems, teams strive to balance engineering design techniques with the constraints set by SCU needs, values, and unknown behaviors of the problem environment as shown in Figure 1 (see also Crawley et al., 2007). SCU values and unknown behaviors can be revealed through qualitative data collection methods. Interacting with SCU focuses on what the specific engineering problem is to solve. This method shapes a different dimensionality of trade spaces where multiple solutions can be generated across a broader range of context and optimization criteria as well as requirements and risks. Values of SCU include but are not limited to accessibility, cost, culture, functionality, policy and regulations, sustainability, or usability (ABET, 2022; Crawley et al., 2007).

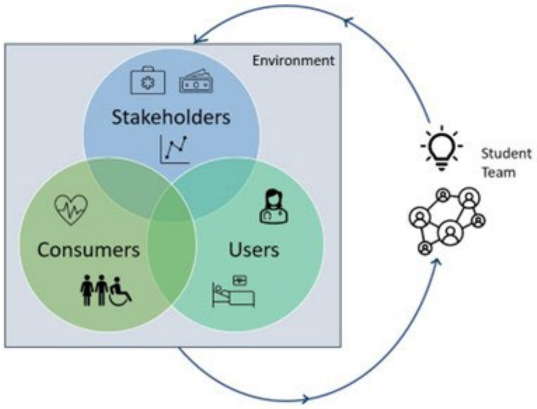

Figure 1. Finding balance between the needs and values of stakeholders, consumers, and users in complex world problems, such as increasing healthcare accessibility.

Active learning with topics relevant to students is hands-on learning in problem discovery, analysis and synthesis of SCU needs, and cross disciplinary problem-solving. These experiences and acquired skills are interchangeable among disciplines (Lynch, 2017). It is critical that students have experience with approaching realistic problems in cross disciplinary teams before entering the workforce. These TE project-based learning experiences give technical knowledge an intuitive application in a low-risk, academic environment. Here, students can reflect on lessons learned such as what could have been improved individually or in the team before the heightened pressure to succeed in industry. The TE approach to project-based learning helps students become aware of and accepting of ideas and methods that are new to them. This process is referred to as Roger's diffusion of innovation (Rogers, 2003). The concepts and practices are not objectively new but new in regards to knowledge of or a decision to adopt by the users (Rogers, 2003). Student teams developing the solution space for their TE project will encounter practices they are unfamiliar with such as collecting qualitative data from stakeholders, consumers, and users (SCUs), considering socio-technical implications like sustainability and environmental factors in the engineering design, or other real world factors that challenge the assumptions used in theory-based coursework. Students not only need to comprehend the new concepts and practices but also support the innovation, continuously apply it, and promote it in their problem approaches for the innovation to become fully integrated (Rogers, 2003).

4. Challenges with incorporating TE project-based learning

TE projects are complex engineering problems which are distinctive for their inherent challenges with the organization, cross functional teamwork, and balancing and quantifying SCUs needs. In the academic environment disruptors arise from tight timelines to stay on track for graduating in four years. Engineering students are subject to heavy course loads so adding more courses or co-curricular projects could adversely affect the ability to devote time diving into a problem and coordinate team members. Feedback from the project-based learning program at UPM showed that more effort and dedication was required by students and faculty. Faculty needed to prepare new material, continuously supervise student performance, and develop new ways to evaluate that performance (Rodríguez et al., 2015). However, project-based learning enhanced student participation and communication skills that were previously lacking in the lecture-based methodology in UPM's space engineering program (Rodríguez et al., 2015). Meanwhile, students practice time management and task prioritization – soft skills look highly upon by employers. Though to have the most fruitful experience, courses should be organized so that students are not attempting to work on multiple large projects in the same timeframe.

In addition to learning time management, applying for funding can be a valuable lesson in TE project-based learning methodologies. For large projects that require resources and travel such as community engagement and global programs, financial support can come from grants. According to Arvizu, UTEP's global programs are funded through the National Science Foundation (NSF) International Research Experiences for Undergraduates (IREU) and 100k Strong in the Americas Innovation Fund. The NSF IREU supports a group of ten undergraduate students to work on a research project with faculty and other researchers at the host institution (Fisher & Frey, 2010). The Innovation Fund supports student training and exchange programs to strengthen regional education cooperation in North and South America (Lynch, 2017). USC's SUNRISE project was funded by grants written by student participants to practice entrepreneurship skills (Ballon, 2021). Grant writing taught students how to extract the value of their research project as well as how to translate the problem and design plan to a broad audience. This activity showed students how to behave as professional engineers and think critically about what problems they choose to solve. Students developed agency and motivation from using personal experiences and values in investigating real world problems. This development is especially critical for retaining underrepresented groups in STEM education.

Lastly, students and faculty should be prepared to collaborate with students from different expertise, domains, or even different academic institutions (Wognum et al., 2018). For students, this could exist as a training course or weaved into introductory engineering courses to learn how to approach society-relevant problems through a transdisciplinary lens, communicate skills to translate knowledge, and create an open and respectful mindset for cross-disciplinary teamwork. Faculty will need to understand how to support students throughout the TE project process as well as evaluate learning and knowledge gained through the experience. This will differ from traditional lecture and test-driven performance analysis. In the project-based learning students are evaluated individually and as a team. Deliverables for projects are often iterative, so teams receive feedback during regular presentations throughout the process before the final presentation. Self-evaluations and peer evaluations are utilized as well. Conducting these types of evaluations prepare students for the more realistic performance reviews they will experience in their careers.

The key themes of this paper are described through the graphic in Figure 2, which illustrates possible learning paths for undergraduate engineering students enrolled in a university that utilizes TE project-based learning. TE project-based learning in education creates an active and low-risk learning arena for students to look at a problem space using STEM theories, stakeholder and user-centered design practices, and personal experiences. In turn, this can improve student career readiness, individual motivation, and retention. The road from the beginning of undergraduate education to graduation will vary student to student and it is often a nonlinear path, as shown by the abstract shaped blue dashed line. First, engineering students start by building a foundation of technical STEM theory and skills. During this process, it can be challenging for students to recognize where their own knowledge and experiences could be utilized for purposeful work, often left feeling disconnected and unmotivated by the concepts they are learning.

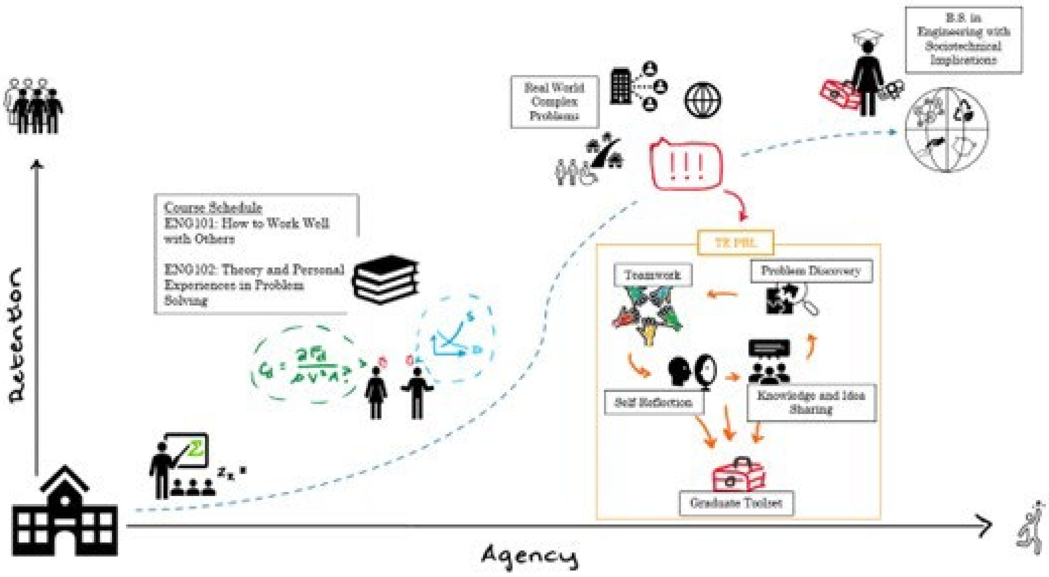

Figure 2. This nonlinear undergraduate education plan utilizes introductory courses in technical knowledge as well as cross-disciplinary communication for applications in transdisciplinary engineering project-based learning (TE PBL) with real world complex problems. Working through realistic, transdisciplinary projects in teams prepares students to consider sociotechnical implications while navigating the problem space.

While going through the technical curriculum of the students' respective disciplines, students should also have training in cross disciplinary communication, knowledge sharing, and teamwork. Using the knowledge and skills obtained through STEM theory curriculum, their own experiences, and the experiences of teammates, students can start learning how to approach complex engineering problems in a holistic manner as opposed trying to find a singular discipline, optimized solution. Often, the problems are intertwined in multiple sociotechnical systems such as social, environmental, economic, and political, as well as multiple diverse stakeholders, consumers, and users. Understanding the implications and needs requires qualitative data collection and analysis approaches.

As a team, and with support from professors and mentors, students apply their theoretical concepts and iterate through problem discovery, knowledge sharing, and idea generation. Individually, students reflect on their values and biases. Ultimately, through these experiences students will graduate with a set of skills for applying holistic approaches to real world complex engineering problems with sociotechnical implications through teamwork and individual reflection.

5. Author's own student experience perspective

At California Polytechnic State University (Cal Poly) in San Luis Obispo, it is highly encouraged to join co-curricular projects that offer hands-on experience with new ideas and technologies that can impact the world. These project teams are cross-disciplinary, student-led, and connected with industry mentors and the San Luis Obispo community. As a first year student, I (Davis, the first author of this paper) joined a new student project, the Prototype Vehicles Laboratory (PROVE Lab). The flagship mission was to design, build, and test a land-speed record challenging solar powered vehicle that did not rely on batteries. On the surface, the approach could be assumed purely a power to weight optimization problem and initially it was only proposed within the aerospace engineering student community. It is important to note that the PROVE project direction and focus were based on the faculty members' areas of expertise and teaching emphasis. Neither human-systems integration nor user-centered design were required courses within the Cal Poly curriculum, and the faculty members involved in PROVE were not active educators or researchers in those areas. The first author, as in-cockpit pilot of the PROVE solar car vehicle, became a user of the vehicle system during critical testing and record challenge runs.

However, designing and building the solar car quickly evolved into a transdisciplinary engineering process as exploring solutions required translating interdisciplinary knowledge, finding funding, and connecting with faculty and industry partners for support and mentorship. Even in the early years, the solar car team functioned like a student-led organization comprised of multiple engineering disciplines as well as journalism, graphic design and communications, and business disciplines. Additionally, the team members ranged from first-year to fourth-year students with diverse backgrounds and interests. What brought the team together on weekends and late nights was a passion for trying to do the unprecedented, break the land-speed record, and demonstrate the capabilities of alternative energy vehicles.

Soon after joining the team, I found myself placed in the role of the test driver. As the test driver, I collaborated with the subsystem leads to learn a high level understanding of how their components worked together and how the system worked as whole. One of the most memorable aspects of the experience was discovering that human-systems integration plays a role in every subsystem. However, the implications from designing for a user were not considered until the solar car was heading into the integration phase. As the solar car project was originally viewed as a power to weight optimization problem (and framed based on those faculty emphases), user-centered design was not initially presented as a technical area of engineering design or consideration for project completion. These new constraints represented considerable challenges for the solar car team, as human-systems integration was not a concept taught in formal STEM theory courses or addressed in subsystem designs or trade space analyses.

The aforementioned diffusion of innovation process existed throughout the project life cycle. Though methods for effective human-systems integration were not objectively new, the team, including myself, was not aware of best practices for designing the layout of the driver controls, ingress and egress support, and communication systems. These disciplinary exclusions and lack of human-systems integration knowledge soon became evident, with major impacts on project evolution. For instance, in the design review leading to system integration, one issue arose with the anti-lift flap designed to deploy if the car pitched to a specified angle. The function of the flap is to provide additional downforce on the car, and operated similarly to a car hood (a mechanism the designers had seen before in real-world applications). However, the flap was designed to pop up while I was still driving down the test strip, and then be reset manually once I had stopped the vehicle and safety personnel reached me. An outcome of this design is a total loss of driver visibility, as the flap would block the entire windshield of the cockpit. I worked with the engineers to redesign a user-friendly automated flap system with linear actuators that would briefly activate a shortened flap to counteract the lift generated then reset itself to mitigate visibility issues. This experience introduced the solar car team to confronting issues in a design despite organizational hierarchies or how far along the project is in development. While the solar car was not intended to be a commercial vehicle, there is still a user whose needs and values should be prioritized in designs for improved safety and operator performance. One of the key takeaways for the team was hands-on experience learning about and applying subjectively novel concepts of human-systems integration. From this experience, I decided to merge my evolving (but still not formally trained) interest in user-centered design from my test driver role with my formal aerospace engineering education by pursuing human-system interactions in space exploration.

Without this experience I would not be aware of the criticality in designing for human-systems integration in every engineering system, even space systems. Space systems like launch vehicles and shuttles are massive technologically complex engineering feats. However, when I learned about how to design these vehicles, the human-systems integration and sociotechnical systems were not included. While a launch vehicle may not be carrying a crewed payload, there are still design decisions that impact users to be considered. The heightened interest in space from commercial companies and tourism will increase space debris and air pollutant emissions into the upper atmosphere (Ryan et al., 2022). This is an environmental threat with global impacts yet the space sector remains unregulated. Undergraduate engineering education programs and student projects should demonstrate how to identify user impacts and emergent sociotechnical implications in seemingly technical problems such as those in the aerospace engineering industry.

6. Conclusion

Integrating complementary TE PBL experiences into undergraduate education has demonstrated a variety of benefits for preparing the next generation of engineers. TE projects can be derived from industry partnerships, needs of surrounding underrepresented communities, and international connections. Adding TE projects into student coursework and co-curricular activities can be challenging with the tight timelines of four-year undegradaute programs for both students and faculty. Part of the TE PBL process is establishing a foundation for students to practice using transdisciplinary engineering tools. This requires training students in cross disciplinary teamwork, communication of knowledge, and how to recognize sociotechnical contexts of problem spaces which is achieved through scaffolding instructional techniques.

Proposing a realistic and existing problem gives students an understanding of the contextual elements and challenges in the problem to design better solutions that balance the exigencies of SCUs. Relevant world problems are inclusive to a diverse engineering student body and students feel motivation in having their ideas and experiences heard and utilized. Universities that have included effective complementary TE project-based learning found that students participated more actively and acquired skills in cross-disciplinary teamwork, customer and problem discovery, and developing solutions that considered the environmental and social implications of the application. Ultimately, students graduate with a valuable skillset to seek creative and holistic approaches to the world's complex problems collaborating with multidisciplinary teams and SCUs.

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