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# Student Recognition, Use, and Understanding of Engineering for One Planet Competencies and Outcomes in Project-based Learning

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# STUDENT RECOGNITION, USE, AND UNDERSTANDING OF ENGINEERING FOR ONE PLANET COMPETENCIES AND OUTCOMES IN PROJECT-BASED LEARNING


## ABSTRACT

Addressing local-to-global crises at the intersection of environmental protection, climate change, sustainability, and social justice will require new skills and competencies in practicing engineers as well as the ability to learn from and work with non-engineers in society. Project-based learning (PjBL) provides one approach by which students can learn how to creatively tackle important open-ended problems in the world. We examine the impact of a second-year PjBL course within The Polytechnic School's (TPS) Engineering program at Arizona State University's on students' understanding of environmentally and socially responsible engineering. We used a survey approach to collect fixed and open-ended responses from 122 students. Collected data was analyzed through the lens of a newly developed framework called Engineering for One Planet (EOP). Our analyses show that the PjBL course had a moderate to large impact on student competencies that comprise the EOP framework. We believe the EOP framework can be considered as a guiding framework in designing courses and curriculum to better prepare students for future engineering work.


## INTRODUCTION

The following research paper aims to dissect the integration of the newly developed Engineering for One Planet (EOP) framework into undergraduate engineering courses. The *Engineer of 2020* [1] guided academic approaches to engineering education for the first part of the new millennium, but it could not anticipate the magnitude of the challenges facing engineers today. Our goal is to provide foundational evidence to advocate for EOP as a framework for faculty and students to contextualize a global pandemic, legacy, and new global environmental crises facing engineers beyond 2020. Engineers cannot escape the reality that the products and outcomes of their work have, over many decades, played a role in creating such crises. It is simultaneously inescapable that engineering work will play a crucial role in addressing these crises. A more sustainable and just world needs to be designed and built. This will require engineers to be more thoughtful about how they view their roles in creating this world along with the skills needed to address the needs of humanity more responsibly.

Engineering educators are continually working to infuse engineering education with environmental and sustainability considerations, including ways in which social, economic, cultural, and political factors influence how engineers frame and address problems. It is becoming increasingly apparent that more substantive frameworks that challenge engineering educators to holistically integrate these concerns into curricula are necessary. Such frameworks can help engineering educators move beyond simply modifying one or two courses to think more systematically about how various aspects of such content can be infused throughout the undergraduate curriculum and beyond.

This paper examines how students enrolled in a second-year, project-based, use-inspired design course recognized, used, and understood concepts and outcomes related to a new framework focused on environmentally and socially responsible engineering called Engineering for One

Planet (EOP) [2]. The intent is to leverage these results to further impact the entire curriculum by exploring the following research questions:

1. *In what ways do students recognize the practice of EOP concepts while working on open-ended projects in a project-based course?*
2. *How did understanding of EOP concepts improve or develop through the project-based experience?*

## LITERATURE REVIEW

### ***Environmentally, Socially, and Sustainability-Focused Engineering Pedagogies***

Engineers have long been identified as crucial actors in achieving sustainable development. Disciplines oftentimes worked in isolation towards their own definitions of sustainability before the United Nations Sustainable Development Goals (UN SDGs) were explicitly enumerated [3]. *The Engineer of 2020* was a guiding framework for high-level curriculum design and discusses sustainability in the terms of 'green engineering' [1]. This expresses a need for systems thinking as engineers consider, for example, the supply chains of their design materials, the impacts of their suggested manufacturing processes on labor, and the larger social and environmental consequences of their design decisions. Engineers must be able to generally recognize how the systems they build (e.g., energy, transportation, biomedical, communications, etc.) affect the social, technical, and ecological systems in which they are embedded. The broad and radically cross-disciplinary nature of the UN SDGS requires academic units to converge around an understanding of sustainability within and without the university [4]. The public and private sectors aligned in this shared understanding allows multidisciplinary collaboration to occur once engineers and other experts in STEM, liberal arts, and labor are trained to recognize the importance of sustainable development as sociotechnical systems are modernized for the world following 2020.

Higher education institutions have implemented sustainability into their existing pedagogy with varying extent and success, based on how existing curricula are adapted to include new competencies [4]. A 2009 benchmarking study of sustainability in engineering education at US universities found that students in traditional engineering programs would only be exposed to sustainability-focused courses if they elected to take one [5]. Sustainability engineering stood as its own discipline in most cases, with major and minor degrees. A Bachelor of Science program at Carnegie Mellon's Department of Engineering and Public Policy offers a double major to students completing a core group of multidisciplinary and PjBL courses including decision analysis, economics, statistics, and technical topics, so long as this group is coupled with a traditional engineering or computer science course of study [5]. This study also found that there was a significant difference in how sustainability was presented between engineering disciplines. For example, chemical and materials engineering programs focused their definition of sustainability on pollution prevention. The call for "the development of a set of community standards for sustainable engineering" [5] has certainly been met with the UN SDGs providing a comprehensive and universal starting point for conversations about sustainable engineering design, practice, and education.

A crucial responsibility of engineering educators is to ensure that the concepts surrounding social and environmental concerns are not brushed off as superfluous by engineering students that have internalized misunderstandings about related concepts. There has been increasing evidence suggesting engineering education leads to a decline in students' concern for public welfare [6-7]. One way to foster this sense of social responsibility would be to ask students to engage directly with the communities in which they live and work [8]. Some STEM higher education institutions focusing on sustainability often ground the curricula for those topics in community work using three pillars of engagement: social, environmental, and economic [8]. Community engagement, as a form of service-based learning, has proven to be a viable method for grounding sustainability factors in technical education, so that such concepts are not so easily dismissed by students driven by pragmatic, purely technical conceptions of engineering.

There are still knowledge gaps in how engineers could apply higher levels of sustainability expertise in their careers [9]. This could perpetuate a notion that sustainability programs produce effete engineers unable to apply their conceptual understanding of sustainability in practice [9]. A perceived unimportance of nontechnical knowledge as well as the preconceived notion that technical work is superior to social work is often a part of the engineering identity [7, 10, 11]. Sustainability can only be grasped effectively when abstractive elements of engineering and design are brought forth by the learner. Each individual student must learn to engage their technical skills while holding social and environmental sustainability of their work to fully foster an engineering culture of sustainability. This might require addressing the definition of public good. El-Zein and Hedemann [10] note that "the public good that engineering serves remains poorly defined and is rarely discussed...An alternative, hypothetical formulation of the public good could shape different disciplinary boundaries that are better aligned with self-defined engineering goals" related to addressing long standing social and environmental concerns.

***PjBL as a Vehicle for Delivering Sustainability***

Engineering educators face a constant challenge of covering a diversity of topics in limited amounts of time. Requirements to earn an engineering degree are already vast, which means incorporating new knowledge difficult. To provide scaffolding for knowledge transfer in a PjBL course, instructors should learn to recognize each learner's unique relationship with their project (in how they understand it), and should not expect self-direction in students if they are only allowed to command self-instructional techniques [12, 13 p29]. Progressive pedagogies (e.g., flipped classroom model [14] or transformative learning [15]) can also allow for a greater breadth of material to be covered.

A project-based pedagogical approach is the scaffolding of knowledge structures and curation of content that stimulates learners by inviting them to bring their own experiences directly to their designs [13, 16]. PjBL is a balancing act containing curricular elements that blend traditional and flipped classrooms, frontal classroom teaching and 'on-the-job' training; all to engage the variability of local circumstances [16]. Guerra's [17] analysis of sustainability in problem-based learning (PBL) shows similarities to the first author's examination of the junior-level PjBL course in TPS, in their suggestion that the enhancement of professional expertise and technical competencies is contingent upon learner's ability to direct themselves [18]. This distributive approach to scaffolding specifically allows for the acquisition of nontechnical knowledge and development of nontechnical skills to be unified with the development of technical expertise [19]. A project-based pedagogical approach serves curriculum designers with its capacity for a wide array of theories and frameworks, as the focus is on setting the initial conditions for promoting self-directed learning rather than taxing oversight throughout the course [18, 20]. Engineers must have adaptive expertise to navigate new design challenges with the accelerating pace of innovation and the shortening of time-to-market for new technologies [21]. Self-directed learners that tinker with new technologies to create technological artifacts provide a useful analog for engineering students in higher education [22]. Project management, teamwork, critical thinking, and decision making are all practiced as students form groups, engage with tools and workspaces, and present projects to their peers. This environment more accurately emulates professional reality and has a greater capacity for the breadth of learning outcomes expected to be achieved as long as the embedded autonomy is not interpreted as a lack of support [25]. Expertise will be measured from the breadth of areas from which engineers can pull experience as engineering work becomes more cross-disciplinary [24]. A curricular focus on systems thinking and adaptivity will better serve engineers throughout their careers as lifelong learners than a snapshot of current technological paradigms. The prioritization of affording students authentic control in scoping their projects gives engineering educators more bandwidth to introduce multidisciplinary perspectives as new design challenges [13].

Given the nature of social, environmental, and sustainability challenges, PjBL might be an effective way of simultaneously integrating knowledge and skill-building in engineering students [17]. Project-based pedagogies on their own are far from ubiquitous, which can make it challenging to reform entire programs using this approach [26, 27]. A gap also exists in understanding the broad efficacy of PjBL in equipping students with the skills and competencies necessary for socially and environmentally responsible engineering exists with only a handful of studies in this intersectional space. Recent studies indicate a method for optimizing PjBL for introducing sustainability in a first-year engineering course, and throughout the entirety of undergraduate programs [28, 29]. This is encouraging, but the scope and urgency of the environmental crises facing engineers today demand a more expedited dissemination of sustainability concepts. The project-based pedagogical approach can be tailored to deliver the wide array of learning outcomes associated with sustainability and multidisciplinary collaboration that will define the engineering field for decades to come.

## ***ENGINEERING FOR ONE PLANET FRAMEWORK***

The Lemelson Foundation and VentureWell have led the development of the *Engineering for One Planet* (EOP) framework. This framework was created with the input of hundreds of stakeholders involved in engineering education, practice, and policy [2]. The EOP initiative seeks to create systemic change by establishing environmentally sustainable engineering as a core tenet of engineering curricula. The framework represents fundamental learning outcomes and is designed for flexible adoption within higher education institutions, programs, and courses, such that "[a]ll engineers will be equipped to design, build, code and invent with the planet in mind." It suggests the role engineers will play in achieving sustainability:

> To make long-lasting systemic change, engineers and engineering programs offer critical opportunities for intervention because engineers create, construct, and massively proliferate the technologies and products of tomorrow. Engineers are the linchpin to ensure that the things we build are ultimately compatible (or not) with the health of the planet and the lives it sustains [Lemelson Foundation].

The EOP framework conceptualizes "student outcomes" in alignment with ABET's definition: "Student outcomes describe what students are expected to know and be able to do by the time of graduation. These relate to the knowledge, skills and behaviors that students acquire as they progress through the program." The student outcomes in the EOP framework (Figure 1) are structured to follow three main categories [2]:

1. *Systems thinking*: shift from component parts of a design to consideration of broader boundaries, i.e., the environment
2. *Knowledge and understanding*: environmental literacy, social responsibility, and responsible business and economy
3. *Skills, experiences and behaviors*: technical skills (e.g., environmental impact measurement, materials choice, and design) and leadership skills (e.g., critical thinking; and communication and teamwork)

We use the terms "EOP outcomes" and "EOP competencies" because the stated outcomes are a function of *practicing them conceptually*.


*Figure 1: The Engineering for One Planet Framework [2]*

The central focus around systems thinking with branches into social, economic, and environmental factors provides flexibility to coordinate curricular efforts between courses, programs, colleges, and universities.

## RESEARCH DESIGN AND METHODOLOGY

Our research unfolds at the intersection of expanding the awareness, skills, and competencies necessary for engineering students to think about their work through the lens of environmental and social responsibility, and using PjBL as the vehicle by which this learning is delivered.

### ***Study Setting***

An initial effort to integrate the EOP Framework into an engineering curriculum was undertaken at a large US institution during the Fall 2020 semester. The course is required of all second-year students as part of the "project-based spine," which is a series of eight project-based courses intended to be taken over a student's four-year education. The course's learning outcomes align with ABET Criterion 3: Learning Outcomes 1, 2, 3, 5 and 6. This course provides students with an important first opportunity to experience user-driven engineering practice within a multidisciplinary project setting. Previous iterations of the course implemented projects woven throughout and framed by the college's core research themes: energy, health, sustainability, education, and security. The EOP framework provides specific learning outcomes that the course instructors (Third and Fourth Authors of this paper were two of three instructors teaching the course in Fall 2020) embedded throughout the course. Instructors made the decision to *not* explicitly mention or show the EOP framework or how the course learning outcomes were tied to notions of environmentally responsible engineering because the goal of the course was not to learn the framework itself. Every effort was made to have the students understand and grapple with the notion that these learning outcomes are an inherent part of engineering that all engineers should be able to incorporate into their work, regardless of their discipline or career aspirations.

Instruction in Fall 2020 was entirely remote given the COVID-19 pandemic. Student learning was centered around two projects, each of which took approximately half a semester:

1. *Product archaeology*: decomposition of a battery-powered toothbrush situated in the context of global oral health
2. *Design project*: design of an artifact to address the UN SDGs

Each project consisted of a number of tasks and assignments. Student experiences varied depending on their chosen modality of learning, i.e., either fully remote, in-person, or hybrid. The instructional materials and the assignments were the same for all students regardless of modality they chose since the instructors were remote.

## ***Data Collection***

Student experiences and perception of the course were gathered at the end of the semester using a short survey facilitated using Qualtrics. The survey was developed using the expert designed EOP framework to align with students' *use* and *understanding* of the key EOP competencies: 1) systems thinking, 2) environmental literacy, 3) responsible business and economy, 4) social responsibility, 5) environmental impact measurement, 6) materials choice, 7) design, 8) critical thinking, and 9) communication and teamwork. This course is the third design course required of all students majoring in engineering, so students may have been exposed to some of the EOP competencies in prior classes. The survey provided a brief description of each concept to level-set all students' vocabulary regardless of previous experience with the concepts.

The overall framing question of the survey was: "Which of these competencies did you practice in EGR 201 while working on your projects?" Students were then presented with each concept one at a time. Their responses were given on a 4-point scale with the following options: none, small extent, moderate extent, and large extent. Students responding with anything other than 'none' were then prompted with an open-ended question asking them to write: "In two to three sentences, what did you learn about [EOP competency] and how did your understanding improve or develop?" In this way, students responded to each EOP competency using a fixed item question followed sequentially by an open-ended question.

All students enrolled in Fall 2020 ($n$ = 182) were instructed to complete the survey as an assignment for course credit; a total of 160 surveys were completed. A subset of 122 students consented to participate in the study and were subsequently included in this analysis (76%). Five of the responses were removed from the analysis because they answered "none" in more than five of the nine EOP competencies. This step was taken to address the possibility that some students chose "none" more readily near the end of the survey after learning that such a response would allow them to avoid having to respond to the open-ended question provided to all other responses. The final sample included in the statistical analysis was 117 of the 160 students (73%).

***Demographics of the participants***
A subset of 104 participants self-reported demographic characteristics. Approximately 68% reported that they were a first-generation college student and 2% reported that they were veterans. Most students reported they were male (87%), 12% reported that they were female, and 1% non-binary. The majority of students (80%) were 18 to 23 years of age. Self-reported race included: 49% white, 24% Hispanic/Latino, 17% Asian, 5% mixed race, 3% African American, and 1% Native American, The most common major was mechanical systems (28%) followed closely by robotics (27%) and automotive systems (24%). The remaining students reported electrical systems (13%) and manufacturing (7%), which means that all possible engineering majors and concentrations offered by the school were represented in the sample. Lastly, 20% reported transferring to ASU from another college. Many students (59%) reported holding at least one job, and of those that reported having a job, 73% stated that their job interferes to some extent or significantly with their school work.

***Data Analysis***
The analysis of data included a mix of quantitative and qualitative techniques to capture the overall effectiveness of PjBL in transferring EOP competencies. We sought to investigate whether students *recognized* various EOP competencies and *used* them in their projects as well as their *understanding* of these concepts. Inferential statistical analysis included correlations among independent and dependent variables, ANOVA for multiple group analysis, and independent t-tests for comparisons by binary student demographic data; all analyses were run using SPSS.

Open-ended responses were compiled and imported into Taguette, an open-source software tool for qualitative analysis. Survey results were compiled into an anonymized list with responses from students only grouped by the parent question. Once imported into Taguette, the first author applied a deductive codebook derived from the EOP competencies shown in Figure 1. The deductive analysis was performed as a case study of this specific use-inspired design course across multiple instructors [30].

Additional qualitative reasoning was included in this study to note the pragmatic validation of the deductive coding [31]. There is a justifiable need to augment the deductive analysis with inductive analysis, so that emergent themes distill the essence of the experience and its alignment with expected outcomes [32]. The inductive analysis was a phenomenological exploration, to characterize the impressions students received from their experiences [30]. Examination of statement significance and meaning are thought to have illuminated more universally applicable principles about EOP and PjBL that will be useful to curriculum designers in other programs.

## LIMITATIONS
This examination was conducted at one institution within one course taught by three instructors. The work is intended to provide a baseline of understanding but is limited in the sample obtained for this course. Steps were not taken prior to the start of class to collect student perceptions prior to the course experience. We also discovered a shortcoming in the design of our survey based on the choice to allow respondents who chose 'none' to skip the open-ended portion of the question. This choice made practical sense in our initial design, but

may have led to some data inaccuracies as students hoped to complete the survey more quickly for credit in the course. Students needed their own internal motivation to complete each question accurately and comprehensively. Responses were removed to account for this limitation, which also reduced our overall sample size.

## RESULTS AND DISCUSSION

***EOP competencies***.

Student reports of the use of EOP competencies within their projects were all positively correlated with each other (Table 1). This supports the overall concepts included within the EOP framework were all significantly associated with one another.

*Table 1: Correlation Matrix for EOP competencies as Reported by Student Application (Competencies numbered 1-9)*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1. Systems Thinking | -- | | | | | | | | |
| 2. Environmental Literacy | .284** | -- | | | | | | | |
| 3. Responsible Business | .394*** | .297** | -- | | | | | | |
| 4. Social Responsibility | .350*** | .280** | .462*** | -- | | | | | |
| 5. Environmental Impact | .424*** | .346*** | .447*** | .345*** | -- | | | | |
| 6. Materials Choice | .381*** | .259** | .417*** | .456*** | .507*** | -- | | | |
| 7. Design | .397*** | .290** | .524*** | .479*** | .413*** | .535*** | -- | | |
| 8. Critical Thinking | .427*** | .237* | .432*** | .454*** | .513*** | .434*** | .512*** | -- | |
| 9. Communication & Teamwork | .282** | .265** | .255** | .217* | .282** | .274** | .254** | .401*** | -- |

* $p < .05$; ** $p < .01$; *** $p < .001$

***Student Recognition and Use of EOP competencies***

Figure 2 indicates the percentage of students recognizing and using the EOP competencies in the course. Only a small percentage (1-7%) selected 'none' for any one concept. Most responses were to a moderate extent or greater (74-96%). These findings suggest students' ability to identify key concepts embedded and applied within the course projects. No concepts, except materials choice, revealed more than 5% of students reporting that the concept did not apply to their coursework. The fixed-item survey data indicate an overall successful effort to provide students with an implicit opportunity to practice EOP competencies using a PjBL approach.

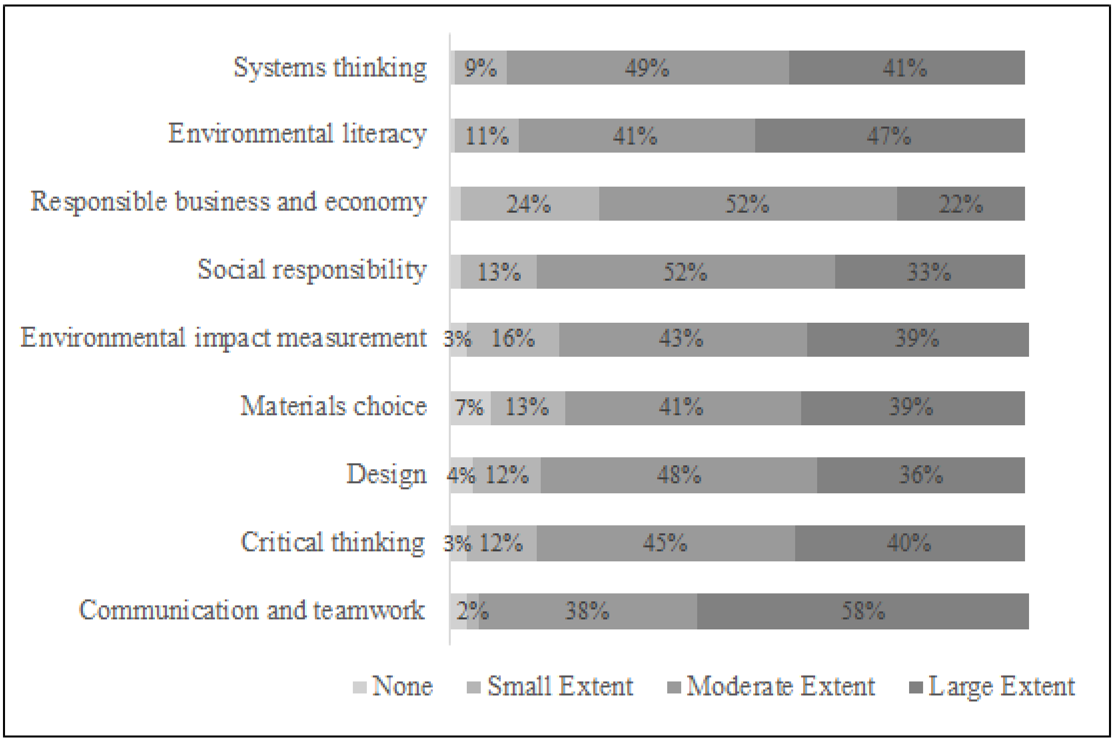


*Figure 2: Percentage of students selecting the extent to which they practiced each EOP competency.*

***<u>Students Connecting EOP Competencies to PjBL</u>***

Student responses to open-ended questions provided to those who selected any option but 'none' were analyzed using deductive and inductive coding techniques. This analysis sheds light on: 1) students explicitly connecting their learning of EOP competencies to PjBL, and 2) the depth and complexity of student *understanding* of EOP competencies. Deductive coding explored the frequency in which student responses connected the EOP competencies explicitly to PjBL (Table 2). The 117 students who volunteered to participate in this study made a total of 221 such statements. PjBL utterances were noted when participants mentioned their projects, PjBL, or the artifacts of their dissection and design. Statements alluding to multiple EOP competencies were counted for each competency identified.

Design, communication and teamwork, and critical thinking were mentioned most frequently, which is in line with faculty expectations for team-based design projects. The number of connections made to PjBL for several other concepts (e.g., systems thinking and environmental literacy) was rather low.

Those making connections made substantive connections as seen in Table 2. Most concepts were connected to PjBL with less than half the class. This opens up questions about whether it is important that students make these connections. We believe that student *recognition* of the use of EOP concepts, rather than simply "doing" EOP-focused practices without fully comprehending what they are doing opens up possibilities of individual and collective critical reflection, dialogue, and agency over what is considered important in engineering practice, and how to constantly improve it.

*Table 2: Frequency in which learning was connected to PjBL.*

| EOP Competency | Number of Standalone Mentions | Mentions Alongside PjBL | Sample Statement Containing EOP Competency and PjBL (EOP competency in BLUE, PjBL in RED) |
|---|---|---|---|
| Systems Thinking | 147 | 26 | "I mostly learned about **systems thinking** when researching the different SDG's and thinking about **possible solutions for our final project**." |
| Environmental Literacy | 148 | 26 | "**In our final project, we focused on** plastic's effects on marine life, so we learned a lot about **how to look at all aspects of a global environmental problem**." |
| Responsible Business and Economy | 164 | 25 | "The cost of items before **purchasing for a project** and ways we can reduce cost with replacing parts. For poorer countries a lot of the project is based on **how many it can reach or how to acquire items locally in order to reduce cost.**" |
| Social Responsibility | 177 | 33 | "I improved my knowledge of social responsibility in terms of engineering **during the brainstorming process of our projects**. I learned that it was that **some solutions can have negative impacts on certain groups of people so you have to be understanding** of the effects your project will have." |
| Communication and Teamwork | 177 | 56 | "**With our projects focusing on the SDG's** we learn a lot about these topics. Even if you are not researching a topic **you learn great amounts from your peers and their great ideas**." |
| Critical Thinking | 262 | 58 | "Though the course did not necessarily teach this it did give **[project] assignments that required me to do research** that allowed me to quantify specific things. It made me realize that **this task can actually be pretty difficult and you need to be aware** of the sites you are trusting." |
| Design | 399 | 86 | "**[The toothbrush project] improved my thinking and understanding** by **focusing more on the end user** and their needs instead of just what I think." |
| Materials Choice | 203 | 44 | "Materials choice was **factored into many of our projects**. What **materials are available in certain regions due to limited resources and/or financial abilities**? It made us think of what is actually going to be a feasible option." |
| Environmental Impact Measurement | 213 | 33 | "I learned that everything we use has a environmental impact. **With the first project**, I had a deep understanding the toothbrush and how it can relate to equality, equity and justice." |

We recognize the complexity of PjBL as a pedagogical approach when considering existing curricular materials, faculty, students, and classroom culture. Incorporating EOP will require significant changes be made to many existing courses and program structures. The process of synthesizing the particular philosophies and learning principles with universal competencies creates the unique characteristics and knowledge of that implementation of PjBL. The program discussed here was shaped by early adopters of PjBL as a pedagogical framework throughout the entire school almost two decades ago [28, 29].

***Student Understanding of EOP Competencies***

Coding student responses deductively revealed emergent themes in the student responses related to each EOP competency. These themes highlight the knowledge, skills, and approaches students associated with each of these concepts (Table 3). Each emergent theme was coded using the language students provided, or language inferred in analysis. All reported themes were mentioned at least three times in the statements made about those EOP competencies. Tradeoffs were mentioned explicitly, whereas ideas of pollution, degradation, runoff, and byproducts were all categorized as material waste and mapped across competencies. The themes show overlapping threads between EOP competencies, which provides interesting insights into how students are grounding EOP competencies in their work and frame of reference for future work.

*Table 3: Emergent inductive themes identifying specific concepts learned for each EOP competency.*

| **EOP competency** | **Themes** |
|---|---|
| Systems Thinking | Supply Chain Awareness, Assembly, Applied Work, Tradeoffs, Iteration |
| Environmental Literacy | Material Waste, Asset-Based Approach, Longevity, Applied Work, Iteration, Innovation |
| Responsible Business and Economy | Supply Chain Awareness, User-Centered Design, Material Waste, Applied Work, Leadership |
| Social Responsibility | User-Centered Design, Longevity, Applied Work, Leadership |
| Communication and Teamwork | Leadership, User-Centered Design, Adaptive Expertise, Iteration |
| Critical Thinking | Applied Work, Longevity, Trade-offs, Adaptive Expertise, Iteration, Assembly |
| Design | Applied Work, Supply Chain Awareness, User-Centered Design, Longevity, Trade-offs, Iteration, Material Waste, Innovation |
| Materials Choice | Asset-Based Approach, Supply Chain Awareness, Applied Work, Material Waste |
| Environmental Impact Measurement | Longevity, Material Waste, Tradeoffs, Applied Work, User-Centered Design |

This phenomenological investigation contains further contribution to literature with the elucidation of the conceptual overlaps seen in this inductive analysis. “Supply Chain Awareness” for instance was a code that emerged early on when students noted sourcing, refinement, and logistics of materials they used in their design. This awareness is brought on by the physicality of the materials they use and was brought up frequently in their responses to four different EOP competencies. Curricula could be further refined to address specific concepts without explicitly recognition. The fact that many of the emergent themes like “iteration” and “supply chain awareness” show up under multiple EOP competencies might be an indication that students intuitively applied systems thinking principles in their projects. Further analysis is needed to support this hypothesis.

***Extrapolating our findings: EOP across PjBL Courses and Beyond***

The EOP framework is multi-faceted and comprehensive, with different interdependencies across the embedded competencies (as seen in Table 3). It is virtually impossible to meaningfully engage with all of the competencies in a single course. If one assumes—or believes, as we do—that *all* of the EOP competencies are important for students to experience by the time they graduate, it behooves us to think about how to deliver these competencies *across a curriculum*.

The engineering curriculum in which this study occurred is designed to provide at least one PjBL class each semester. We envision a delivery of different subsets of the EOP framework competencies across the project-spine to ensure meaningful engagement is achieved for all competencies. This approach allows for at least two synergistic pedagogical and research opportunities: 1) emphasizing a different subset of EOP competencies in different PjBL courses allows students to see the interdependencies between those competencies in more depth; and 2) spreading the EOP framework across a curriculum allows us to investigate the impact on graduating students' ability to meaningfully engage with the entire framework. Enacting such an approach "across the curriculum" can "collectively…produce substantial results;" employing a "just-in-time" strategy can minimize the theory-practice gap, and "mirror ways in which…issues arise in day-to-day engineering practice" [33, p545].

We recognize that not all engineering faculty teach PjBL classes, which can be resource intensive, or not suited to particular curricula. Infusion of EOP competencies can still be accomplished easily through different kinds of assignments, discussions, and collective activities as desired or necessary in existing course. This suggestion echoes Riley's [34] suggestions and ideas on reforming thermodynamics classes with modules related to ethics, communication, social context, and contemporary issues.

## CONCLUSIONS AND FUTURE WORK

Engineers must consider ever more breadth of technical and nontechnical knowledge as their stakeholder groups become more apparent, aware, and vocal about the outcomes of engineering work. Educators must respond by designing engineers to be adaptive; fluid and agile in their mindset, able to adopt new technologies and synthesize new information. Exposure to experiential learning in project-based learning environments prepares students to grapple with challenges as they are generated by their choices, leaving them to practice the reasoning they will employ in their work. The earlier in their education engineers are exposed to the layers of abstraction associated with the leaps from experiment to project and product, the more they will be able to advance not only their own craft, but the field altogether. The stakeholders who benefit from a self-reflective engineering force will live comfortably and sustainably, so long as engineers are equipped to recognize all the abstract constraints they face in the design of their processes and products.

Frameworks like *Engineering for One Planet* help offset the simple unfathomability of challenges on time scales incomprehensible to engineers and their stakeholders today. EOP in particular takes advantage of the logical conclusion of engineering fields undergoing 'expansive disintegration,' that engineers will need to think in terms of the larger and more complex systems for which they design and fabricate devices and components [35]. Systems thinking is common between the knowledge, understanding, skills, experiences, and behaviors associated with engineering. The development of leadership and technical skills requires the recognition of these concepts and the reasons and values associated them. This affects the thoughts and actions engineers make in their careers and will be implemented across-the-curriculum.

With the pilot implementation in EGR 201 and the survey conducted, we confirmed that students are able to recognize the EOP concepts from the context of their thought and action. We found that most students felt like they: 1) used most of the EOP competencies in the PjBL class even though the instructors explicitly did *not* state these concepts in class, 2) directly associated their knowledge with each of these competencies with the project assignments in class and 3) thought about each of the EOP competencies in multi-faceted ways that that made connections between the competencies. Limitations in this study and its scope affected our ability to ascertain greater insights as to how students improve and develop their practice of EOP competencies through the various artifacts they produce in their design. The findings of this research paper will inform the authors' efforts to implement EOP across TPS project-spine, and some of the direct associations between competencies and to PjBL might be of interest to others exploring the implementation of the EOP framework.

Our long-term goal is to create a roadmap for how to infuse various components of the EOP framework throughout TPS's four-year General Engineering curriculum. This semester's pilot study will inform future iterations of this course, as well as other course offerings. Modifications to data collection (e.g., collecting pre and post-perceptions) will be used to gain further understanding. Data collection techniques and preliminary results have been shared in discussions with other universities implementing EOP to explore variations across different contexts. Modifications to curriculum will happen continuously and incrementally as students provide continuous insight into how well this framework impresses on them. The sum of these findings will provide the foundation for scaled infusion of EOP throughout the curriculum and potential adoption of this approach across many engineering and design programs.

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