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Reverse Engineering as a Tool for Enhancing Sustainability Understanding in a First-Year Design Course

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Abstract

This Complete Evidence-Based Practice paper presents the implementation of a reverse engineering project in a first-year Introduction to Engineering Design course as a tool to help students understand the interconnected nature of design decisions. While many early engineering design classes ask students to consider factors such as sustainability, economic drivers, and societal effects of a product, students often struggle to make connections between them. True sustainability requires the consideration of multiple driving factors beyond the environmental, balancing diverse and sometimes competing needs. To assess the efficacy of this course design, students completed a survey on their views of design and sustainability at both the start and end of the semester, enabling us to track how their perspectives evolved as they engaged with the project. By comparing survey responses from the beginning and end of the course, we assessed how students' understanding of sustainability and its role in the design process has evolved.

The primary focus of this required first year class was the reverse engineering of a garbage disposal unit to explore its motor design. From day one, students were introduced to an overarching question that served as the central theme throughout the course: "Which motor configuration is best suited for a home garbage disposal system?" This question was revisited in each module, with sub-questions guiding the investigation. These sub-questions examined key aspects such as stakeholder needs, product construction, motor functionality, material selection, and life cycle analysis, all aimed at building a comprehensive understanding to address the primary question.

For each sub-question, students investigated relevant factors and were asked to consider competing needs and requirements with respect to broader sustainability, such as environmental, economic, and societal sustainability, as described in the Engineering for One Planet framework. Students shared their results as a memo with an analysis of choices and a justification or recommendation for how to balance the competing needs.

The survey results provided insights into how engaging with the multiple factors involved in the garbage disposal motor design enhances students' appreciation of sustainability as an essential element of engineering decision-making. By taking this approach in a first year engineering course, students become prepared to apply this broader definition of sustainability to future projects within and beyond the classroom.

Introduction

Introduction to Engineering Design is a common course within engineering higher education. However, its content and implementation can vary drastically between programs. This study is focused on the Introduction to Engineering Design course in a non-disciplinary startup program at a small, undergraduate-focused institution. The course is required for all first-year engineering students and is one of their first contact points with the engineering department.

The course is centered on the reverse engineering process of an existing product, allowing students to examine its components and the design decisions made by professional engineers. By working with a commercial product, students gain hands-on experience with the design process, while receiving more guidance and concrete examples than they would when designing a product from scratch [1]. This approach also offers several benefits in introductory courses, including low cost, minimal faculty overhead, and the promotion of teamwork among students [2].

For the Fall 2024 semester, two sections of students reverse engineered a garbage disposal. Students worked in groups of 3-4 students to investigate the garbage disposal and break it down into its components. They then focused more specifically on the motor of the garbage disposal and the design choices that were embedded within it. The two sections had different garbage disposal models. One section worked with a model that had a single-phase induction motor while the other section investigated one with a permanent magnet DC motor.

This product was chosen based on a connection with the Whirlpool-owned company InSinkErator, a leading manufacturer of garbage disposals. The company is geographically local and was interested in working with engineering students. The company supplied garbage disposals for the classes free of charge. Additionally, the engineers at the company were willing to engage with the students by presenting content, answering questions, attending student presentations, and giving tours of both their research and manufacturing facilities.

This course was the third iteration following the reverse engineering process. In the first iteration, student groups were able to choose an arbitrary product to deconstruct. While the students successfully analyzed some design decisions for their product, the wide spread of chosen products limited interaction between groups and proved harder to generalize as a class. Additionally, the groups chose products with varying levels of complexity which proved difficult to compare.

In the second iteration, InSinkErator provided two models of garbage disposals, one new, and one to be discontinued, for the students to investigate. While the students benefited from investigating the same product and discussing their findings with industry experts, their main takeaways seemed to be more pointed to how a garbage disposal works instead of what competing design decisions influence the product. Students had difficulties connecting disparate design aspects, such as manufacturing methods and materials choices, and struggled to weigh relative costs and benefits of a design change. For example, students suggested switching to biodegradable plastics as a sustainability solution without considering costs, availability, or even if the material was robust enough for the standard product conditions.

In this third iteration, the goal was to narrow the focus onto a specific aspect of the garbage disposal, the motor, and provide clear guiding questions, in hopes that this would build a strong foundation to help students understand that they must look at a product as a whole in addition to understanding the specific parts.

We used the Engineering for One Planet (EOP) Framework as a guide to explore relevant aspects of engineering design with a general lens on how a product can have a positive impact on the world [3]. Similar to the UN Sustainability Goals [4] and the NAE Grand Challenges [5], the EOP Framework offers a comprehensive suite of freely available tools designed to cultivate a sustainability-oriented mindset infused with social responsibility in future engineers. It was developed collaboratively by academic and industry partners with support from the Lemelson Foundation and VentureWell [6]. Other institutions have incorporated the framework in engineering classes across the disciplines through mini-modules on sustainable manufacturing [7], guest lectures and field trips [8], and project-based learning [9], among other uses.

At the center of the EOP framework is the concept of systems thinking. Systems thinking is a holistic approach that explores how systems operate as a whole, focusing on their interactions, processes, boundaries, and the balance between direct and indirect influences [10]. This approach was important to implement in first year engineering because it equips students with the ability to tackle complex sociotechnical problems that they will encounter in their future careers [11]. Collaborating with an industry partner on a real-world product allowed students to experience the interconnectedness of engineering design firsthand, fostering a deeper appreciation for the importance of integrating diverse perspectives and disciplines in problem-solving.

This paper describes the redesign of the Introduction to Engineering Design course for Fall 2024. The structure and rationale of the course design is discussed, including the integration of the EOP Framework and an assessment method based on writing engineering memos. Results of an IRB approved (Protocol 2232887-1) survey taken at the beginning and end of the semester are also included. The goal of the survey was to assess how the students' understanding of the interconnected nature of design decisions, especially in terms of how sustainability encompasses more than just environmental concerns, evolved throughout the semester.

Course design

Two course sections of Introduction to Engineering Design ran in Fall 2024. Both sections were composed of first year students who indicated Engineering as their primary choice of study. The two sections were taught by different faculty members following the same structure. The two sections ran simultaneously, engaging 43 total students. Students were approximately evenly split between the two sections.

The class had an overarching question that was proposed to the students on day one and revisited throughout the semester: *Which motor configuration is best suited for the application of a home garbage disposal system?* In a final report, the students had to provide an answer to the question, supporting their answer with findings throughout the semester. This question was chosen in collaboration with InSinkErator, as they were actively comparing motor types between a range of Whirlpool-owned disposals. The goal was to provide students with a real engineering question at a low technical level which did not feel contrived.

Throughout the semester, each course section focused on their assigned model/motor configuration of the garbage disposal. Checkpoints throughout the semester allowed the class sections to learn about the other configuration through assignments, presentations, and discussion.

To equip the students with the necessary knowledge to answer the overarching question by the end of the semester, the ideas within the overarching question were broken down into five sub-questions that the class was structured around, with each question corresponding to one module of the course. These five questions were:

1. How do market demands, stakeholder interests, and use cases shape the decision-making process of garbage disposal design?
2. How does each component of a garbage disposal contribute to its overall functionality?
3. What features and specifications of your motor configuration make it appropriate for a garbage disposal?
4. How does evidence-based material identification inform the design of the garbage disposal motor?
5. What competing sustainability factors are involved in the overall lifecycle of the garbage disposal motor?

The posed questions were mapped to the EOP framework, as shown in Figure 1. The framework consists of eight categories around a central goal of *Systems Thinking*. The categories are *Critical Thinking, Communication and Teamwork, Design, Materials Selection, Environmental Impact Assessment, Social Responsibility, Responsible Business and Economics,* and *Environmental Literacy*. Each category can be expanded into multiple subcategories and has many components [3]. The goal of the course was not to fully understand each component, but to recognize that the categories are all interconnected and collectively contribute to globally responsible engineering design. No overarching class questions or sub-questions directly addressed *Social Responsibility* or *Environmental Literacy* in this iteration of the course due to time constraints. However, the interconnected nature of engineering design and overlap in EOP categories meant that some integration of the topics did exist. Continued work will be done to further integrate the topics in future iterations of the course. *Communication and Teamwork* was embedded into the course through group work as well as the assessment methods of memos and presentations.

For each module of the course, students obtained information through online research, hands-on deconstruction, physical testing, interaction with professionals, and/or other readings and lessons. At the end of each course module, students were asked to write a one-page memo about their findings. These memos followed a standard format representing that used by a working engineer. Students also prepared presentations on the different aspects within the sub-questions which were given in front of their peers and the InSinkErator contacts.

While the class was presented with the sustainability survey on day one and the schedule of overarching questions on day two, the students were not made explicitly aware that the EOP framework was guiding the class. Instead, each module was developed to address a guiding question that mapped to the EOP framework (see Figure 1). In the second half of the semester, the topic of sustainability was formally introduced with an emphasis on five factors related to

ABET Outcome 2: Global, Economic, Environmental, Cultural, and Social sustainability [12]. This allowed the students to revisit previous ideas with a new lens and make connections between relevant factors.

Figure 1: Mapping of course guiding questions to the EOP Framework. No questions specifically mapped to *Social Responsibility* and *Environmental Literacy*; these instead holistically informed our discussion of the other questions. Figure was modified from the general Framework schematic [3].

Module 1 addressed the question: *How do market demands, stakeholder interest, and use cases shape the decision-making process of garbage disposal design?* This question was asked first for several reasons. First, this topic addresses economic sustainability. Generally, the students enter the class with a basic knowledge and understanding of business, namely that a company wants to make a profit by selling a product for a markup. By asking this question, it allowed the students to consider and reframe their intuitions in an engineering context and begin to recognize that engineering is not an isolated aspect solely focused on making a product that meets technical specifications. Second, the topic required online research and organization of information for a technical presentation, two skills that the students typically lack upon entry. When the course was taught previously, it was assumed that the students could find and interpret relevant information. However, student feedback mentioned that this was one of the hardest parts of the class; students either relied on the limited information generated through AI or were overwhelmed by the variety of sources and had difficulty differentiating good vs. bad, relevant vs. irrelevant information. To combat this, students were guided through the research process and received feedback on their compilation of information into a cohesive one-page memo. By beginning the class addressing the "Who Cares" question, the students became invested in an aspect that they had not previously viewed relevant to the engineering design process. Additionally, through presentations by industry partners, students gained insight into the significant impact of market shifts on engineering decisions.

Module 2 summarized the students' key findings from the deconstruction process by addressing the question: *How does each component of a garbage disposal contribute to its overall functionality?* Students presented their findings in a memo which included a primary figure of an exploded model illustrating the garbage disposal components. This question provided an opportunity for students to enhance their communication skills through collaboration with group members and industry experts. Within their groups, students carefully deconstructed the garbage disposal and documented their findings, promoting direct collaboration and leadership development. Their proposed functions and interactions of each component were confirmed or denied by the industry experts. Through both the written memo and oral presentation, students demonstrated critical thinking as they explained the function of each component of the garbage disposal.

A change made to the course for the third iteration was to direct focus to the motor of the garbage disposal. This proved advantageous as it allowed the students to reduce their focus from the 50+ components that comprise the full garbage disposal down to ~5. In module 3, the students addressed the question: *What features and specifications of your motor configuration make it appropriate for a garbage disposal?* The students dug into the technical workings of permanent magnet and induction motors and reported their results in a memo. They learned to read and compare the torque-speed curves of the two motors and calculate parameters such as efficiency and power. Having a technical focus allowed the students to relate the underlying scientific principles of motor function to the overarching engineering design process. By making these connections, the students were able to see the importance of understanding both technical content and application as an engineer. Through conversations with industry experts, students learned about the history of various types of motors, their influence on marketing strategies, and how these factors could shape future design decisions.

In module 4, the students continued to investigate the motor to answer: *How does evidence-based material identification inform the design of the garbage disposal motor?* To answer this question, the students performed very simple physical tests on the motor components (e.g. corrosion, conductivity, magnetism) to determine the material of each component. Similar to memo 3, the students used technical skills and data but had to relate their findings to application and communicate them through a memo. At this point of the semester, the students were beginning to see how every decision made by an engineer has consequences that affect more than technical performance. For example, copper is a more conductive material for motor windings but aluminum is lower cost and lighter. These choices required students to weigh the tradeoffs in motor performance vs company profit.

Sustainability was finally formally introduced in module 5 where the students addressed the question: *What competing sustainability factors are involved in the overall lifecycle of the garbage disposal motor?* To answer this question, the students were guided through a life cycle analysis of the motor components from raw material to manufacturing to application to disposal. Even though the process was significantly broken down, the students were overwhelmed with the breadth of competing factors. Hearing their conversations encompass "but what about…" was exactly where we hoped this question would lead. The students were integrating their knowledge and understanding formed in previous memos to contemplate the same question through the lens of sustainability. Through these discussions, it was made clear that the goal was not to find the "right" answer, but rather to make a decision and defend it with data. They reported and justified their choices through a memo. It was at this point in the semester that the majority of students began to see their interactions with the industry professionals not as teacher/student, but rather mentor/mentee. This transition was important as our students start to form their identity as an engineer and progress further through the design sequence in the program.

In a final report, the students answered the final question: *What is one specific change or improvement you would propose to enhance the product or process, particularly with regard to sustainability or overall impact?* Here, the students took a final stance on which motor configuration is best suited for a home garbage disposal. They had to compile their findings from the previous five memos and make an engineering evaluation. Their grade was not dependent on giving the "right" answer, but their ability to weigh different factors in their decision-making process. While some students still struggled, the majority were at least able to identify multiple factors and recognize that some of the factors were in competition with others.

The structure of the course guided students to conclude that there is often no single "right" answer in engineering product development, but rather engineering is about weighing competing factors and defending their decision. Through asking guided questions that map to the EOP framework, the students were able to take away the importance of balancing a variety of factors to create a sustainable product and process. They developed these skills by investigating a specific motor configuration of a garbage disposal, and will continue to improve them in their future design courses in the program.

Pre- and Post-Course Survey

Students completed a survey on their views of design and sustainability at both the start and end of the semester. The pre- and post-course survey was identical and was collected and compared anonymously. The goal of the survey was to assess how the students' understanding of the interconnected nature of design decisions evolved throughout the semester to see a potential growth in systems thinking. It especially focused on the relevance of sustainability as encompassing more than just environmental concerns.

The results come from a total of 38 anonymous survey answers at the beginning of the semester and 31 anonymous survey answers at the end of the semester. The survey consisted of 6 questions: 2 open-ended, and 4 ranking. The full survey is provided in the appendix. The unrestricted nature of the survey produced mixed results when comparing the pre- and post-surveys.

Question 1 was open-ended: *List what aspects companies should consider when designing a product.* The absolute number of answers for Q1 was counted pre- and post-course.

At the beginning of the course, students generated an average list size of 5.2 itemized factors in their answers. At the end of the course, students generated an average of 6.1 items, an increase of 0.9 answers per student, as shown in Figure 2a. The open-ended nature of the question meant that the generated factors varied greatly. Some common key factors listed in the pre-course survey include materials, safety, sustainability, risk, consumer, and money/cost/profit/budget. In the post-survey, these factors were listed again, in addition to several new factors that were mentioned throughout the semester, such as manufacturing and tariffs. There was an increase in 10 responses each for materials, consumer, and cost and an increase in 5 responses for sustainability and lifespan, all factors that were discussed throughout the semester. Additionally, it was evident that the students adopted more common language, a prime example being where "money/budget/etc." was replaced with "cost." This is a result of conversations held with industry partners which affirms the importance of introducing these interactions early on in the classroom.

The student question 1 responses were also analyzed to map to the eight categories of the EOP Framework. These categories are *Environmental Literacy, Responsible Business and Economy, Social Responsibility, Environmental Impact, Material Selection, Design, Critical Thinking,* and *Communication and Teamwork*. Each response provided by a student was analyzed to see if their listed items fit into any of the categories of the framework. Each item of the responses was coded to the most accurate fit by matching the listed item with the keywords for each category of the EOP framework [3]. Items that did not match any category keywords were not counted. The number of different categories of the EOP framework identified by a student based on their responses was counted. If a student listed multiple items that all fit under one category, that category was only counted once for that student.

After coding between student responses and the categories of the EOP framework, the number of categories identified by each student went from an average of 2.6 at the beginning of the course to an average of 3.7 at the end of the course, an increase of 1.1 categories per student, as shown in Figure 2b. No responses mapped to the categories of *Critical Thinking* or *Communication and Teamwork*, likely because students do not consider those as separate design aspects. With the exception of *Social Responsibility*, there was a rise in responses for all EOP framework categories, shown in Figure 2c. The increase in both the raw number of itemized factors generated by the students and the increase in number of categories mentioned is significant because it suggests that students developed a broader understanding of the EOP framework over the course of the class. The increase in the number of identified categories per student indicates a deeper engagement with the framework's concepts, reflecting growth in their ability to recognize and apply ethical, operational, and professional considerations in engineering practice. The decline in responses related to *Social Responsibility* may highlight an area for further curriculum enhancement to ensure a more balanced development across all framework categories. While these results do not indicate that students have integrated other factors into their definition of sustainability, it does suggest that the course has helped students build a broader understanding of the factors an engineer must consider.

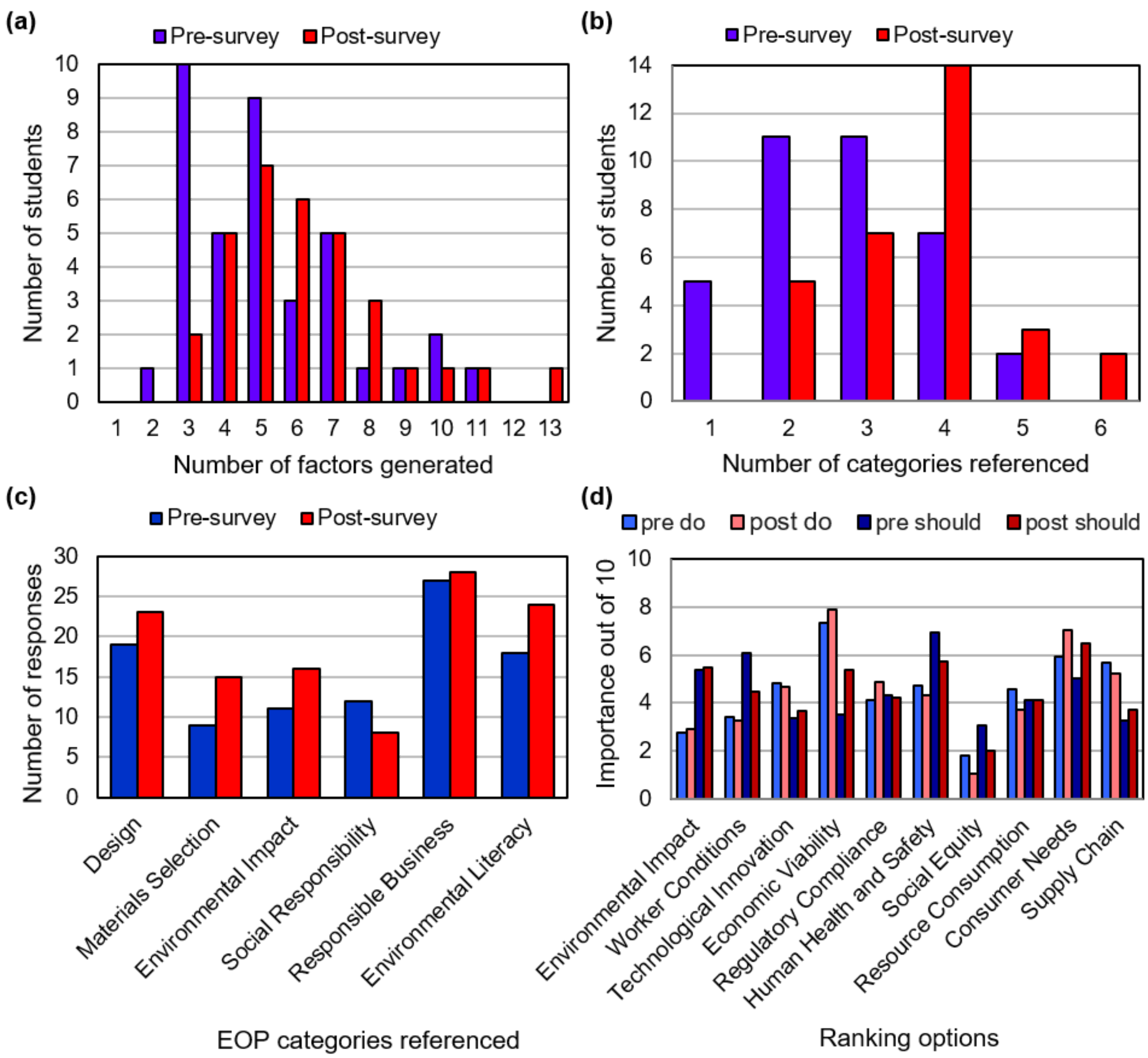

Figure 2: Survey results for student responses to questions 1-3. Question 1: *List what aspects companies should consider when designing a product.* An increase in (a) raw number of itemized factors generated and (b) the number of EOP framework categories referenced, was identified. This increase is represented by the shift of the answer distribution rightward between the pre-survey (blue) and the post-survey (red). (c) With the exception of social responsibility, there was a rise in responses for all EOP framework categories. (d) Student responses to question 2 and 3: *Rank the importance of given factors that companies do/should consider when designing a product*. Trends are weak and likely obscured by the number of factors.

Questions 2 and 3 asked students to rank, from most important to least important, a variety of factors that may play a role in engineering. The provided factors were *environmental impact, worker conditions, technological innovation, economic viability, regulatory compliance, human health and safety, social equity, resource consumption, consumer needs,* and *supply chain* (see Appendix for survey). Question 2 asked students to rank as they thought companies *do* rank these, with question 3 being how they thought companies *should* rank these. Rankings are shown in Figure 2d. A weak, but interesting trend that was observed was how the human-centered aspects changed in ranked importance. The aspects that stressed the treatment and well-being of people (worker conditions, human health and safety, social equity) decreased from the pre- and post- survey while the aspects that stressed human desires (economic viability and consumer needs) increased from the pre- and post-survey. This follows for both rankings how companies currently and should prioritize the different aspects. The other factors (environmental impact, technological innovation, regulatory compliance, resource consumption, supply chain) showed no clear pre- to post-course trends.

It should be noted that these trends are limited, and for most, incremental at best. We believe this may be due to asking the students to compare too many options with potential nuances in the options. However, it could also be affected by the structuring of the class topics. The human-desire aspects were introduced in module 1 and were revisited throughout the entire semester while some of the other aspects were specifically discussed little or late in the semester.

Question 4 was an open-ended question: *Define "sustainability" in the context of engineering design.* These responses were analyzed to see if students generated common definitions of sustainability. Answers frequently mentioned the environment and the lifespan of the product. No significant difference was observed between pre- and post-survey responses. Students did not include aspects of the EOP framework such as *Materials Selection* or *Design* that were discussed in class. This suggests to us that, while students have started to consider and weigh a wider range of factors for engineering design, those factors are not yet integrated into a broader definition of sustainability.

Questions 5 and 6 asked about the importance placed on sustainability, with question 5 being *How important do you believe sustainability is in the design of engineering products?* and question 6 being *How much do you think companies prioritize sustainability when designing their products?* Students were asked to rank the importance on a scale from 1-10, with 10 being the most important. Importance values were compared pre- and post-course. Comparing the pre- and post-course survey responses displayed essentially no change in response. For question 5, students gave average personal importance values of 8.8 ± 1.0 pre-course and 8.5 ± 1.4 post-course. For question 6, students gave average company importance values of 6.2 ± 1.9 pre-course and 6.8 ± 1.8 post-course. For both pre- and post-course, the students positioned sustainability as slightly more important to the student than the company, which follows a larger trend across engineering showing increased attention to sustainability [13,14]. As the students already exemplify a strong desire to implement sustainable practices in engineering design, it is important that we continue to inform and encourage sustainable practices in future courses.

These survey results suggest mixed overall success in the goal of expanding students' definition of sustainability. The increase in factors listed in question 1 shows that students were able to recognize that there are more factors across a wider range of topics than the technical specifications that need to be considered in engineering design. However, the results of question

4 show those factors are not yet defined as part of "sustainability" in the students' mindsets. Student responses to the paired questions 2 and 3 as well as 5 and 6 indicate that students support a shift in industry practices to place greater emphasis on sustainability, which is an outlook we will continue to reinforce in future courses.

Conclusions

In conclusion, we integrated aspects of the EOP Framework into a first-year Introduction to Engineering Design course to help students understand the interconnectedness of design considerations in product development. Through the reverse engineering of a garbage disposal, students explored embedded design decisions within the system. The course was centered around the guiding question: "Which motor configuration is best suited for the application of a home garbage disposal system?" To demonstrate their understanding, students wrote memos for each module analyzing various aspects of the garbage disposal motor system.

The overall class structure of modules with guiding questions connected to the EOP framework will be continued in future iterations of this course. The memo-based assessments and student presentations provided valuable opportunities for students to begin to communicate like engineers. However, we need to explicitly discuss how each guiding question relates to a broader definition of sustainability earlier in the course. We plan to do so at the introduction of each module in future iterations. We will also integrate the areas of the EOP framework that were not integrated into this iteration, *Social Responsibility* and *Environmental Literacy*. *Environmental Literacy* will be integrated with *Environmental Impact*, as understanding one can help a student understand the other. While some students independently identified the importance of *Social Responsibility*, we will bring in discussions of it in each module. We will also continue to integrate the EOP framework in more depth in the sophomore-level design courses.

Comparisons between pre-course and post-course surveys revealed that students were able to recognize more factors that should be considered when engineering a product. Additionally, final reports indicated that students began weighing and comparing different factors when proposing design changes. However, they had not yet fully integrated these factors into their broader definition of sustainability.

The structure of an overarching class question, broken down into modules around sub-questions, provided essential scaffolding for students, while focusing on the motor kept the scope manageable. The course will continue to use the EOP Framework as a guide in reverse engineering projects to help students refine their understanding of sustainability and its application in design, preparing them to address the complex, multifaceted challenges of future engineering practice.

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Appendix: Survey given pre- and post-course

Question 1: List what aspects companies should consider when designing a product.

Question 2: Rank the importance you believe companies CURRENTLY place on each of the following aspects when designing a product. Put the most important aspect as 1 and the least important as 10.

________ **Environmental Impact** (carbon footprint, waste/disposal, pollution, etc)

________ **Worker Conditions** (fair wages and safety)

________ **Technological Innovation** (cutting-edge development)

________ **Economic viability** (making a profit)

________ **Regulatory Compliance** (following governmental rules and laws)

________ **Human Health and Safety** (avoiding harm during manufacturing)

________ **Social Equity** (fair distribution of benefits and burdens)

________ **Resource Consumption** (energy and material use)

________ **Consumer Needs** (demands and expectations of customers)

________ **Supply Chain** (accessibility of parts and materials)

Question 3: Rank the importance you believe companies SHOULD place on each of the following aspects when designing a product. Put the most important aspect as 1 and the least important as 10.

________ **Environmental Impact** (carbon footprint, waste/disposal, pollution, etc)

________ **Worker Conditions** (fair wages and safety)

________ **Technological Innovation** (cutting-edge development)

________ **Economic viability** (making a profit)

________ **Regulatory Compliance** (following governmental rules and laws)

________ **Human Health and Safety** (avoiding harm during manufacturing)

_________ **Social Equity** (fair distribution of benefits and burdens)

_________ **Resource Consumption** (energy and material use)

_________ **Consumer Needs** (demands and expectations of customers)

_________ **Supply Chain** (accessibility of parts and materials)

Question 4: Define "sustainability" in the context of engineering design.

Question 5: How important do you believe sustainability is in the design of engineering products? 1 = not important, 10 = Extremely important

1 2 3 4 5 6 7 8 9 10

Question 6: How much do you think companies prioritize sustainability when designing their products? 1 = not important, 10 = Extremely important

1 2 3 4 5 6 7 8 9 10